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Thermal Water–Supplied Swimming Pools: A Scoping Review of Regulatory Frameworks, Disinfection Challenges, and Emerging Contaminants

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Thermal Water–Supplied Swimming Pools: A Scoping Review of Regulatory Frameworks, Disinfection Challenges, and Emerging Contaminants

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What are the main findings?

- Thermal pools combine therapeutic benefits with complex health and safety risks.
- Global regulations are fragmented and lack harmonized standards.
- DBPs, CECs and AMR emerge as underexplored risks in thermal pool systems

What are the implications of the main findings?

- Disinfection strategies must balance microbiological safety and water integrity.
- Harmonized regulations are needed for safe thermal pool management.
- One Health approaches can guide sustainable thermal water use.

Abstract

Thermal water–supplied swimming pools are increasingly used worldwide for recreation, wellness, and therapeutic purposes. However, their management presents unique challenges due to the complex physicochemical properties of thermal and mineral waters and the need to ensure microbiological safety while preserving their natural characteristics. This scoping review examines the main health benefits and safety issues associated with thermal pools and provides a comparative analysis of regulatory frameworks governing these facilities in 39 countries worldwide. Particular attention is dedicated to microbiological hazards, chemical risks related to disinfection practices, and the potential formation of disinfection byproducts (DBPs) in treated thermal waters. The review also discusses emerging contaminants (CECs), including pharmaceuticals and personal care products (PPCPs), and the potential role of thermal water environments in the spread of antibiotic and antimicrobial resistance. The analysis highlights significant global heterogeneity in regulatory approaches, especially regarding disinfection strategies and water quality monitoring. Interactions between natural water composition, anthropogenic contaminants, and disinfection processes may create chemically complex mixtures whose toxicological implications remain insufficiently studied. Adopting a One Health perspective, this review emphasizes the need for integrated management strategies and more harmonized regulatory frameworks to ensure the safe and sustainable use of thermal water pools.

Keywords: thermal water pools; public health; emerging chemical contaminants (CECs); pharmaceuticals and personal care products (PPCPs); disinfection by-products (DBPs); antimicrobial resistance (AMR); antibiotic resistance; microbiological safety; environmental sustainability

1. Introduction

The global use of thermal waters has experienced substantial growth in recent years, driven by the rapid expansion of the wellness economy and a renewed scientific and clinical interest in the therapeutic properties of mineral-rich waters. Thermal and mineral waters have long been used in balneotherapy and spa medicine, and increasing scientific evidence supports their potential therapeutic role in several chronic conditions. Recent systematic reviews and meta-analyses have reported beneficial effects particularly in dermatological diseases, musculoskeletal disorders such as osteoarthritis, and frailty associated with rheumatic conditions, with improvements observed in pain reduction, functional status, and quality of life [1–4].

The therapeutic effects of thermal waters are traditionally attributed to their distinctive physicochemical composition, characterized by high concentrations of inorganic minerals and trace elements, often combined with bioactive organic compounds of natural origin. These characteristics may contribute to anti-inflammatory, analgesic, and immunomodulatory effects observed in several therapeutic applications [5].

Recent economic data highlight the magnitude of this sector. According to the Global Wellness Institute, the global wellness economy reached a value of approximately $6.8 trillion in 2024 and is projected to grow at an annual rate of about 7.6%, potentially reaching $9.8 trillion by 2029. Within this global market, the thermal and mineral springs sector currently includes more than 31,000 establishments across 130 countries, generating direct revenues of approximately $71.7 billion—over one third higher than pre-pandemic levels [6,7].

However, this growth raises significant challenges regarding water quality management and public health safety [7]. Thermal waters, naturally rich in minerals and often maintained at elevated temperatures, represent favourable environments for the proliferation of opportunistic pathogens and the development of complex microbial communities and biofilms within water systems [8–10]. Recent environmental studies have also highlighted that recreational hot springs may act as environmental reservoirs of potentially multidrug-resistant microorganisms and antibiotic resistance genes, raising additional concerns for public health and environmental safety [8].

The fundamental challenge lies in balancing the preservation of the water's natural physicochemical properties with the need for effective disinfection to protect users, who may be particularly vulnerable due to underlying health conditions. In this context, the existing regulatory framework for thermal waters remains highly heterogeneous. While some jurisdictions emphasize the preservation of the “original purity” and therapeutic integrity of the source water, limiting invasive chemical treatments [11], others simplify management by assimilating thermal facilities to conventional swimming pool standards [12]. This lack of harmonization complicates the implementation of standardized safety protocols and evidence-based risk management strategies [9,12,13]. The use of disinfectant agents, while essential to ensuring microbiological requirements, particularly in indoor environments, triggers unintended chemical reactions with the water’s mineral matrix and organic matter (both natural and exogenous) [14]. This leads to the formation of disinfection by-products (DBPs) [15,16] whose concentration and toxicity are often exacerbated by the unique chemical signature of thermal waters. The management of these compounds, combined with the health risks posed by emerging contaminants (CECs) [17] and environmental contamination from untreated thermal wastewater containing pharmaceutical or chemical residues, represents the key issues for the sustainability and safety of modern thermal facilities [17,19–21].

The need for this review arises from the rapid expansion of facilities using thermal waters, not only for traditional spa treatments but also for wellness, rehabilitation and sport [5], which exceeds the speed of the development of integrated safety guidelines and highlights existing gaps. To date, they remain fragmented, focusing separately on health benefits and microbiological or chemical risks, without cohesive synthesis. Furthermore, a modern analysis cannot ignore the implications of One Health and Planetary Health [22]. Emerging research suggests that DBPs and chemical stress within aqueous matrices can act as selective pressures, potentially promoting the spread of antimicrobial

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resistance (AMR) in the environment [8,23,24]. Therefore, thermal water management is no longer just a matter of users' safety, but a broader challenge for public health and environment integrity.

The objective of this scoping review is to provide a critical and integrated assessment of the complex issues surrounding thermal facilities by jointly analysing their therapeutic benefits, health safety risks, and environmental implications. Particular attention is also devoted to the analysis of existing regulatory frameworks governing thermal water management, highlighting differences in national and international approaches and the challenges associated with harmonizing safety standards. By integrating evidence from clinical, environmental, and regulatory perspectives, this review aims to identify current knowledge gaps and contribute to the development of sustainable and evidence-based management strategies for thermal facilities within a One Health framework.

The present review therefore addresses three interconnected dimensions: (i) documented health benefits of thermal water use; (ii) regulatory approaches governing thermal water facilities across different countries; (iii) microbiological and chemical risks associated with thermal pools.

2. Materials and Methods

This study is a scoping review conducted to map both the global legislative framework governing thermal water pools and emerging risks associated with their operation and related to disinfection, focusing on microbiological and chemical risks (DBPs), emerging contaminants (CECs), and the spread of antibiotic resistance (AMR). The review was conducted in accordance with the Joanna Briggs Institute (JBI) methodological framework [25] and is reported in accordance with the PRISMA-ScR checklist (Table S1 in Supplementary Materials).

A multidisciplinary research team of four members was established before starting the research: two specialists with backgrounds in environmental chemistry and water quality, a specialist in microbiology with expertise in aquatic microbial dynamics, and a senior researcher with specific expertise in hygiene, public health, thermal waters and systematic review methodologies, responsible for the methodological rigor of the review.

The literature search was conducted between January and February 2026. A two-pronged search strategy was employed:

- Regulatory Framework: Official institutional websites of national and local health authorities (Europe and international) and legislative portals were consulted to retrieve regulations and technical guidelines regarding swimming pools, thermal, mineral, and therapeutic water quality.
- Scientific Literature: Web of Science, Scopus, and PubMed were searched for peer-reviewed articles published up to February 2026.

The search used combinations of Boolean operators and keywords: “thermal water”, “thermal springs”, “swimming pools”, “disinfection”, “disinfection by-products”, “DBPs”, “emerging contaminants”, “antibiotic resistance”, “ARGs”.

Due to the scarcity of literature specifically addressing chemical risks in thermal waters, the search criteria were widened to encompass general pool environments and water systems. This broader approach was necessary to synthesize the mechanisms of DBP formation and AMR selection. To supplement this, we conducted also a manual 'snowball' search for the bibliographies of all relevant primary studies and review papers to ensure maximum coverage of the thermal water field.

Documents were included if they met the following criteria:

- Official regulatory texts or guidelines published in original languages.
- Scientific articles and reviews published in English and focusing on water quality, safety, and disinfection methods, with primary focus on thermal pools and spas.
- Scientific research providing primary data on physicochemical parameters, DBP formation and microbiological risks, including the spread of antibiotic resistance genes (ARGs) in water.

The selection process followed two distinct pathways:

- Scientific literature: A two-stage screening process was applied. Initially, titles and abstracts were screened for relevance, followed by a full-text review by two independent reviewers.
- Regulatory documents: Regulations and technical guidelines were directly evaluated for their applicability to thermal water and swimming pool safety standards.

Discrepancies in both pathways were resolved through consensus or consultation with a third team member. The data were synthesized using a thematic approach, categorizing the findings into key sections: (1) description and classification of swimming pools and spas, (2) global regulatory framework (organized alphabetically by country in Table 1), (3) microbiological risks, (4) state-of the art of thermal water disinfection, (5) chemical DBP-related risks for human health and environment, (6) risk of antibiotic resistance, (7) chemical CECs-related risks.

3. Results

3.1. Conceptual Framework

The expression "thermal water–supplied swimming pools" refers to aquatic facilities in which the filling water consists wholly or predominantly of natural mineral thermal waters originating from geothermal aquifers, whose chemical, physical, and biological characteristics are at least partially preserved within the artificial pool environment. This definition is not merely technical but conceptual, as these systems occupy an intermediate position between traditional balneotherapy environments and conventional recreational swimming pools. As discussed in the public health framework proposed by Valeriani and colleagues [9], thermal waters possess a specific "identity" linked to their mineral composition and ecological origin. Consequently, their management involves a fundamental dilemma between preserving their natural properties and ensuring adequate microbiological safety.

Natural thermal waters are typically characterized by elevated emergence temperatures and by a relatively stable mineral fingerprint. Hydrochemical classification is commonly based on fixed residue and dominant ions, including bicarbonate, sulfate, chloride, calcium, and magnesium [26]. In sulfur-rich contexts, hydrogen sulfide, sulfates, and other reduced sulfur species may occur in biologically relevant concentrations [26,27]. These compounds are not chemically inert; rather, they are redox-active molecules capable of interacting with biological systems. As highlighted in recent molecular analyses of sulfur compounds in mineral waters, hydrogen sulfide acts as a gasotransmitter involved in vasodilation, redox signaling, mitochondrial regulation, and modulation of inflammatory pathways [1–3]. Thermal water should therefore not be considered simply as heated water containing dissolved salts, but rather as a chemically and biologically active exposure matrix [28,29].

In addition to their mineral composition, natural thermal waters host specific microbial communities adapted to defined physicochemical conditions. The concept of a "microbial signature," increasingly explored through next-generation sequencing approaches, supports the view that spa waters represent ecological systems in which chemical and biological components are closely interconnected [29,30]. The presence of sulfur compounds, for instance, may select for sulfate-reducing bacteria and other specialized microbial populations, contributing to the ecological uniqueness of each thermal spring. When such waters are transferred into artificial pool systems, hydraulic management, aeration, dilution, and possible treatment processes may alter both mineral equilibrium and microbial community structure, potentially modifying the characteristics that underpin their therapeutic claims.

Temperature represents another defining parameter of thermal bathing environments. Balneotherapy protocols generally involve immersion in warm mineral waters, most commonly within the range of 35–38 °C, as consistently reported in clinical studies addressing dermatological and musculoskeletal conditions [1–3]. This temperature range is not merely a comfort factor but a biologically active stimulus capable of influencing thermoregulation, peripheral vasodilation, hydrostatic pressure dynamics, and autonomic balance. The thermal component contributes to anti-inflammatory and immunomodulatory responses through neuroendocrine mechanisms, including β-endorphin release, and has been associated with improvements in pain perception, functional capacity, and quality of life in patients affected by psoriasis and osteoarthritis [1–3].

However, elevated temperatures also introduce important safety considerations. Warm aquatic environments favor microbial proliferation and biofilm formation and may increase the volatility of dissolved gases, including hydrogen sulfide in sulfur-rich waters. In addition, higher temperatures accelerate the kinetics of chemical reactions, particularly those leading to disinfection by-product formation when oxidizing agents are applied [21]. Temperature therefore acts simultaneously as a therapeutic parameter and as a variable influencing potential health risks within thermal pool systems.

Thermal water–supplied swimming pools frequently operate as mixed or integrated systems in which natural mineral water is partially diluted with freshwater and managed through recirculation and filtration. In such systems, the application of conventional disinfectants may alter mineral equilibria and interact with naturally occurring compounds, particularly in high-salinity or sulfur-rich waters [21]. Molecular studies on sulfur species further indicate that oxidative treatments may shift the equilibrium between reduced and oxidized sulfur forms, potentially modifying both biological activity and chemical safety profiles [22]. Consequently, thermal pools cannot be managed exclusively according to the same criteria applied to conventional freshwater pools but require tailored, site-specific Water Safety Plans integrating hydrochemistry, microbiology, and exposure assessment.

In light of these considerations, thermal water–supplied swimming pools should be conceptualized as hybrid ecological and technological systems rather than simple recreational infrastructures. They represent environments in which mineral chemistry, sulfur redox biology, microbial ecology, thermophysiology, and hydraulic engineering converge. Preserving the therapeutic identity of thermal waters while ensuring user safety therefore requires integrated governance models capable of respecting the chemical and biological uniqueness of these waters while maintaining modern standards of public health protection.

3.2. Regulatory Framework and Guidelines

The global regulatory landscape for thermal water pools is characterized by high heterogeneity and a lack of harmonized international standards. The main challenge is the need to reconcile two often different and conflicting regulatory frameworks: those governing public health in recreational facilities, and the specific sector for thermal, mineral and medicinal waters. As summarized in Table 1 which provides an overview of regulations across 39 countries and 4 continents [31–144], the management of thermal water facilities often requires a delicate balance between ensuring microbiological safety through disinfection and preserving the intrinsic physicochemical and therapeutic properties that define "thermal" or "medicinal" status. The survey reveals a "regulatory spectrum": some countries strictly separate thermal waters from conventional pool regulations to prevent chemical alteration of the source; and others mandate standard disinfection regardless of the water's origin. This complexity is illustrated by the following examples:

Albania: The Regulation VKM 835/2011 [31] concerns swimming pools (sports and recreational), filled with water for portable use, but does not cover thermal waters, considered to be mineral and medicinal resources. These waters are regulated by Law No. 111/2012 [32], and they are subject to authorization from the national agency. The country tends to follow the principle of non-alteration of thermal waters, so as not to nullify their healing effects, favoring continuous water renewal.

Australia: The regulation of public recreational aquatic facilities follows a territorial model, where federal states hold primary legislative responsibility for public health. For instance, New South Wales regulates public pools and spas under the NSW Public Health Regulation 2022 [33], which explicitly excludes "natural swimming pools" and does not specifically define thermal waters. However, states like Queensland [34], Victoria [35], and Western Australia [36] provide the guidelines or codes of practices for safety of public swimming pools, spas and facilities such as

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"hydrotherapy pools". The latter are defined as heated water environments used for therapeutic needs, including rehabilitation and fitness. While not explicitly mentioning natural spring o thermal water they represent the closest regulatory equivalent for therapeutic treatments. These facilities are not exempted from mandatory disinfection; notably, Australian Standard AS 3979-2006 [37] provides technical recommendations, discouraging saltwater chlorinators and bromide-based disinfectants for these environments. Microbiological compliance is rigorous, requiring the absence of coliforms and *P. aeruginosa*, with mandatory monitoring for Legionella.

Austria: The regulatory framework is hierarchical and well-defined. The Federal Law (BHygG) [38] provides the legal basis for health protection in all public bathing establishments, including those thermals using water from a local natural healing resource. The technical implementation of the law is entrusted to the Regulation (BHygV 2012) [39], which specifies the microbiological and physicochemical parameters and permits deviations from these regulations for thermal facilities, provided that they are due to the natural characteristics of the natural healing resource and that the hygienic quality of the bathing water does not pose a risk to the health of bathers. This federal system is complemented by regional laws on natural healing resources and health resorts, which are similar for the Länder (e.g., the most recent ones in Upper Austria and Salzburg [40,41]), specifically governing the recognition and protection of healing and thermal springs.

Belgium: Hygiene regulations for swimming pools are regionalized, and the management of therapeutic baths is integrated into general pool legislation. In Brussels, the Government Decree of 16 February 2023 [42], prioritizes water from the public distribution network, though alternative sources are permitted if they meet drinking water standards at the intake. In Flanders, VLAREM II [43] defines "therapy pools" as circulatory pools used exclusively for medical treatments. This regulation requires continuous disinfection and compliance with the same physicochemical parameters as other pools, apart from the maximum temperature limit. While natural (biological) pools are permitted, they cannot be considered thermal pools as their temperatures must remain below 23°C to ensure safety. In Wallonia, home to the historic "Spa" springs, thermal waters are subject to the Water Code for extraction and protection, but the basins themselves must comply with the "Government Decree on the conditions relating to covered and open swimming pools used for purposes other than purely private use 13 June 2013" [44], which govern hygiene and safety. Across all regions, microbiological safety remains paramount: all public facilities are subject to strict limits (e.g. for *E. coli* and *P. aeruginosa*) and rigorous *Legionella* prevention protocols, with no exceptions granted for the water's natural mineral origin. However, Brussels offers some microbiological derogation for uncovered swimming pools and other baths with biological treatment, upon a reasoned request.

Brazil: Recreational waters such as swimming pools are regulated by national technical standards, primarily NBR 10339:2018 [45] and NBR 10818:2016 [46], which define the technical criteria for pool construction, operation, and water quality. Specifically, NBR 10339 categorizes swimming pools by water type, explicitly allowing the use of "medicinal water", while NBR 10818 establishes water microbiological and physicochemical parameters for bathing safety. Furthermore, mineral and thermal water are governed by the National Mining Agency (Mineral Water Code of 8 August 1945 (as amended) [47]. It outlines the procedures for the official analysis and exploitation of mineral and thermal waters, including those intended for spas purposes. In practice, the management of thermal pools requires a balance between the sanitary requirements of NBR 10818 and the preservation of the water's medicinal properties as mandated by mining regulations.

Bulgaria: The safety management of therapeutic and recreational waters is regulated by a centralized state legislative framework. While "Instruction No. 34 on hygiene of sports facilities and equipment" [48] provides hygiene requirements for water in sports swimming facilities, it does not specifically address medicinal waters. The therapeutic use of mineral water and the operation of balneology centres and spas are regulated by the Health Law through the ordinances. Specifically, "Regulation No. 14 of 1987 on resort resources, resort areas, and resorts" [49] serves as primary guide for the declaration, categorization, and protection of curative resources. It stipulates that mineral

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waters used for medicinal and recreational purposes must be microbiologically compliant to ensure consumer safety, requiring, for example, the total absence of coliforms and *P. aeruginosa*.

Canada: Safety requirements for water in recreational swimming facilities are not established by the federal government but independently by the provinces through their respective legal acts or guidelines. Alberta regulates aquatic facilities via its "Pool Standards, July 2014" (as amended) [50]. The regulation rules apply to all types of public pools, including therapeutic ones, without specific mention of hot springs, mineral, or therapeutic water. It mandates disinfection using chlorine-based or other oxidizing agents and sets free chlorine residual levels based on water temperature. It also regulates pH and alkalinity, as well as microbiological indicators (e.g., the absence of *P. aeruginosa* when water temperature exceeds 30°C and the absence of coliforms). British Columbia applies the "Public Health Act Pool Regulation 296/2010" (as amended) [51] to all public swimming pools. Article 10 mandates that the "microbiological quality of pool water must not present a risk to the health of users patrons" and prescribes pH and alkalinity levels, allowed disinfectants (chlorine and bromine), and their concentrations based on water temperature. It also sets requirements for circulation rates, though providing exemptions from some of these provisions for specific hot spring pools. The specific microbiological indicators to be monitored (e.g., total and fecal coliforms, *E. coli* and *P. aeruginosa*) are detailed in the "BC Guidelines for pool operations 2025" [52]. Nova Scotia's "Operational guidelines for aquatic facilities 2014" [53] apply to all public spas, hot tubs and therapeutic spas. These guidelines require more intensive disinfection, primarily with chlorine compounds or, more frequently, bromine for the latter, due to higher contamination loads resulting from lower water volumes and higher temperatures. Ontario's "R.R.O. 1990 Regulation 565: Public Pools" (as amended) [54] applies to all public pools and spas, without specific mention of therapeutic use or water. It requires that water be safe for bathers and disinfected with chlorine- or bromine-based compounds (either alone or with secondary UV treatment). It regulates pH and alkalinity and requires a higher residual disinfectant for water temperatures exceeding 35°C. Microbiological indicators are regulated by a series of supplementary guidelines, e.g., "Legionella investigation reference document 2025" [55]. Quebec's "Regulation respecting water quality in swimming pools and other artificial pools (Q-2, r. 39)" [56] applies to public pools and whirlpools. It requires disinfection with a residual effect and mandates strict control of fecal coliforms, *E. coli* and *P. aeruginosa* (< 1 CFU/100mL), *Staphylococcus aureus* (< 30 CFU/100mL), as well as various physicochemical indicators. Notably, it explicitly does not apply to pools used solely for medical and rehabilitation purposes, which are managed under the clinical therapeutic protocols.

China: Water safety is governed by a tiered system led by the mandatory national standard GB 37488-2019 "Hygienic indicators and limits for public places" [57], which defines the mandatory hygiene baseline for different public facilities, not only aquatic, to protect human health. While this standard covers artificial and natural pool waters, it does not explicitly categorize thermal waters. The requirements for water in conventional swimming pools are further detailed in technical non mandatory standard CJ/T 244-2016 "Swimming pool water quality standard" [58], which imposes more stringent microbiological and physicochemical parameters than the national GB baseline; however, its scope is limited to artificial pools for sports and recreation, excluding sea- and thermal waters. Thermal facilities are specifically regulated by the touristic industry standard LB/T 081-2020 "Water hygienic quality requirements and management specification of hot spring tourism" [59]. This sector-specific standard acknowledges the natural characteristics of hot springs by allowing more flexible limits, such as a broader pH range and a higher threshold for total coliforms (< 10 CFU/100mL, compared to the total absence required in conventional pools). Conversely, safety remains non-negotiable regarding key pathogens, mandating the total absence of *P. aeruginosa* and *L. pneumophila*. Notably, while disinfection is required by permitting chlorine, ozone, UV, bromine or peroxides, specific limits for DBPs in thermal waters are currently not regulated under this standard.

Croatia: The health safety of swimming pool water is addressed by Ordinance 59/2020 [60], which explicitly excludes from its scope pools using water of a specific composition with medical indications (e.g., thermal, sulfur or other waters with proven therapeutic properties) where disinfection with a residual effect is not performed. These waters are specifically regulated by "Ordinance 79/2019 on health services in health tourism" [61], which defines natural medicinal water by mineralization more than 1 g/L or a source temperature more than 20°C. Crucially, this Ordinance prescribes that water used for balneotherapy must not be disinfected or reused; its purity must be maintained through total daily replacement (continuous flow). Microbiological safety is strictly enforced with a zero-tolerance limit for *E. coli*, *Enterococci*, *P. aeruginosa*, and *Legionella pneumophila*. If the water is chemically disinfected, it loses its therapeutic status and must comply with standard swimming pool regulations of Ordinance 59/2020.

Cyprus: New "Swimming Pool Regulations of 2025" [62] governing the operation, hygiene, water safety, and maintenance of swimming pools came into force recently. Although the term 'mineral water' is not explicitly used, the regulation includes similar facilities through a dedicated Annex 5 (Rules for hydrotherapy centers, hydromassage, spas and relative facilities). Furthermore, the document mandates that the water in the basins must be chemically and microbiologically suitable, meeting prescribed requirements such as pH, total alkalinity, and residual chlorine, while ensuring the total absence of *E. coli* and *P. aeruginosa* through regular disinfection.

Czech Republic: The public safety of recreational waters is regulated by a dual system. Decree 238/2011 [63] defines hygiene requirements for swimming pools and saunas, regulating the safety, quality, and disinfection of all facilities, including those supplied by natural healing or mineral springs. Complementarily, Law 164/2001 (Spa Act) [64] regulates the classification, certification, and protection of natural healing resources, mineral waters, natural healing spas, by defining water for medicinal use based on specific thresholds (dissolved solids ≥ 1 g/L, CO_2 ≥ 1 g/L, content of another chemical element significant for health, temperature > 20°C or radon radioactivity > 1.5 kBq/L). Decree 238/2011 introduces essential exemptions to preserve the therapeutic integrity of these waters. Annex 8 specifies that limit values for free and combined chlorine, turbidity and colour do not apply for hot waters when deviations are caused by the natural properties of the resource and the water is not technically disinfectable without altering its chemical composition. To compensate for reduced residual disinfection, the Decree mandates strict microbiological surveillance (Annexes 8 and 9) regarding *E. coli*, *P. aeruginosa* and *Legionella spp*, with testing frequencies ranging from 14 to 30 days depending on water temperature and aerosol risk.

Denmark: Water safety in swimming facilities is governed by "Executive Order on swimming pools and their water quality BEK 918/2016" [65] and Guidance on controlling swimming pools VEJ 9605 [66]. The regulation framework does not specifically address the use of natural medicinal or thermal waters, mentioning only portable or surface water. It contains a specific provision prohibiting disinfection for pools using surface water (e.g., fjord- or seawater), managing their safety through weekly microbiological monitoring of *E. coli* and *Enterococci*. Conversely, hot water (32–37°C) and therapeutic pools are subject to the most stringent requirements due to their high organic load: they require high free chlorine residuals (1.0–2.0 mg/L), mandatory overflow channels, and rigorous monitoring for *P. aeruginosa* (<1 CFU/100mL) and *Legionella* (<10 CFU/L). For these facilities, authorities may impose additional site-specific operational requirements to compensate for limited disinfection capacity.

Estonia: Thermal and therapeutic pools operate under a transitional framework. The recent "Requirements for swimming pools, bathing establishments, and aquatic centres No. 38" [67] removed the previous explicit exclusion for therapeutic mineral water pools; however, it still exempts facilities using continuous flow-through systems from its requirements. While the "Health protection requirements for mineral water and spring water No. 62" [68] remain in force, they do not explicitly regulate natural mineral water used for therapeutic purposes in pools. Consequently, these facilities are supervised by the Health Board (Terviseamet) under Regulation No. 38. Specifically, they benefit from derogation from chlorination, if alternative methods or continuous flow-through systems ensure disinfection without harmful residuals. This allows spas to preserve the water' natural composition while ensuring microbiological safety. Monthly inspections (publicly available on the

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Terviseamet database) enforce strict mandatory limits: 0 CFU/100mL for *P. aeruginosa*, <20 CFU/100mL for Coliforms, and <10 CFU/100mL for Enterococci.

Finland: The legislative focus is on health protection rather than the geological origin of the water. Consequently, there is no mention or distinct legal classification for "natural mineral thermal water." All aquatic facilities, including public swimming pools, spas, rehabilitation and similar facilities, are governed by a single regulatory framework: the "Health Protection Act 763/1994" [69], while the technical requirements for water disinfection and quality parameters are specified in "Decree on the quality requirements and monitoring studies for pool water in swimming pools and spas 315/2002" [70].

France: The Public Health Code (Book III) [71] addresses the general principles for water safety through a dual-track system. Title II (Articles R1322-1 to R1322-67) specifically governs natural mineral waters, including those utilized for therapeutic purposes in thermal establishments. Instead, Title III (Articles D. 1332-1 to D. 1332-54) regulates recreational swimming pools. Article D. 1332-1 bridges these two blocks, exempting "thermal pools fed by natural mineral water used exclusively for therapeutic purposes" from general pool regulations provisions, except for disinfection requirements. In addition, water quality limits are established by specific Orders. Recreational aquatic facilities must comply with the Orders of 26 May 2021 on swimming pool water (covering both potable [72] and and non-potable [73] supplies). In contrast, thermal facilities are subject to the "Order of 14 October 1937 on the control of mineral water sources" (amended by the Order of 19 June 2000) [74] and the "Order of 22 October 2013 on the control and monitoring analyses of bottled water and natural mineral water used for therapeutic purposes in thermal facilities or distributed in a public drinking fountain" (amended by the Order of 30 December 2022) [75]. Microbiological requirements for thermal facilities are notable stringent: mandating the total absence of *E. coli, Enterococci*, *P. aeruginosa*, and *S. aureus*, as well as *Legionella pneumophila.* Physicochemical monitoring includes pH, conductivity, temperature, alkalinity and characteristic mineral elements (e.g., chlorides, sulfates, total sulfides) [74]. Furthermore, the amended "Order of 22 October 2013" [75] mandates the monitoring of DBPs such as trihalomethanes. This ensures that DBPs remain within the health safety limits when thermal water undergoes disinfection for use in public pools (aligning with the 2021 Order [73]).

Germany: The regulatory framework is highly standardized, centred on Section 37 of the Infection Protection Act (IfSG) [76], which mandates that pool water quality should conform to internationally recognized technical standards, specifically the DIN 19643 series [77–81]. "DIN 19643, Part 1: General requirements" [77] is comprehensive, covering also mineral and therapeutic waters. The core philosophy is preventive safety: water must be microbiologically pure (e.g., free from *E. coli* and *P. aeruginosa*) before it enters the pool. While officially recognized mineral and thermal waters are considered safe, specific chemical risks such as high arsenic content must be mitigated. Given the high temperatures and the vulnerability of therapeutic pool users, safety is achieved through multi-stage physical barriers, namely the specific physicochemical treatments alone or in combination as set out in Parts 2–5 [78–81] of the standard. These treatments, including ozonation and ultrafiltration, are certified for a 99.99% microbiological retention. Regarding *Legionella*, the German approach transcends the concept of a "maximum limit" in favour of a "safe process". Monitoring the filtrate with action thresholds as low as 2 CFU/100mL transforms maintenance from reactive to predictive. This technological rigour protects patients while preserving the therapeutic integrity of the water, relying on advanced treatment rather than massive chemical dosing.

Greece: The hygiene framework for all public swimming pools is based on "Decree Γ1/443/1973 on swimming pools with instructions for their construction and operation" (as amended) [82]. It mandates a water recirculation-cleaning-disinfection system, using oxidative (chlorine or bromine) or non-oxidative disinfectant, alongside regular monitoring of physicochemical and microbiological parameters. Additionally, "Circular 23849/2024 Public health protection measures against Legionnaires' disease" [83] provides updated risk management protocols and measures. However, the spa sector operates under a specialized legal regime, currently regulated by Law No. 4875/2021

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[84] on management of tourist destinations and thermal springs, which classifies thermal spas as "natural healing resources" and assigns jurisdiction to the Ministry of Tourism. Spa facilities must obtain a specific "Special Operational Mark", certifying compliance with health standards and technical requirements for spa tourism. Unlike standard recreational pools, the microbiological quality of thermal waters is specifically governed by Ordinance 61438 [85]. It recognizes the possibility of operating thermal pools without residual chemical disinfection (chlorine), if safety is ensured through high water-turnover rates. It mandates that thermal waters intended for balneotherapy must meet the core requirements of Decree Γ1/443/1973 (Coliforms ≤15/100mL, *E. Coli* 0/100mL). Furthermore, it establishes differentiated limits for *P. aeruginosa*: <1/100mL for disinfected pools and a slightly higher tolerance of <10/100mL for non-disinfected thermal tanks. Notably, the decree imposes a strict limit for *Legionella* at <1/100mL for both types of facilities, ensuring a high level of protection even in the absence of residual disinfectants.

Hungary: The regulatory framework is based on "Decree 510/2023 on the establishment and management of public baths" [86], which regulates the safety of all public aquatic facilities, whether supplied with drinking, natural mineral or medicinal water. To protect the chemical and therapeutic integrity of these recognized and authorized waters, reference is made to "Decree 509/2023 on natural healing factors" [87]. Under Decree 510/2023, untreated medicinal water may only be used in facilities operating with continuous flow or filling-emptying systems. In such pools, water treatment and disinfection are permitted only if they do not alter the concentration of the authorized therapeutic components by more than 20%. In terms of water quality, Decree 510/2023 mandates that fill and refill water must be free of pathogens and harmful concentrations of physical, chemical or radiological substances. According to Annex 6, the facilities must ensure the absence of *E. coli*, *P. aeruginosa* and *Enterococci*. For heated thermal facilities, *Legionella* monitoring is also mandatory. Regarding chemical parameters, the competent health authority may grant derogations from the requirements of Annex 6 for facilities using recognized medicinal water, allowing natural mineral characteristics to supersede standard limits provided health safety is maintained.

Iceland: Public swimming pools and bathing areas are regulated by "Regulations on hygiene at swimming and bathing facilities 814/2010" (as amended) [88]. Its scope explicitly includes thermal pools, rehabilitation and sedimentary pools. While water must generally be filtered and disinfected, health authorities may grant exemptions from chemical disinfection after studying the microbial content of bathing water, as defined in Annex I, if water turnover is sufficient to maintain the microbiological standards defined. In such cases, the absence of disinfectants must be clearly indicated to the public. The mandatory limits set in the annexes are < 10 CFU/100mL for *E. coli* and < 1 CFU/100mL for *P. aeruginosa*.

Ireland: The regulatory framework for aquatic facilities is primarily based on a risk-based management approach rather than detailed statutory technical standards. Operational mmanagement of swimming pools and spas applies general principles of occupational safety and follows a risk-based approach supported by non-binding guidance, notably the "Swimming pool safety guidelines 2021" [89]. Consequently, monitoring of chemical and microbiological parameters is commonly based on internationally recognized technical guidance, particularly standards developed in the United Kingdom.

Italy: In the absence of a national law regarding water safety in public swimming pools (currently under development), reference is made to the "State-Regions Agreement of 16 January 2003" [90]. It defines the microbiological and physicochemical water quality parameters and establishes permitted treatment and disinfection methods (primarily with chlorine-based compounds). It also specifies that pools may be supplied with fresh-, sea- or thermal water, with the regulation of the latter two being delegated to specific regional provisions. The national spa sector is regulated by Law of 24 October 2000 No. 323 "Reorganization of the thermal sector" [91], which defines facilities that use natural mineral waters and establishes the institutional framework for the recognition and therapeutic use of thermal waters, approved by the Ministry of Health. Although it does not focus on the operational hygienic management of thermal pools, it emphasizes the

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preservation of their original physicochemical characteristics. Regarding *Legionella* prevention, the regulatory framework has been recently updated with "Legislative Decree of 19 June 2025 No. 102" [92], which considers <100 CFU/L as acceptable, with risk evaluation. Furthermore, the Decree of 10 February 2015 "Criteria for evaluating the characteristics of natural mineral waters" [93] is the key technical document for assessing therapeutic properties of mineral waters. It defines the parameters of water source to permit its therapeutic acknowledgement (e.g., pH, characteristic minerals, the absence of *E. coli*, coliforms, fecal streptococci, *P. aeruginosa*, sulfite-reducing anaerobes and *Staphylococcus aureus*). Treatments such as ozone are permitted provided that the chemical and therapeutic properties remain unchanged. Additionally, the regions adopted laws on "Regulations for the research, cultivation and use of mineral and thermal waters" [] (e.g., Lombardy (Regional Law 44/1980) [94], Tuscany (Regional Law 38/2004) [95] and Veneto (Regional Law 40/1989) [96]). They typically govern the authorization and protection of natural thermal water resources, requiring that their physicochemical and healing characteristics be preserved during treatment. However, in the absence of specific regulations defining parameters for assessing chemical and hygienic safety, pool spring water testing is sometimes based on regulations applicable to bottled mineral waters [97].

Japan: The use and protection of the therapeutic integrity of hot springs are regulated by the Hot Spring (Onsen) Law [98]. However, the hygienic safety of public swimming pools (except for school pools, governed by separate legislation) is specifically addressed by the "Swimming pool hygiene standard 2007" [99]. This document stipulates that pools filled with hot spring or seawater, provided they operate with a continuous water exchange, may be granted exemptions for certain disinfection and physicochemical parameters, should the natural properties of the raw water necessitate it. Nevertheless, strict microbiological compliance remains mandatory: *E. coli* must be absence and *Legionella* monitoring is required, with a strict limit of less than 10 CFU/100mL [100].

Latvia: "Hygiene requirements for swimming pools and saunas No. 470" [101] applies universally to all public aquatic facilities for sports, including those using mineral or seawater. The regulation specifically exempts fill water from the requirement to meet drinking water safety standards if it is certified mineral water, but there are no specific requirements regarding disinfection. It only mandates that, if the pool is supplied with mineral water, its quality must comply with the microbiological quality indicators listed in Annex 2, including the complete absence of *E. coli*, *P. aeruginosa* and helminths.

Lithuania: The regulatory framework is bifurcated to balance efficient disinfection with the preservation of mineral water properties. General swimming pool safety is governed by Hygiene Norm HN 109:2016 [102], which mandates continuous disinfection, typically using chlorine compounds (alone or with UV/ozone) or bromine compounds (with ozone), alongside strict microbiological limits. For thermal and seawater, Hygiene Norm HN 127:2010 [103] introduces a context-specific approach: when used in general recreational or sports pools, the water must be disinfected and meet the physicochemical requirements of HN 109:2016, in case of therapeutic use in baths, chemical disinfection is not required. Safety is instead guaranteed by a mandatory protocol requiring total water exchange and tub disinfection after each use. In both cases, microbiological indicators must strictly comply with HN 109 limits (e.g., total absence of *E. coli*, *P. aeruginosa*, coagulase-positive *Staphylococci*, and *Legionella spp*.). Furthermore, the regulation provides a detailed classification of therapeutic waters based on temperature, pH, and chemical composition to strictly regulate their medicinal application.

Malta: The regulatory framework is centred on the "Swimming pool regulation L.N. 129/2005" (as amended) [104], which applies to all public and commercial swimming pools, spas and special-purpose pools, regardless of whether they use fresh, sea, or mineral water. It stipulates that pool water shall be disinfected using the methods described in Annex V (e.g., chlorine and bromine-based substances, alone or with ozone; UV light; peroxide). Although the Regulation does not provide broad exemptions for disinfection, Annex I reveals a "dual-track" structure for microbiological safety, distinguishing between disinfected and non-disinfected facilities. While the absolute absence of *E. coli* and *Staphylococcus aureus* is mandatory for all pool types, there are concessions for non-disinfected

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pools and spas, allowing a tolerance level for *P. aeruginosa* of up to <10/100mL. Furthermore, *Legionella* control is required in hot tubs and spas, where the action threshold is set at <1,000 CFU/L. Note 1 acknowledges that for non-chlorinated spas, safety may be ensured through operational protocols such as the "fill-and-drain" method or thermal shock treatment (70 °C), rather than continuous chemical dosing.

Netherlands: The safety of aquatic facilities is regulated by the "Decision on living environment activities (Bal)", Chapter 15 [105]. The Bal does not provide specific guidance for mineral or therapeutic waters, requiring that the intake water used for filling pools meets the quality requirements for drinking water. It contains a section that applies to swimming facilities where the water is disinfected, allowing the use of chlorine compounds and ozone. It also regulates certain physicochemical parameters (with specific deviations for pools with a salt content higher than 14 g/L) and microbiological parameters, requiring: *P. aeruginosa*, intestinal *Enterococci* and spores of sulfite-reducing Clostridia to be < 1 CFU/100mL and *Legionella* < 100 CFU/L.

Norway: General hygiene and water quality in aquatic facilities are governed by the "Regulation of 1996 for swimming facilities, swimming pools and saunas" [106], which applies to a wide range of pools, including saunas, whirlpools and therapy pools, though it does not explicitly categorize mineral or therapeutic waters. The regulation mandates that water be continuously disinfected to prevent microbial growth, specifying chlorine levels (if chlorine is used), based on water temperature and requiring the absence of P. aeruginosa. Additionally, due to the high risk of legionellosis, the "Regulations of 2003 on environmental health protection" [107] mandate rigorous, documented risk assessments and systematic maintenance for heated aerosol-producing aquatic facilities.

Poland: Recreational water facilities are regulated by the "Ordinance of 9 November 2015 on the requirements for swimming pool water" (as amended) [108]. This Ordinance explicitly excludes pools filled with water with medicinal properties, specifically referring for them to the "Act of 28 July 2005 on spa treatments, spa and spa protection area" (as amended) [109]. Consequently, therapeutic basins are subject to specialized technical provisions, such as the "Ordinance of 13 April 2006 on the research required to establish therapeutic properties of natural medicinal raw materials" [110]. It mandates the physicochemical and microbiological criteria for classifying water as medicinal. If intended for bathing, such water must be meet specific limits for turbidity, PAHs, nitrates, and be free of *E. coli*, *Enterococci* and *P. aeruginosa*. Additionally, the "Ordinance of 31 March 2011 on natural mineral waters, spring waters and table waters" [111] prohibits treatments that alter the water's natural microbiota. Since January 2025 spas must also comply with the "Ordinance of 30 September 2024 on the requirements to be meet by spa treatment facilities and equipment" [112]. It allows open therapeutic pools and rehabilitation pools to operate using systems based on continuous water inflow and outflow. Alternatively, partially closed therapeutic pools may treat intake water using physical and chemical methods outside the pool, provided the medicinal water retains its properties during operation.

Portugal: The regulation follows a two-pronged approach, seeking to balance the safety of bathing water with the physicochemical and therapeutic integrity of the source. According to "Circular-Regulatory No. 14/DA of the Directorate General for Health" [113], thermal facilities and hydrotherapy pools are explicitly classified as Type 2 (semi-public). This classification subjects them to the national standard NP 4542:2017 "Swimming pools. Quality and treatment requirements of the water used in the pools" [114], which includes therapeutic pools within its scope, mandates specific monitoring for parameters such as ammoniacal nitrogen to assess organic bather load and doesn't provide a specific exemption from disinfection requirements. However, the definition of water quality limits for thermal facilities follows a specific legislation regime, as indicated in Table 6 of Circular 14/DA. For thermal facilities, the overarching legal framework is Decree-Law No. 142/2004 [115], which prioritizes the preservation of the mineral water's natural properties and mandates that water quality must be ensured through periodic laboratory control of microbiological and physicochemical parameters, in accordance with Decree No. 1220/2000 [116]. To ensure bather safety without compromising the medicinal nature of the water, thermal water must be exempt from parasites, *E. coli*, fecal streptococci, *P. aeruginosa* and *Legionella pneumophila*, while other *Legionella spp*. must remain below a reference value of 100 CFU/L.

Romania: The legislation distinguishes between standard recreational pools and therapeutic facilities using natural mineral waters. Hygiene requirements for the former are established by the "Rules of 4 February 2014 on hygiene and public health of the population living environment" (amended by Order No. 994/2018), Chapter IX [117]. The regulation emphasizes chemical disinfection as a primary safety measure and mandates strict microbiological compliance (e.g., absence of *E. coli*, *Enterococci* and *P. aeruginosa)*. However, these rules do not explicitly cover therapeutic facilities, as its scope for filling water is limited to drinking and seawater. Therapeutic facilities are governed by "Uniform technical rules of 23 July 2004 on the certification and operation of thermal, climatic and balneoclimatic facilities" [118]. The rules prioritize the integrity of the therapeutic resources, without listing specific microbiologic limits for pool basins. The microbiological specifications of mineral waters at source are regulated by the "Technical rules of 1 September 2005 on exploitation and marketing of natural mineral waters" [119].

Slovakia: Recreational waters are regulated by "Decree No. 308/2012 on water quality requirements, water quality control and on the operation, equipment of operating areas, premises and facilities of natural and artificial swimming pools" [120]. It does not mention therapeutic water and requires continuous water recirculation and disinfection for swimming pools. For natural therapeutic spa and healing water sources, the regulatory framework refers instead to "Decree No. 100/2006 on the requirements for natural medicinal water and natural mineral water, on the balneological assessment, distribution, scope of monitoring and content of analyses of natural medicinal and natural mineral waters and their products" [121]. This decree focuses on preserving the original water physicochemical characteristics during its use in therapeutic treatments. Under Article 11, medicinal water source must maintain a high standard of microbiological purity, mandating the absence at the source of pathogenic microorganisms, *E. coli*, *Enterococci*, *P. aeruginosa* and anaerobic spore-forming sulfite-reducing bacteria. Regarding physicochemical stability, Article 9 requires periodic monitoring of specific therapeutic indicators (e.g., characteristic ions, conductivity) to ensure that the water's medicinal properties are not compromised. Unlike general recreational pools, the pH and mineral composition in these facilities are regulated based on the constancy of the authorized source's parameters rather than standardized pool limits.

Slovenia: The safety of recreational waters is regulated by the "Rules on minimum hygiene requirements for bathing areas and swimming pool water. 2015" [122]. Filling water must generally comply with drinking water standards, with permitted deviations for the natural mineral composition of therapeutic waters; if the source is not a public supply, quality must be verified annually. While bathing water preparation typically requires residual disinfection and pH adjustment, Article 5 allows pools supplied with recognized natural medicinal products to operate without disinfection. In such cases, a prominent public warning must be displayed, stating that the water is not disinfected and may pose a microbiological risk. Despite this, water must still aim to meet the microbiological requirements of Annex 1, which mandates the control of *E. coli*, *P. aeruginosa*, *Staphylococcus* and *Legionella*. Additionally, if the concentration of DBPs exceeds regulatory limits due to the filling water, operators are required to implement corrective measures.

South Africa: The regulation of public swimming waters and spas is integrated into the broader framework of public health via the "National Environmental Health Norms and Standards" [123]. These norms provide specific requirements for "natural spas", despite the absence of a formal legal definition for these terms. According to the standards, water used for topping up pools and spas must originate from a treated source. A heightened precautionary approach is applied to warm water environments: while standard pools require quarterly testing for *Legionella spp*., natural spas must be monitored monthly, with a strict limit of <1/100mL. Furthermore, for natural spas, weekly monitoring is mandated for *E. coli* and *P. aeruginosa*. Additionally, these facilities must undergo frequent physical cleaning of surfaces to prevent biofilm formation.

Spain: Health regulation for public recreational pools and spas is primarily established by the "Royal Decree 742/2013 of 27 September on the technical and health criteria for swimming pools" [124]. It explicitly excludes natural and thermal or medicinal-mineral basins from its scope, provided they remain chemically untreated and are used exclusively for medico-thermal treatments. In contrast, other facilities must adhere to mandatory disinfection using chlorine, bromine or other authorized biocides, alongside strict physicochemical and microbiological criteria (e.g., absence of *P. aeruginosa* and *E. coli*). The framework was reinforced by "Royal Decree 487/2022 of 21 June on the health requirements for the prevention and control of legionellosis" [125]. Unlike previous exclusions, this Decree applies to all aerosol-generating aquatic systems, including hot tubs, spas and therapeutic pools. While *Legionella* levels below 100 CFU/L are tolerable under risk assessment, detection above 1,000 CFU/L requires immediate cessation of operations. To minimize risk while preserving natural water properties, the Decree requires medicinal mineral or thermal facilities to prioritize physical or physicochemical treatment systems applied immediately prior to the point of use. Chemical disinfectants are only permitted for recirculating systems and only if microbial growth cannot be maintained through physicochemical methods. Even then, only agents that minimize alterations to the water's properties are allowed. Furthermore, Annex III allows regional health authorities to grant exemptions for specific physicochemical parameters to preserve therapeutic water integrity, provided microbiological standards are strictly met. The microbiological quality of natural mineral waters at the source is governed by "Royal Decree 1798/2010 of 30 December on the exploitation of natural mineral waters" [126], while mining regulations, such as "Royal Decree 2857/1978 of 25 August on the general regulation for the mining regime" [127] safeguard sources from contamination. Regional legislation such as "Law 8/2019 of 23 December on the recreational use of thermal waters in Galicia" [128], further expands this framework by allowing recreational activities in thermal waters provided the water's natural properties and therapeutic integrity remain uncompromised.

Sweden: The "Public Health Agency's general recommendations on swimming in pools HSLF-FS 2021:11" [129] provide a framework for the safe management of public recreational aquatic facilities, supporting supervisory authorities and operators' self-monitoring. This document prescribes physicochemical and microbiological parameters, such as the absence of P. aeruginosa (< 1 CFU/100mL) and the monitoring of Legionella spp. In hot tubes. However, the guideline to these recommendations "Guidance on swimming pools No. 23048" [130], clarifies that swimming pools used exclusively for healthcare purposes, such as treatment and medical rehabilitation, fall outside the Public Health Agency's jurisdiction. Instead, in these clinical settings, water safety is not governed by recreational standards but is integrated into patient safety protocols under the supervision of the Health and Medical Services Inspectorate.

Switzerland: The country was one of the global pioneers in swimming water quality regulation, publishing its first standards for public baths in 1968. Currently, hygienic requirements for water quality and operative monitoring in public bathing facilities, including thermal and mineral pools, are governed by the Federal Department of Home Affairs (EDI) through the "Ordinance on drinking water and water in public baths and shower facilities 817.022.11" (TBDV) [131]. Technical aspects for the design and operation of treatment systems are further detailed in the engineering standard SIA 385/9:2023 [132]. Additional health safety measures regarding concerning aerosol-associated risks are provided through the detailed "Recommendations on Legionella and Legionellosis" (BAG/BLV) [133]. Notably, this framework does not grant specific exemptions for thermal facilities from the treatment, disinfection (mostly through chlorination and ozonation) and enforces self-monitoring to ensure public safety. Annexes 5-6 of the TBDV define the compliance requirements for water in the basins for microbiological indicators (e.g., absence of *E. coli* and *P. aeruginosa*, a threshold for *Legionella* at 100 CFU/L) and physicochemical (pH, turbidity, residual disinfectant), as well as a stringent limit for some DBPs.

Turkey: Water management for recreational and therapeutic purposes is set up by a dual regulatory system. While the hygiene of public swimming basins is strictly regulated by the

"Regulation on health principles to be followed by swimming pools" [134], the therapeutic efficacy of the natural water sources is protected by the "Hot Spring regulation" [135]. The latter covers thermal and mineral springs, spas, thalassotherapy centres and other facilities using therapeutic water for recreation purposes. It allows only controlled physical processes and disinfection exclusively with Ministry-approved products, if they do not degrade the medicinal properties of natural thermal waters used in spa treatment.

United Kingdom (UK): Health and Safety Guidance (HSG) system, supported by the PWTAG (Pool Water Treatment Advisory Group) Code of Practice [136] and technical standards, governs bathing facility safety. "HSG179. Managing health and safety in swimming pools" [137] covers all type of swimming pools, including therapeutics, while excluding natural bathing pools and spas. The latter are regulated by "HSG282. The control of legionella and other infectious agents in spa-pool system" [138]. Notably, neither document explicitly mentions the use of thermal water, however, both mandate filtration and disinfection of pool water. Continuous primary disinfection is required to eliminate virus and bacteria, while secondary disinfection (e.g., UV or ozone) is strongly recommended to neutralize chlorine-resistant organisms, such as *Cryptosporidium*. The targeted control for spa-pool systems includes physicochemical parameters (pH, temperature, alkalinity, total dissolved solids, and calcium hardness) and microbiological parameters (e.g., *Legionella* < 100CFU/L, *P. aeruginosa* < 10 CFU/100mL, *E. Coli* and coliforms < 1 CFU/100mL). The recommendation to control Legionella in hot and cold-water systems, as well as other risk systems is provided by "HSG274. Legionnaires' disease: Technical guidance" [139].

United States (US): Public aquatic facility safety is regulated not at the federal, but at the state level, though the federal agency US Centres for Disease Control and Prevention (CDC), provides a comprehensive technical baseline through "2024 Model Aquatic Health Code" (MAHC) [140]. The MAHC applies to all public facilities and classifies therapy pools and spas as "increased risk aquatic venues" due to elevated water temperatures and users' vulnerability. Regarding disinfection, rather than fixed microbiological parameters, the MAHC focuses on "Log Inactivation". It mandates a 3-log reduction of *Cryptosporidium* through the mandatory secondary disinfection (e.g., ozone) in therapy pools, as these protozoans are chlorine-tolerant. For facilities exceeding 34°C, a high turnover rate of water (≤ 0.5 hour) is required to mitigate microbial growth. Additionally, cyanuric acid use is prohibited in therapy pools to maintain the oxidation potential of chlorine. While potable water is the standard filling source, the MAHC allows alternative sources (e.g., natural springs, subject to local approval). Implementation varies between states jurisdictions. Arkansas in its "Rules and regulations pertaining to swimming pools and other related facilities" [141] exempts 'class E therapy pools/spas designed for athletic or medical water therapy' from rules if they operate as 'fill-and-drain' systems. The rules require higher water turnover for spas, mandates disinfection primarily with chlorine or bromine (other treatment should be approved by authorities), requiring the absence of *E. coli* and meeting the mandatory chemical parameters (e.g., pH, total alkalinity). Colorado "Code of Regulations. Swimming pools and mineral baths. 5 CCR 1003-5" [142] includes mineral baths within its scope, but without explicit disinfection exemptions. It defines specific water microbiological indicators to be met (e.g., fecal coliform density ≤ 1/100mL), as well as physicochemical (e.g., pH, total alkalinity and calcium hardness). In Florida "Administrative Code. Chapter 64E-9. Public swimming pools and bathing places" [143], provides specific exemptions for saltwater filling sources, which are waived from potable water chemical standards (except for iron and color), provided they remain free of coliforms. It also mandates high disinfectant residuals for spa-type pools to ensure rapid pathogen inactivation. A unique chemical approach is found in Hawaii, where thermal waters may fall under the definition of 'saltwater' if their total concentration of dissolved inorganic ions exceeds 0.5 g/L. Hawaii "Code of Rules. § 11-10-2 Public swimming pools" [144] mandates that disinfection is not required for such saltwater outdoor facilities if microbiological safety requirements are met through water circulation and complete water replacement at least every six hours.

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Table 1. Overview of national regulatory frameworks on thermal and swimming pool facilities.

Country	Regulation	Scope of Application, *Type of Filling Water*	Ref.
Albania	• Regulation "Hygienic and sanitary requirements for swimming pools" No. 835	Public/collective SPs for sport, recreational and mixed activities, use by children, in hotels, schools, universities, gyms, condominiums with >4 units. Does not apply to private SPs, condominiums with ≤4 units, thermal and therapeutic SPs. *Potable water and other waters tested on suitability for drinking purposes.*	[31]
	• Law No. 111/2012 on integrated water resources management. Amended by laws No. 6/2018; No. 29/2024	*Therapeutic, mineral, thermomineral and geothermal waters*	[32]
Australia	• AS 3979-2006. Hydrotherapy pools	Public hydrotherapy pools with heated water to meet therapeutic needs of people.	[37]
New South Wales	• Public Health Regulation 2022. Part 3. Public swimming pools and spa pools. + Schedule 1.	Public SPs or spas, waterparks or other recreational facilities. Does not apply to natural SPs. *Public water supply.*	[33]
Queensland	• Water quality guidelines for public aquatic facilities. 2019	All public aquatic facilities: SPs, spas, hydrotherapy pools, waterparks, splash pads.	[34]
Victoria	• Water quality guidelines for public aquatic facilities. 2020	All public SPs, spas, incl. those in hotels, gyms, schools; hydrotherapy pools.	[35]
Western Australia	• Code of practice for the design, construction, operation, management and maintenance of aquatic facilities. 2024	SPs, spas, hydrotherapy pools, water- and river rides, water spray grounds and other water facilities for sport, rehabilitation, recreation, fitness.	[36]
Austria	• Federal Law (BhygG) on hygiene in baths, hot tubs (whirlpools), saunas, warm air and steam baths and small bathing ponds and on bathing water quality	Artificial outdoor and indoor SPs, whirlpools, saunas, warm air and steam baths, small bathing ponds, baths in surface waters; baths operating in natural healing resources, spas, sanatoriums (exc. For Section II). Does not apply to the facilities operating in condominiums with <6 units.	[38]
	• Regulation 2012 (Bhyg) on hygiene in baths, hot tubs (whirlpools), saunas, warm air and steam baths and small bathing ponds	Baths, whirlpools and spas, including those filled with water from a local natural healing resource (deviations due to the characteristics of the source are permitted, if there is no risk to the users' health), saunas, warm air and steam baths, baths in surface waters and small ponds.	[39]
	• Upper Austria Law on natural healing resources and health resorts (HKG); Salzburg healing springs and spas Act (HKG 1997):	*Healing springs, peloilds and factors*	[40,41]
Belgium ***Brussels-Capital Region***	Government Order of 16 February 2023 setting operating conditions for swimming pools and other baths	SPs, spas and other baths, excluding exclusively domestic. Does not apply to SPs and baths with water treatment different from chemical disinfection or biological treatment.	[42]

		Drinking water from the distribution network. Otherwise, authorization is requested.	
Flanders	Title II of VLAREM. Government Decree of 1 June 1995 containing general and sectoral provisions regarding environmental hygiene. Art. 5.32.8.1.	Permanent and natural SPs, hot tubs, plunge, splash, and therapy pools, open swimming areas, recreation zones. Does not apply to private and nonpublic hotels SPs, which must comply with the provisions on water treatment and the chemicals storage. *Freshwater or saltwater.*	[43]
Walloon	Government Order of 13 June 2013 on conditions for indoor and outdoor swimming pools used for a purpose other than purely private within the family circle.	Indoor and outdoor SPs used non-privately within the family, when the surface area ≤ 100 m^2 or the depth is ≤ 40 cm, chlorine disinfected. *Drinking water from public distribution network. Filling water not coming from public networks should meet the tap water standards.*	[44]
Brazil	• ABNT NBR 10339:2018. Swimming pool – Design, implementation and maintenance	Public/collective SPs for sport, recreational, mixed or special uses, and uses by children, in hotels, hospitals, schools, clubs, condominiums, etc. *Fresh-, salt- and medicinal water.*	[45]
	• ABNT NBR 10818:2016. Quality of pool water – Procedure		[46]
	• Mineral Water Code of 1945 amended by Resolution No. 193/2024	*Mineral, thermal, potable water or water intended for spa purposes;*	[47]
Bulgaria	• Instruction No. 34 on hygiene of sports facilities and equipment	Facilities for sports competitions and training.	[48]
	• Regulation No. 14 of 1987 on resort resources, resort areas and resorts	*Mineral waters, medicinal mud and areas with favorable factors for healing, prevention and rest.*	[49]
Canada			
Alberta	• Pool Standards, July 2014. Amended 2018	SPs recreational and therapeutic, wading pools, water spray park, saunas, whirlpools.	[50]
British Columbia	• Pool regulation 296/2010. Amended 27.10.2025 • Guidelines for pool operations. Version 3. April 2025	Does not apply to private pools; SPs drained and cleaned after each use; SPs in camping with <4 units	[51] [52]
Nova Scotia	• Operational Guidelines for Aquatic Facilities 2014	Public SPs, water parks, splash pads, SPs in hotels, daycare and others	[53]
Ontario	• RRO 1990 Regulation 565 Public pools. Amended 2024 • Legionella Investigation Reference Document 2025	Does not apply to private SPs and condominium with less than six units or suites.	[54] [55]
Quebec	• Regulation respecting water quality in swimming pools and other artificial pools Q-2, r. 39	Does not apply to private, medical, therapeutic and temporary pools for competitions	[56]
China	• GB 37488 2019 "Hygienic indicators and limits for public places"	Air and water quality of public places (e.g., hotels, public baths and SPs, beauty salons, cinemas, concert halls, stadiums, museums, galleries, libraries, shopping malls, waiting rooms).	[57]

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	• CJ/T 244-2016 "Swimming pool water quality standard"	Indoor and outdoor artificial SPs. Does not apply to seawater, hot spring water, natural water and infant SPs.	[58]
	• LB/T 081-2020 "Water hygienic quality requirements and management specification of hot spring tourism"	*Hot spring water*	[59]
Croatia	• Ordinance on sanitary, technical, and hygienic conditions of swimming pools and health safety of swimming pool waters. 59/2020	Does not apply to private SPs, SPs with therapeutic water (e.g., thermal) and not disinfected with residual effect, saunas and hot tubs where the water is used once, lagoons, flow pools and seawater water slides. *Water from a public water supply system, seawater*	[60]
	• Ordinance on the forms of health services provided in the field of health tourism and standards and norms for their performance. 79/2019		[61]
Cyprus	Swimming Pool Regulations of 2025. K.D.P. 231/2025	Public SPs for sport and training, water parks, spas, physiotherapy pools, SP in hotels, hospitals, schools, gyms and other facilities. *Water in basins should be chemically and microbiologically suitable.*	[62]
Czech Republic	• Decree No. 238/2011 on the hygienic requirements for swimming pools, saunas and hygienic limits of sand in sandpits of outdoor play areas (amended)	Natural and artificial SPs and saunas. *Water from public portable supply or from natural medicinal source certified according* ***[Error! Bookmark not defined.]***	[63]
	• Law No. 164/2001 on natural healing resources, natural mineral water resources, natural healing spas and spa places (Spa Act)	Natural healing and natural mineral water, natural healing resources and spas	[64]
Denmark	• Executive Order on swimming pools and their water quality. BEK No. 918	Public SPs and hot water facilities, spas, water parks, recreational and therapy pools. Does not apply to private SPs, paddling pools where the water is discarded after a few hours, steam, showers and similar facilities. *Potable water and surface water*	[65]
	• Guidance on controlling swimming pools. VEJ No. 9605		[66]
Estonia	• Requirements for swimming pools, swimming pools and aquatic centers. No. 38	SPs and aquatic centers. Do not apply to natural cold-water pools and baths where surface water is used and with flow-through water exchange. *Water must meet the requirements for drinking water established in Water Act.*	[67]
	• Health protection requirements for mineral water and spring water. No. 62	Do not apply to natural mineral and spring water which is used for therapeutic purposes in a thermal or mineral water pool.	[68]
Finland	• Health Protection Act 763/1994. 19.8.1994	Public SPs; spas; water parks; recreation and rehabilitation facilities.	[69]
	• Decree "On the quality requirements and monitoring studies of pool water in swimming pools and spas. 315/2002	*Mention filling water rich of bromine.*	[70]
France	• Public Health Code (PHC). Part 1. Book III: - Title II. Chapter II: Natural mineral waters.		[71]

	(Articles R1322-1 to R1322-67) - Title III Swimming pools and bathing. (Articles D. 1332-1–D. 1332-54)	Natural mineral water uses for therapeutic purposes in thermal facilities. Public SPs. Does not apply, except for disinfection provisions, to thermal SPs supplied by natural mineral water used for therapeutic purposes.	
	• Decree of 26 May 2021 on swimming pool water quality limits and reference values, pursuant to Article D. 1332-2 of the PHC	*SPs supplied with drinking water*	[72]
	• Order of 26 May 2021 on the use of water not from a drinking water distribution to supply swimming pools, pursuant to articles D. 1332-4 and D. 1332-10 of the PHC	*SPs supplied with non-potable water*	[73]
	• Order of 14 October 1937 on the control of mineral water sources, amended on 19.06.2000	*Natural mineral water extracted at the source and during use in thermal facilities*	[74]
	• Order of 22 October 2013 on the control and monitoring of bottled water and natural mineral water used for therapeutic purposes in thermal facilities or distributed in a public drinking fountain, amended on 30.12.2022		[75]
Germany	• Infection Protection Act (IfSG). § 37. Quality of water for human consumption and for swimming or bathing in pools or ponds, monitoring	Public SPs and other facilities. Does not apply to private baths; systems with biological or discontinuous water treatment, water playgrounds, floating systems/pools.	[76]
	• DIN 19643-1:2023-06. Part 1 • DIN 19643-2:2023-06. Part 2 • DIN 19643-3:2023-06. Part 3 • DIN 19643-4:2023-06. Part 4 • DIN 19643-5:2021. Part 5	*Water, including seawater, mineral, medicinal, artificially produced brine and thermal water.*	[77] [78] [79] [80] [81]
Greece	• Decree Γ1/443/1973 on swimming pools with instructions for their construction and operation. Amended by Decrees: Γ4/1150/1976, ΔΥΓ2 /80825/05.2006, Δ1δ/ΓΠ.οικ. 57290/2019	Public swimming pools.	[82]
	• Circular 23849/2024 "Public health protection measures against Legionnaires' disease"		[83]
	• Law 4875/2021. Model integrated management of tourist destinations, thermal springs and other facilities		[84]
	• Ordinance 61438. Microbiological quality of thermal waters	Thermal water facilities.	[85]
Hungary	• Decree 510/2023. (XI. 20.) on the construction and operation of public baths	Public baths, saunas and steam baths. Does not apply to private baths, artificial bathing lakes, natural bathing water.	[86]
	• Decree 509/2023. (XI. 20.) on natural medicinal factors	*Baths providing balneotherapy and using medicinal water, medicinal water.*	[87]
Iceland	Regulations on hygiene at swimming and bathing facilities 814/2010 with amendments	All types of SPs, whirlpools, thermal and rehabilitation pools, children's pools, pools at hotels and resorts, and natural bathing areas.	[88]
Ireland	Swimming Pool Safety Guidelines 2021		[89]
Italy	• State-Regions Agreement of 16 January 2003 on the health and hygiene aspects for the construction, maintenance and supervision of swimming pools	Public SPs for swimming, training, recreation, SPs for children and multipurpose use. Does not apply to SPs for rehabilitation, curative and thermal use.	[90]

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		Freshwater (surface or underground) which meets the potability requirements.	
	• Law of 24 October 2000 No. 323 "Reorganization of the thermal sector"		[91]
	• Legislative Decree of 19 June 2025 No. 102	Legionella risk assessment	[92]
	• Decree of 10 February 2015 "Criteria for evaluating the characteristics of natural mineral waters"		[93]
	• "Regulations for the research, cultivation and use of mineral and thermal waters": Lombardy Regional Law 44/1980; Tuscany Regional Law 38/2004; Veneto Regional Law 40/1989		[94–96]
Japan	• Swimming pool hygiene standards. 2007	Public SPs. Does not apply to SPs at schools. *SPs, if filled with sea- or hot spring water and constantly renewed water, may in some cases not apply the set physicochemical parameters.*	[99]
	• Hot Spring (Onsen) Law No. 125 of 1948		[98]
	• Guidelines for adding Legionnaires' disease prevention measures of 29 October 2002		[100]
Latvia	Regulation No. 470 "Hygiene requirements for pool and sauna services"	SPs or saunas, including those in educational, social care, healthcare institutions, sports, hotels, entertainment or recreation facilities *Potable water must meet the safety requirements for drinking water; sea- or mineral water*	[101]
Lithuania	• Hygiene Norm HN 109:2016 "Public Health Safety requirements for swimming pools".	*Freshwater.*	[102]
	• Hygiene Norm HN 127:2010 "Mineral and seawater for external use. Health safety requirements".	*Mineral and seawater.*	[103]
Malta	Public Health Act "Swimming Pools Regulations, 2005". L.N. 129. Amended by L.N. 135 of 2008.	Public SPs for swimming, recreation, diving, therapeutic and special use; saunas and mineral baths. Does not apply to private SPs.	[104]
Netherlands	Environmental Activities Decision (Bal). Chapter 15. Providing opportunities for swimming and bathing	Does not apply to household SPs; SPs for only 24h use; SPs intended for human-animal contact; SPs on vessels not permanently moored. *Water meeting drinking water quality requirements.*	[105]
Norway	• Regulation of 1996 for swimming facilities, swimming pools and saunas, etc.	Public SPs, saunas, water slides, splash and diving facilities, therapy pools, whirlpools.	[106]
	• Regulation of 2003 on environmental health protection		[107]
Poland	• Ordinance of 9 November 2015 on the requirements for swimming pool water. Amended by Item 1230/2022	Does not apply to swimming pools filled with water with medicinal properties.	[108]
	• Act of 28 July 2005 on spa treatments, spa and spa protection area. Amended by Item 1135/2025	Spa treatment, spas resorts, spa protection areas and spa municipalities.	[109]

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	• Ordinance of 13 April 2006 on the research required to establish therapeutic properties of natural medicinal raw material	Natural medicinal raw materials and the medicinal properties of the climate, the criteria for their assessment	[110]
	• Ordinance of 31 March 2011 on natural mineral waters, spring waters and table waters	*Natural mineral waters, spring waters and table waters*	[111]
	• Ordinance of 30 September 2024 on the requirements to be met by spa treatment facilities and equipment	Therapeutic and rehabilitative spa facilities	[112]
Portugal	• Circular-Normative No. 14/DA. Swimming pool health surveillance program	Public SPs for sport, recreation/leisure, water parks, therapeutic pools. Does not apply to jacuzzis, whirlpools, private SPs.	[113]
	• NP 4542:2017. Swimming pools. Quality and treatment requirements of the water used in the pools	*Public potable water supply network. Other water sources request health authorization.*	[114]
	• Decree-Law No. 142/2004 of 11 June	Thermal facilities.	[115]
	• Decree No. 1220/2000 of 29 December	*Natural mineral waters and spring waters.*	[116]
Romania	• Rules of 4 February 2014 on hygiene and public health for the population living environment. Amended by Order No. 994 of 9 August 2018	Public swimming pools. *Drinking or seawater. Water not coming from drinking water networks must comply with legal provisions*	[117]
	• Uniform technical rules of 23 July 2004 on the certification and operation of thermal, climatic and balneoclimatic facilities		[118]
	• Technical rules of 1 September 2005 on exploitation and marketing of natural mineral waters		[119]
Slovakia	• Decree No. 308/2012 on water quality requirements, water quality control and on the operation, equipment of operating areas, premises and facilities of natural and artificial swimming pools	Natural and artificial SPs. *Not specified*	[120]
	• Decree No. 100/2006 on the requirements for natural medicinal water and natural mineral water, on the balneological assessment, distribution, scope of monitoring and content of analyses of natural medicinal and natural mineral waters and their products	*Natural medicinal waters and natural mineral waters, natural therapeutic spas, spa areas.*	[121]
Slovenia	Rules on minimum hygiene requirements for bathing areas and swimming pool water. 2015	Bathing areas and water in conventional and biological SPs. Do not apply to natural bathing areas and SPs used by individuals or families. *Freshwater, seawater and mineral water*	[122]
South Africa	National Environmental Health Norms and Standards. No. 6740	Public SPs and spas	[123]
Spain	• Royal Decree 742/2013 of 27 September on the technical and health criteria for swimming pools	Public SPs and spas. Households SPs, SPs in agritourism, colleges or similar facilities must comply with some provisions. Does not apply to natural thermal or mineral medicinal pools.	[124]
	• Royal Decree 487/2022 of 21 June on the health requirements for prevention and control of legionellosis	SPs, spas, therapeutic and thermal baths, whirlpools, pressure jet treatments and other systems.	[125]
	• Royal Decree 1798/2010 of 30 December on the exploitation of natural mineral waters	*Natural mineral water*	[126]

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Galicia	• Royal Decree 2857/1978 of 25 August on the general regulation for the mining regime • Law 8/2019 of 23 December on the recreational use of thermal waters in Galicia	*Thermal waters*	[127] [128]
Sweden	• Public Health Agency's general recommendations on swimming in pools HSLF-FS 2021:11	Public SPs for swimming, spas, hot tubs and water parks and similar.	[129]
	• Guidance on swimming pools No. 230481	Does not apply to private and therapeutic pools.	[130]
Switzerland	• Ordinance of the EDI on drinking water and water in publicly accessible baths and shower facilities. (TBDV) 817.022.11. Amended on 08.12.2023 • SIA 385/9:2023. Water and water treatment plants in public swimming pools and similar facilities – Requirements and supplementary provisions for construction and operation	Public SPs, whirlpools, thermal, mineral and brine baths, wellness and therapy baths, children's paddling pools, biological pools.	[131] [132]
	• Recommendations on Legionella and Legionellosis (BAG/BLV). 2018	Whirlpools or pools warmer than 23°C, other facilities with a water circulation system that promotes aerosol formation	[133]
Turkey	• Regulation on Health Principles to be followed by Swimming Pools. 2011	Indoor and outdoor pools for swimming.	[134]
	• Hot Springs Regulation. 2001	All health facilities in thermal springs, mineral springs and climate cure centers where natural healing elements are used.	[135]
UK	• Code of Practice. Management and treatment of swimming pool water. PWTAG. July 2021 (update 2025) • HSG179. Health and safety in swimming pools	Public SPs, water parks, leisure and therapeutic pools, SPs in schools, hotels, etc. Does not cover domestic and natural bathing pools, spas.	[136] [137]
	• HSG282. Control of Legionella and other infectious agents in spa-pool systems • HSG274. Legionnaires' disease: Technical guidance	Spa pools, hot and cold water and other risk systems	[138] [139]
US	• 2024 Model Aquatic Health Code. 5th Edition. + Annex Scientific Rationale	SPs, spas, therapy pools, hot tubs, wave pools, lazy rivers, surf and waterslide landing pools, spray pads, artificial swimming lagoons, etc. *Public water systems and other approved sources (incl. springs)*	[140]
Arkansas	• Rules and regulations pertaining to swimming pools and other related facilities	Public SPs, spas, special purpose spas/SPs for therapy, wading and spray pools, water slides. Does not apply to fill-and-drain therapy spas used for medical treatment	[141]
Colorado	• Code of Regulations. Swimming pools and mineral baths. 5 CCR 1003-5	SPs, mineral baths and natural swimming area	[142]
Florida	• Administrative Code. Chapter 64E-9. Public swimming pools and bathing places	Public SPs, spas and bathing places. *Freshwater and saltwater.*	[143]
Hawaii	• Code of Rules. Title 11. Subtitle. 1. Chapter 10 - Public swimming pools	Public SPs and spas. Does not apply to private SPs and beach venues. *Freshwater and saltwater.*	[144]

The regulatory landscape previously described reveals a significant lack of international consensus, with some jurisdictions mandating disinfection to ensure bather safety while others prohibit it to preserve the "naturalness" and therapeutic integrity of the source. This fragmentation is the direct reflection of a profound cost-benefit dualism that continues to make the treatment of therapeutic waters a matter of "to be or not to be". As the analysis of national laws suggests, the decision to disinfect is not merely a legal choice but a complex technical challenge, as thermal water constitutes a unique ecosystem where physicochemical composition, native non-pathogenic microorganisms and healing properties exist in a delicate, source-dependent balance.

The uniqueness of these waters must be the primary consideration when evaluating the impact of different disinfection approaches. Excessive or improper treatment, if mandated by rigid hygiene standards, can trigger oxidation of therapeutic components and lead to mineral precipitation, loss of volatile compounds and overall microbiome imbalance, effectively striping the water of its therapeutic properties. For example, during traditional hypochlorite treatment, a 40–99% reduction in sulfide, bromide, and iodide ions can occur [145]. This problem can be further complicated by the formation of DBPs, as will be demonstrated in the next chapter. Conversely, the "no-treatment" stance favored by more permissive regulations and based solely on "fill-and-drain" can face the reality of poor microbial water quality. Non-compliance rates in therapeutic pools can be as high as 75%, posing serious infection risks (e.g., presence of *P. aeruginosa*) for vulnerable bathers [145]. Technical evidence suggests that regulatory focus should shift from a binary "yes/no" approach to a tailored "treatment train" approach, as the feasibility of disinfection depends heavily on the specific water matrix. Research indicates, that for example in Hungary, while sodium hypochlorite may be chemically compatible with only a small fraction of therapeutic water profiles due to its high reactivity, other agents like hydrogen peroxide-based systems appear significantly more adaptable [146]. Beyond traditional chemical disinfectants, alternative practices such as UV light and ultrafiltration have been suggested as they do not alter sulfide some natural components of the treated water, although they fail to provide the residual disinfection necessary to control bather-derived contamination throughout the pool [146]. To resolve this limitation, a multi-barrier approach is often required, where physical treatments are combined with low-impact chemical agents. In these cases, the high mineral and organic content of the water makes it essential to maintain strict control of residual concentrations and to implement localized preventative measures, such as shock treatments at high-risk points like filters, to ensure safety without compromising the water's therapeutic integrity.

3.3. Safety and Health Risks

Thermal water–supplied swimming pools represent complex exposure environments in which therapeutic benefits and public health protection must coexist. Although the positive effects of balneotherapy on dermatological and musculoskeletal conditions are increasingly supported by clinical evidence, the transfer of natural thermal waters into engineered pool systems introduces additional microbiological and chemical variables that may influence safety.

Compared with conventional freshwater pools, thermal systems operate under distinct physicochemical conditions—including elevated temperature, mineral composition, sulfur compounds, and specific hydraulic configurations—which may influence microbial ecology and chemical reactions within the water matrix. Alongside traditional microbiological hazards and disinfection by-products, increasing attention is now directed toward contaminants of emerging concern (CECs), which may enter aquatic systems through human use or environmental sources and undergo transformation processes in warm, mineral-rich environments.

These aspects highlight the need to consider thermal pools as dynamic chemical–biological systems requiring integrated risk assessment approaches. The following sections examine the principal microbiological and chemical determinants of safety in thermal aquatic environments.

3.3.1. Microbiological Risks

Thermal water–supplied swimming pools represent complex exposure environments in which therapeutic value and public health protection must coexist. Although the beneficial effects of balneotherapy on dermatological and musculoskeletal conditions are increasingly supported by clinical evidence [1–3], the transformation of natural thermal waters into semi-artificial pool systems introduces structural, microbiological, and chemical variables that require dedicated risk assessment approaches. In this context, thermal facilities should be evaluated not only as therapeutic infrastructures but also as engineered aquatic environments where hydrochemistry, microbiology, and operational management interact.

Traditionally, safety management in aquatic facilities has focused on regulated microbiological indicators and on the control of disinfection by-products formed during water treatment. In thermal systems, however, risk profiles are influenced by additional environmental determinants, including elevated temperatures, mineral composition, sulfur compounds, and hydraulic design characteristics [9]. These physicochemical features create ecological conditions that differ substantially from those of conventional freshwater pools and may selectively favor specific microbial communities, particularly in warm and recirculated environments.

Among waterborne pathogens, *Legionella* spp. represents one of the most relevant public health concerns associated with warm aquatic systems. *Legionella* is a ubiquitous Gram-negative bacterium widely distributed in both natural and engineered water environments, where its persistence is strongly influenced by temperature, hydraulic conditions, and microbial interactions [147,148]. The bacterium proliferates within a temperature range between 20 °C and 45 °C, with optimal growth around 35–37 °C [149]. Transmission occurs primarily through inhalation of aerosolized water droplets containing *Legionella*, leading to clinical manifestations that range from Pontiac fever to severe pneumonia known as Legionnaires' disease [150].

Because of their temperature and mineral composition, thermal waters represent environments of particular epidemiological interest for *Legionella* proliferation. The persistence of this microorganism in thermal infrastructures is not determined solely by temperature but results from the combined influence of hydraulic complexity, biofilm formation, and microbial ecology. Consequently, the evaluation of *Legionella* risk in thermal facilities requires an integrated environmental and microbiological perspective [151,152].

Several epidemiological investigations have documented outbreaks and sporadic cases of legionellosis associated with exposure to thermal facilities. A notable investigation conducted in the United States between 2018 and 2019 reported an association between Legionnaires' disease and exposure to untreated thermal water in Hot Springs National Park (Arkansas). Environmental assessments identified Legionella spp. in piped thermal water, including samples collected from stagnant sections of the distribution system at temperatures exceeding 55 °C [153]. These findings demonstrate that high water temperature alone does not guarantee microbiological safety in complex plumbing systems, where hydraulic heterogeneity may create localized stagnation zones with uneven heat distribution.

In Japan, where public baths and hot springs (onsen) are culturally widespread, thermal facilities have been extensively investigated as potential reservoirs of *Legionella*. Longitudinal environmental monitoring conducted in Kobe between 2016 and 2021 analyzed hundreds of *Legionella*-positive samples collected from public bathing infrastructures, including hot spring systems. The study revealed distinct differences in species composition and genotype distribution between hot springs and non-thermal public baths, highlighting the presence of several non-pneumophila species such as L. israelensis, L. londiniensis, and L. micdadei [154]. This diversity likely reflects the physicochemical complexity of thermal waters, which sustain heterogeneous microbial ecosystems characterized by protozoan hosts and extensive biofilm development.

Environmental surveillance studies conducted in Italy further confirm the relevance of thermal infrastructures as potential *Legionella* reservoirs. Long-term monitoring programs have documented recurrent detection of *Legionella spp*. in thermal and hot-water circuits, with Legionella pneumophila—particularly serogroup 1—being the most frequently isolated species [155]. Water temperature was identified as a major risk factor, as many thermal systems operate within the temperature range optimal for bacterial growth. Additional surveillance conducted in spa therapy

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facilities has also highlighted contamination in aerosol-generating therapeutic areas such as inhalation therapy and mud treatment rooms [156].

The epidemiological patterns observed in thermal facilities can be interpreted considering specific ecological mechanisms that support *Legionella* persistence. In aquatic systems, bacterial survival is strongly influenced by biofilm formation, protozoan hosts, temperature gradients, and hydraulic complexity [157,158]. A central mechanism involves the intracellular replication of Legionella within free-living protozoa, particularly amoebae [159–161]. This intracellular niche protects bacteria from environmental stressors, including disinfectants and temperature fluctuations, thereby enhancing their survival potential.

Multispecies biofilms further contribute to the persistence of *Legionella* in engineered water systems. Biofilms formed on pipe surfaces, tanks, and hydraulic infrastructures create microenvironments characterized by reduced disinfectant penetration, stable microclimates, and sustained nutrient availability. These ecological refugees help explain recurrent contamination patterns observed in environmental monitoring studies. Importantly, Legionella has demonstrated the ability to survive even in saline or mineral-rich waters, challenging the assumption that such environments are intrinsically protective against microbial colonization [162,163].

Recent events such as the COVID-19 pandemic have also highlighted the vulnerability of engineered water systems to operational disruptions. Prolonged facility closures during lockdown periods led to water stagnation and deterioration of control measures, potentially increasing the risk of *Legionella* proliferation upon reopening [14]. These findings underscore the importance of proactive environmental monitoring and hydraulic management strategies in thermal infrastructures.

Among other opportunistic pathogens, *Pseudomonas spp.*, particularly *Pseudomonas aeruginosa*, represents another relevant microbiological concern in warm aquatic systems. This bacterium is characterized by remarkable environmental adaptability, intrinsic resistance mechanisms, and an exceptional ability to form structured biofilms in engineered water infrastructures. Recent investigations on environmental strains isolated from hot spring environments have demonstrated significant thermotolerance, with growth observed at temperatures approaching 45–50 °C [164].

In recreational and therapeutic aquatic environments, *P. aeruginosa* has been associated with infections such as *folliculitis* and *otitis externa*, as well as more severe manifestations in immunocompromised individuals [165]. Epidemiological investigations conducted in treated recreational water systems have reported outbreaks linked to inadequate disinfection or insufficient hydraulic management in pools and spa facilities [166].

Beyond its pathogenic potential, *P. aeruginosa* plays a significant ecological role in aquatic microbial communities. Bacterium is a prolific biofilm-forming organism capable of contributing to the development of complex multispecies microbial matrices that can function as ecological niches for other opportunistic pathogens [167]. Within microbial consortia, organisms such as *Legionella pneumophila* may exploit structural protection and metabolic interactions provided by surrounding microorganisms, thereby enhancing environmental persistence and resistance to disinfection processes.

In thermal water infrastructures, where warm temperatures, mineral deposition, and recirculation systems promote microbial attachment and surface colonization, these biofilm-mediated interactions may be particularly significant. The emergence of thermotolerant and potentially multidrug-resistant strains in thermal environments further raises concerns regarding the role of such infrastructures as environmental reservoirs of antimicrobial resistance determinants [168].

Advances in molecular sequencing technologies have demonstrated that thermal waters host distinct microbial signatures shaped by hydrogeological origin and chemical composition [9]. Most microorganisms present in natural thermal waters are harmless components of the environmental hydrobiome. However, when thermal water is transferred into engineered pool systems characterized by recirculation, aeration, and anthropogenic inputs, ecological equilibrium may shift.

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In facilities frequently attended by older adults, rehabilitative patients, children, and frequent users, the distinction between environmental microbiota and opportunistic pathogens becomes particularly relevant from a preventive medicine perspective. Consequently, risk management strategies in thermal facilities should integrate microbiological surveillance, hydraulic management, and environmental monitoring within comprehensive Water Safety Plans capable of balancing therapeutic benefits with modern public health standards.

3.3.2. Chemical Risks and Disinfection By-Products

Studies on DBP levels in disinfected thermal pools are extremely limited, compared to freshwater and seawater pools, and this reveals a scientific gap that still needs to be explored to reconstruct a more complete picture. The chemical profile of DBPs is not only influenced by the thermal water's natural matrix but also by the "anthropogenic load", such as body fluids (e.g., urea, sweat, hair, skin cells) and personal care products [169,170]. The specific geological location of source and the resulting mineral composition of water act as a "chemical fingerprint", making DBP formation highly site-specific and difficult to generalize [169].

Regarding exposure routes, while drinking water involves primarily oral ingestion and traditional swimming pools include five distinct pathways (dermal, oral, buccal, inhalation and auricular) thermal environments prioritize dermal and inhalation routes [171]. High water temperatures or intensive aeration (e.g., in hot tubs or oxygen reactors) can facilitate DBP volatilization, shifting the primary risk toward inhalation for both users and staff. The cumulative exposure to DBPs is a major concern, as epidemiological studies associate chronic contact with them with far-reaching health issues beyond respiratory and eye irritation [172]. For instance, the prolonged inhalation of volatile DBPs at the air-water interface can promote the development of allergic rhinitis, bronchial hyperreactivity and asthma, driven by increased lung epithelial permeability [169,170,172,173]. Chronic contact with DBPs has been linked to metabolic alterations [174], some DBPs can induce oxidative stress and act as endocrine disruptors [175,176]. Furthermore, DBPs have been shown as mutagenic, cytotoxic, genotoxic and teratogenic [175,177]. They are suspected to be carcinogenic for the bladder [173], liver, kidney [175], digestive tract [177] and colon [178]. Exposure to DBPs raises also substantial concerns regarding reproductive health and fetal development [179,180].

These health issues can be further exacerbated by the "chemical fingerprint" of the water. Ss the thermal waters often contain natural bromide (they rank midway between freshwater and seawater for this parameter), it has been found that their disinfection cause a significant shift in DBP speciation through the so-called "bromine incorporation" process [169] and the formation of brominated DBPs (Br-DBPs), which are generally more cytotoxic, genotoxic, and mutagenic than their chlorinated analogous, so much so that brominated spas can be almost twice as mutagenic as chlorinated ones [170].

It has also been determined that unlike freshwater pools, where frequently a prevalent class is trihalocetic acids (HAAs), in thermal pools, volatile trihalomethanes (THMs) predominate [169]. HAAs (sum of five or nine compounds) and THMs (sum of four compounds) are commonly regulated in drinking water, with only the latter group being regulated in swimming pool water, along with chloramines in air. Regulatory limits and reported concentrations for these regulated THMs, along with inorganic DBPs, are summarized in Table 2.

Table 2. Regulatory limits for swimming pool water and reported concentrations of THMs and inorganic DBPs in thermal spas.

DBP	Measured concentration in thermal spas	Ref.	Quality limits in pool water set by regulations			
			Country	QL	Note	Ref.
	14.5-97.3		Croatia	100	Conventional pools	[60]

Total THMs (4THM), µg/L	32.6-237	[146**Error! Bookmark not defined.**] [169]	Denmark	25 50	--Indoor SPs with temperature ≤34 °C -SPs with T ≥34°C and outdoor pools	[65]
			France	100	If filling water is not from a drinking water distribution network	[73**Error! Bookmark not defined.**]
			Germany	20	Indoor SPs. Higher concentrations are allowed in outdoor SPs.	[77]
			Hungary	50	Only in case of disinfection with chlorine, alone or in combination	[86]
			Japan	200		[99]
			Netherlands	50		[105]
			Poland	100	Conventional pools	[108]
			Portugal	100		[114]
			Slovenia	50		[122**Error! Bookmark not defined.**]
			Sweden	100		[129**Error! Bookmark not defined.**]
			Switzerland	20 50	-Indoor SPs -Outdoor SPs	[131**Error! Bookmark not defined.**]
Chloroform, µg/L			China	100	Artificial SPs. Not applied to hot springs SPs	[58]
			Finland	50	Not applicable to outdoor SPs	[70]
			Lithuania	100	If chlorine-based compounds are used for disinfection	[102]
			Poland	30	Conventional pools	[108]
Bromate, mg/L	<LOD-2.4	[169]	Germany	2		[77**Error! Bookmark not defined.**]
			Netherlands	0.1		[105]
			Switzerland	0.2		[131**Error! Bookmark not defined.**]
Chlorite, mg/L	<LOD-0.19	[169]	Croatia	0.4	Only in conventional pools, if chlorine dioxide is used for disinfection	[60]
			Slovenia	0.1	Only in conventional pools, if chlorine dioxide is used for disinfection	[122]
Chlorite + chlorate, mg/L			Czech Republic	20	Only if chlorine dioxide, sodium or calcium hypochlorite or their preparations are used in disinfection	[63]
			Germany	30		[77]
Chlorate, mg/L	1.1-1.6 <LOD-20	[146**Error! Bookmark not defined.**] [169]	Hungary	10	Only in case of disinfection with active chlorine, alone or in combination	[86]
			Netherlands	30		[105]
			Switzerland	10		[131**Error! Bookmark not defined.**]

Note: QL – quality limit; LOD – limit of detection.

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The calculated Bromine Incorporation Factor (BIF) demonstrated that thermal pools predominantly form brominated and mixed-halogenated species [169]. While in freshwater pools, among 4THMs, chloroform predominates, meanwhile bromoform in seawater pools, in thermal pools, mixed species such as bromodichloromethane (BDCM) and dibromochloromethane predominate [169]. Chloroform and BDCM are for a long classified as "possible human carcinogens" in Group 2B by IARC [181]. Therefore, to reduce the formation of Br-DBPs, it is necessary to exclude the usage of bromine-based disinfectants, as is the case in Germany, where only chlorination with additional ozonation is permitted for thermal therapy spa treatment [169]. However, even the latter method must be applied in a controlled manner (the pH should be neutral to acidic) as it leads to the oxidation of bromide to form bromate, an inorganic DBP, regulated both in drinking and pools water because is possibly carcinogenic to humans (Group 2B) according to IARC [169,181] and mutagenic both in vitro and in vivo [182].

The shift in speciation in thermal pools is toxicologically alarming, because it has been found that THMs and HAAs only account for less than 15% of the total calculated cytotoxicity, leaving a significant unregulated fraction of potentially more toxic compounds such as haloacetonitriles (HANs), haloacetaldehydes (HALs), halonitromethanes (HNMs), aldehydes and nitrosamines [169,177]. In thermal spas, HANs have been found to be particularly critical, being the second prevalent class after THMs they are accounting for more than 60% of CHO-cytotoxicity and 70% of genotoxicity, followed by HALs and bromate [169]. In general, it has been found that the pools filled with thermal water had 36 times higher calculated toxicity than the pools filled with drinking water.

Recent advancements in DBPs analysis have revealed that the chemical risk in thermal pools is far more complex than previously thought. Non-targeted screening resulted in the detection of 131 gas chromatography-derived and 223 liquid chromatography-derived signals, corresponding to distinct molecular entities, some of which remain unidentified [170,183]. The detection for the first time in thermal water of pentachloroacetone, pentabromopropanal, as well as representative of cyclic halofuranones, trihalo-hydroxy-cyclopentene-diones and tribromofuroic acid, is highlighting a presence of high-molecular-weight halogenated species [183].

The use of bioassays and hierarchical clustering confirmed that the presence of regulated THMs and HAAs, often fail to explain the total toxicity observed in thermal waters. Interestingly, some bioassays indicated that the actual biological effect does not always correlate linearly with the concentration of Br-DBPs, supposed because of their lower stability compared to Cl-DBPs. The presence in thermal waters of N-containing classes such as haloacetonitriles (HANs) and haloacetamides (HAMs), short-chain halogenated carboxylic acids as well as iodinated DBPs (I-DBPs), among the most genotoxic and cytotoxic DBPs in absolute terms, may be a more important driver for toxicity [183]. In thermal pools were also detected UV-filters (e.g., octotrylene, cinoxate, avobenzone), as well as preservatives (e.g., parabens) and plasticizers, belonging to the endocrine disruptors (EDCs) [183].

Such class of CECs as pharmaceuticals and personal care products (PPCPs), is particularly relevant in recreational and therapeutic water systems. PPCPs, including pharmaceuticals, cosmetics, shampoos, repellents, lotions, creams, fragrances, insect repellents, and other widely used therapeutic products, are continuously released into the aquatic environment and represent a growing concern due to their potential adverse effects (directly or as DBP precursors) on human health and the environment [183–187].

Although establishing a direct exposure–response relationship remains complex, numerous studies reported associations between PPCPs and potential genotoxicity, carcinogenicity, neurotoxicity, bioaccumulation, induction of antibiotic resistance, and endocrine and reproductive disruption [183–186,188–190].

Even at very low concentrations (ng/L–µg/L), PPCPs may significantly affect aquatic biota and contribute to alterations in microbial communities and biofilm dynamics. In swimming pool systems supplied with thermal water, these contaminants are primarily introduced through anthropogenic activities, particularly via the release of bathers' body fluids, as well as the direct wash-off of personal care products during immersion [170,186,190–193]. Furthermore, certain pharmaceutical active ingredients may be excreted in unchanged form due to incomplete human metabolism, while metabolic processes can generate transformation products that are not easily identifiable, thereby increasing the complexity of the contaminant profile [186,187,194].

Beyond their direct toxicity, PPCPs are recognized as reactive chemical precursors of novel DBPs during disinfection processes, capable of altering the overall toxicological burden of treated thermal waters. Many PPCPs contain aromatic rings, amino groups, or activated functional groups that react rapidly with free chlorine or bromine species present in disinfected water, leading to the formation of Cl-DBPs, Br-DBPs, or mixed halo-DBPs, and generating more toxic species (e.g., HANs, HNMs, halobenzoquinones (HBQs), and N-nitrosamines) [183,195–200].

Table 3 lists the PPCPs, as well as illicit drugs, investigated in thermal waters as reported in recent literature, classified according to their therapeutic, cosmetic, or pharmacological use, along with the potential DBPs that could be formed during disinfection processes based on chemical structure and functional groups. The predicted DBPs are inferred from the main reactive functional groups present (e.g., primary, secondary, or tertiary amines, activated aromatic rings and phenolic moieties), which are known to favor the formation of N-nitrosamines, HANs and halogenated aromatic derivatives [189,195–200].

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Table 3. PPCPs, illicit drugs and metabolites investigated in thermal waters and their potential role as DBP precursors during disinfection processes.

Compound	Therapeutic / use class	Main reactive functional groups	Main potential DBP classes	[Ref.]
6-Acetylmorphine	Illicit drug	Phenolic	Halo-DBPs	[201,202]
Amitriptyline	Antidepressant	Tertiary amine, aromatic rings	N-DBPs, Halo-DBPs	[195]
Amphetamine / Methamphetamine	Illicit stimulants	Primary amine	N- DBPs, Halo-DBPs	[195]
Atenolol / Metoprolol / Bisoprolol / Propranolol / Sotalol	Beta-blockers	Secondary amine	N- DBPs, Halo-DBPs, HBQs	[195]
Atorvastatin / Rosuvastatin	Cardiovascular drugs	Aromatic rings	Halo- DBPs,	[200]
Azithromycin / Clarithromycin / Erythromycin	Antibiotics	Tertiary amines	N- DBPs	[195]
Benzoylecgonine	Illicit drug metabolite	Aromatic ring	Halo- DBPs	[201,202]
Caffeine	Stimulant; cosmetic ingredient	Heterocyclic nitrogen ring	N- DBPs	[198]
Carbamazepine (CBZ)	Antiepileptic	Aromatic ring + amide	HANs, HBQs	[201,202]
CBZ-10,11-epoxide / 10,11-dihydro-CBZ	CBZ metabolites	Epoxide + aromatic	N- DBPs, Halo-DBPs, HBQs	[201,202]
Cetirizine / Diphenhydramine / Clemastine / Fexofenadine / Meclozine / Chlorphenamine	Antihistamines	Amine + aromatic rings	N- DBPs	[195]
Citalopram	Antidepressant	Secondary amine	N- DBPs , Halo-DBPs	[195]
Clindamycin / Clindamycin sulfoxide	Antibiotics	Amine + sulfur	Mixed Halo/S-DBPs	[197]
Clomipramine	Antidepressant	Tertiary amine	N- DBPs, Halo-DBPs	[195]
Cocaine	Illicit drug	Ester + amine	HANs, N- DBPs	[189,201,202]
Codeine / Morphine	Opioid analgesics	Phenolic + amine groups	N- DBPs, Halo-DBPs	[189]
Diclofenac	NSAID	Aromatic amine	THMs, HAAs, Halo- DBPs	[197]
Fenofibrate / Bezafibrate	Cardiovascular drug	Aromatic rings	THMs, HAAs, Halo- DBPs	[200]
Iopromide	Contrast agent	Iodinated aromatic rings	I- DBPs	[198]
Ketamine / Norketamine	Anesthetics	Secondary amine	THMs, Halo-DBPs	[195]
Lamotrigine / Oxcarbazepine	Antiepileptics	Aromatic amine	Halo- DBPs, N-DBPs	[200]
LSD metabolite (2-Oxo-3-hydroxy-LSD)	Illicit drug metabolite	Aromatic amide	THMs, Halo-DBPs	[201]
Maprotiline / Mianserin / Mirtazapine	Antidepressants	Aromatic amines	N- DBPs, Halo-DBPs	[195]
MDMA / MDA / MDEA	Illicit drugs	Aromatic amine	HANs, N- DBPs	[201,202]
Mephedrone / Cathinone	Synthetic cathinones	Ketone + amine	N-DBPs	[201]
Methadone	Opioid	Tertiary amine	N- DBPs, Halo-DBPs	[195]
Miconazole / Terbinafine	Antifungals	Heterocyclic amine	Halo- DBPs, N-DBPs	[198]

N-Desmethylcitalopram	Antidepressant metabolite	Secondary amine	N- DBPs, Halo-DBPs	[195]
Oxazepam / Alprazolam / Clonazepam	Benzodiazepines	Amide, aromatic rings	N- DBPs, Halo-DBPs	[195]
Oxycodone	Opioid	Ketone + amine	N- DBPs, Halo-DBPs	[195]
Sertraline / Norsertraline	Antidepressant	Secondary amine, aromatic rings	N- DBPs, Halo-DBPs	[195]
Sulfamethoxazole & sulfonamides (Sulfadiazine, Sulfamerazine, Sulfamethazine, Sulfamethizole, Sulfapyridine)	Sulfonamide antibiotics	Aromatic amine	HANs, HNMs	[197]
THC-COOH / Cannabinol	Illicit drug	Phenolic rings	THMs, HAAs, Halo- DBPs	[199]
Theophylline	Xanthine metabolite	Amide, heterocycle	Halo- DBPs	[198]
Tramadol	Analgesic	Tertiary amine	N- DBPs, Halo-DBPs	[195]
Trazodone	Antidepressant	Aromatic amine	N- DBPs, Halo-DBPs	[195]
Trimethoprim	Antibiotic	Aromatic amine	Mixed Halo/S-DBPs	[197]
Valsartan / Irbesartan / Telmisartan	Cardiovascular drug	Aromatic rings	Halo- DBPs	[200]
Venlafaxine / O-Desmethylvenlafaxine	Antidepressant	Tertiary amine	N- DBPs, Halo-DBPs	[195]
Verapamil / Diltiazem	Cardiovascular drug	Tertiary amine	Halo- DBPs	[200]
Vortioxetine	Antidepressant	Aromatic amine	N- DBPs, Halo-DBPs	[195]

Recent studies have investigated the occurrence of pharmaceutical residues and other anthropogenic substances in thermal pool waters and associated wastewater. Numerous pharmaceuticals, illicit drugs, and several of their metabolites were identified in water samples collected from thermal pools. These findings revealed an asymmetric distribution of concentrations and varying prevalence of substance classes depending on pool typology and user profile. Caffeine was the most frequently detected compound, followed by its metabolite theophylline and cardiovascular drugs such as bisoprolol, metoprolol, metoprololic acid, and telmisartan. Antidepressants, antihistamines, the analgesic tramadol, and the antiepileptic carbamazepine were also identified. Among illicit substances, methamphetamine, cocaine, and benzoylecgonine were most frequently detected, with evidence of bioaccumulation and potential ecotoxicological effects associated with their degradation products [201,202].

A further, often neglected source of DBP precursors in thermal and wellness facilities is the addition of herbal medicines (e.g., ginseng, rosemary, mint) for therapeutic purposes. The introduction of these organic matrices into chlorinated spa water significantly accelerates the formation of THMs [203]. The high-water temperatures typical of spas, facilitate the extraction of essential oils, proteins and phenolic compounds (e.g., caffeic and vanillic acids) from herbs, which act as “fast formers" of DBPs. Research indicates that at least 50% of the THMs are produced within the first six hours of reaction, often causing their levels to exceed the limit of 100 μg/L in water containing herbal medicines. This highlights a critical paradox in wellness tourism: while herbal baths are used to treat skin conditions and reduce stress, the resulting environment characterized by increased concentrations of volatile DBPs at the air-water interface may pose significant respiratory and dermal health risks to users and staff [203].

Another issue related to PPCPs and DBPs is their potential ecotoxicity. The effects of discharges of treated thermal water effluents, containing chemical contaminants and disinfectant residues, into

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natural water bodies has raised growing concerns about their potential environmental impact, leading to a significant intensification of research in this area [180,204–209]. The environmental risk is further complicated by synergistic effects between DBPs and other water stressors, such as micro and nano plastics [210] and a wide range of other CECs [199,200]. Currently, the literature lacks ecotoxicological studies specifically conducted on disinfected thermal effluents. Consequently, environmental impacts must be inferred from other disinfected aqueous matrices with similar resulting DBP classes [212–214] though these do not consider the unique thermal waters "chemical fingerprint".

The studies reveal that DBPs act as potent stressors across various aquatic levels. It has been found they can disrupt the membrane potential of marine heterotrophic bacteria [200,211,214], as well as cause significant phytotoxicity in plant models [200,206**Error! Bookmark not defined.**] and photosynthetic organisms [204,205]. In particularly, DBPs can intensify oxidative stress, inhibiting photosynthesis and biomass growth, as well as seed germination [204,206,211,214]. These effects scale up to the community level; where DBPs can disrupt the competitive fitness of algae, potentially destabilizing the base of the aquatic food web [180,204**Error! Bookmark not defined.**]. Their acute toxicity extends to broad range of taxa, with documented bioaccumulation [207], increased mortality rate and developmental delays in annelids, larvae, crustaceans and invertebrates [180,200,205,209–213]. Recent advances in artificial intelligence and machine learning have enabled the high-throughput computational screening of nearly 900 DBPs to evaluate and predict their ecotoxicity effects [207]. It has been demonstrated that aquatic risk is intrinsically linked to DBPs molecular architecture and the high-risk DBPs, particularly aromatics [180], are characterized by greater structural complexity and conformational flexibility. These features enhance their binding affinity for target proteins involved in oxidative stress, apoptosis, and neurotoxicity across different trophic levels, from primary producers to vertebrates [180,207].

Finally, a growing body of evidence highlights other issues related to DBPs, suggesting a necessary paradigm shift in disinfection risk assessment. Firstly, it is important to consider that chronic exposure of aquatic populations to biocides and DBPs can develop pollution-induced tolerance [215] and could compromise their long-term resilience, reducing their ability to withstand concomitant environmental stressors such as climate change. This evolutionary pressure is particularly alarming in microbial communities, where biocides, DBPs, CECs and their transformation products can act as drivers for the selection and spread of antibiotic and antimicrobial resistance [8,215–227].

Recent works, although conducted on aqueous matrices other than thermal waters, suggests that this phenomenon is mainly driven by the synergy between physical cellular damage and genetic alterations [215]. In has been found, that the chlorination of waters rich of halides such as Br^- and I^-, such as many thermal systems, generates a potent mixture of free and combined halogenated oxidants ($HOCl/OCl^-$+ $HOBr/OBr^-$ or HOI/OI^-) that induce a stronger oxidative stress than chlorine alone [217]. This "combined attack" can upregulate the key stress regulatory genes (e.g., *rpoS*), outer membrane proteins (e.g., *ompC*) and conjugation-specific genes (e.g., *trbBp*, *trfAp*), significantly enhancing horizontal gene transfer (HGT) [217]. This halogen-mediated stress causes the structural damage, both by creating pores that increase membrane permeability [219,225] and by facilitating the plasmid-based conjugative transfer between living cells (further accelerated by metals, microplastics and other micropollutants present in environment [221,222]) and the uptake of extracellular DNA released from inactivated bacteria [215,217,220]. This physical alteration can be further compounded by inorganic DBPs such as bromate and chlorite [218], and N-DBPs like bromoacetamide [219]. Although short time exposure to these compounds may initially inhibit HGT by interfering with cellular respiration and ATP production, prolonged contact leads to a bioenergetic recovery [218]. This restoration of energy supply, coupled with the primary mechanisms through which non-antibiotic chemicals facilitate conjugative HGT, namely activation of the SOS response and reactive oxygen species (ROS) over accumulation [218,219,225], can increase gene transfer frequency by up to 3.6-fold [224].

It has been shown that THMs and HAAs had positive correlations with various antibiotic resistance genes (ARGs) in different eluents, being important contributors to the enrichment and spread of ARGs in water [226]. However, it appears that different DBP concentrations can cause different ROS-mediated regulation: while their presence at levels around 100 μg/L causes moderate oxidative stress and facilitates ARGs integration, extreme stress (>1 mg/L) can temporarily inhibit transfer by disrupting DNA uptake mechanisms, such as the pilus complex [224]. At the transcriptional level, bacteria respond to DBPs by reducing high-energy processes (e.g., sulfur metabolism [219]) and enhancing the biosynthesis of protective amino acids, ensuring the persistence and propagation of newly ARGs [219]. Furthermore, such highly toxic I-DBPs, as iodoacetic acid, can exert "antibiotic-like" effects [216], which amplifies the health risks of chlorination. Its sub-inhibitory concentrations (sub-MIC), as well as those of other DBPs (e.g., chloroform, dichloroacetonitrile, and trichloroacetic acid) can select the phenotypes with significantly higher levels of resistance than the effects of massive doses of DBPs [225**Error! Bookmark not defined.**]. This occurs through targeted mutations in key genes (*gyrA*, *marR*) and promotes the emergence of multi-drug resistance (MDR**)** [216,220]. Crucially, the risk can be significantly amplified by the synergistic interaction between DBPs and residual antibiotics [220,221]. Long-term co-exposure enhances the diversity and mobility of resistance determinants, facilitating the co-occurrence of ARGs, virulence factors or biocide resistance genes (BRGs), and mobile genetic elements within the same genome [215,220,223], particularly in opportunistic pathogens (e.g., *E. Coli*) [216,220**Error! Bookmark not defined.**,227]. The physical environment of the water infrastructure plays a decisive role in this selection. Biofilms act as dynamic reservoirs, where the extracellular polymeric substance matrix sequesters ARGs [222] and protects subpopulations from disinfectants (sometimes increasing their chlorine tolerance to the point of requiring its 200-fold higher concentrations [215]), creating so high-density "evolutionary hotspots" [226,227]. From a disinfection efficiency perspective, it has been found that while chlorination and hybrid methods can reduce total bacterial counts, they can also enhance co-selection between BRGs and ARGs and increase the relative abundance of intracellular and extracellular ARGs, thus creating a persistent “long-term resistance” even after the residual chlorine has dissipated [222,223,227**Error! Bookmark not defined.**].

This suggests that the toxicity of thermal pools can the result of a complex "cocktail effect," where the specific mineral signature of the spring interacts with anthropogenic precursors to create a unique toxicological profile [203]. Consequently, modern safety protocols should integrate effect-based methods alongside chemical analysis to capture the total risk posed by the emerging contaminants. Overall, this indicates that not only general control measures, including pre-swim showering, increasing the water exchange and an efficient filtration system, but improved ventilation are needed as precautionary measure to reduce the volatile DBP exposure [203].

3.3.3. Environmental Sustainability Challenges

Thermal water facilities rely on natural geothermal aquifers that often represent limited and slow-renewing hydrogeological resources. The exploitation of thermal groundwater must therefore be carefully balanced with the natural recharge capacity of the aquifer systems. Excessive abstraction may alter hydrogeological equilibrium, potentially leading to reduced water availability, temperature variations, or modifications in mineral composition that may affect both environmental sustainability and therapeutic properties of the resource [228,229].

In many thermal regions, groundwater recharge occurs over long geological timescales and is controlled by complex hydrogeological processes such as deep circulation, infiltration through fractured rock systems, and interactions between surface and subsurface water bodies. Consequently, the resilience of thermal aquifers depends strongly on sustainable withdrawal rates and on effective monitoring of hydrogeological parameters [228,230].

Another relevant challenge concerns the potential conflict between different uses of thermal resources. Thermal waters may simultaneously support therapeutic applications, tourism development, recreational activities, and environmental conservation objectives. These competing

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demands can generate tensions between economic development and long-term resource protection, highlighting the need of sustainable governance frameworks capable to ensure that thermal water exploitation remains compatible with aquifer protection, ecosystem preservation, and public health objectives [6,228,231].

Thermal water facilities may also contribute to environmental pressures through their energy demand and associated greenhouse gas emissions. Although thermal waters naturally emerge at elevated temperatures, energy is often required for pumping, distribution, temperature stabilization, ventilation, and operation of treatment systems. Additional energy consumption may arise from water circulation, filtration, and disinfection processes required to maintain hygienic conditions in pool environments. Heating requirements may be particularly relevant in facilities where thermal waters are cooled or mixed with freshwater and subsequently reheated to reach optimal therapeutic temperatures. Indoor spa infrastructures may further increase energy demand due to ventilation and humidity control requirements [232].

Environmental pressures may also arise from wastewater discharge and the use of treatment chemicals. Thermal waters discharged from spa facilities can contain residual disinfectants, DBPs, bathers-derived organic contaminants, and natural mineral components. As discussed in Section 3.3.2, treatment agents and processes, as well as generation of by-products, imply further environmental considerations, as the effluents may influence receiving aquatic ecosystems, particularly in areas where thermal facilities are located near rivers, coastal systems, or groundwater recharge zones.

Effective wastewater management strategies optimized chemical use, and the adoption of environmentally compatible treatment technologies represent key priorities for reducing the ecological impact of thermal facilities while maintaining public health protection [11,203].

4. Discussion

4.1. Balancing Health, Safety, and Sustainability: An Integrated Perspective

Thermal water facilities represent a complex interface between therapeutic use, public health protection, and environmental sustainability. The analysis conducted in this review highlights how the management of these facilities is characterized by a persistent trade-off between preserving the natural characteristics of thermal waters and ensuring adequate hygienic safety for users.

Adopting a One Health perspective may help address these interconnected challenges. In this framework, human health, environmental protection, and ecosystem integrity are considered interdependent components of a single system. Thermal facilities illustrate this interconnection particularly clearly, as water quality, microbial ecology, chemical composition, and environmental management practices directly influence both therapeutic outcomes and safety.

The regulatory analysis revealed a highly heterogeneous international landscape. Different countries adopt markedly diverse approaches to thermal water management, ranging from strict disinfection requirements similar to those applied to conventional swimming pools to regulatory frameworks that prioritize the preservation of the natural characteristics of thermal waters. This heterogeneity reflects the intrinsic complexity of thermal aquatic environments, where physicochemical composition, microbiome, and therapeutic properties are strongly site-specific.

From a public health perspective, microbiological risks remain the primary concern in thermal pools. Elevated water temperatures and high organic load introduced by bathers create conditions favourable for microbial proliferation, biofilm formation, and persistence of opportunistic pathogens. At the same time, the adoption of disinfection practices intended to mitigate microbiological risks introduces additional chemical concerns.

Increasing disinfection intensity may enhance microbiological safety but can also lead to higher chemical consumption, increased formation of DBPs, and greater environmental burden. Although DBPs occurrence has been extensively investigated in conventional swimming pools and drinking water systems, studies specifically addressing thermal pool environments remain scarce. The few available studies suggest that DBP formation in thermal waters may be strongly influenced by the natural mineral composition of the source water and by the presence of anthropogenic contaminants introduced by bathers. PPCPs may act both as direct contaminants and as potential precursors of DBP formation, further increasing the complexity of chemical exposure scenarios. In parallel, growing attention has been directed toward the potential role of aquatic recreational environments in the dissemination of antimicrobial resistance. Interactions between disinfectants, chemical contaminants, microbial communities, and biofilms may contribute to the selection and persistence of resistant microorganisms, although specific evidence for thermal pool environments remains limited and requires further investigation.

Conversely, management strategies that prioritize the preservation of the natural characteristics of thermal waters may reduce chemical inputs but potentially increase microbiological risks if not supported by adequate monitoring and control strategies.

For these reasons, the management of thermal aquatic environments requires integrated risk assessment approaches that consider both health and environmental indicators. Combining microbiological surveillance, chemical monitoring, and environmental performance indicators may help support evidence-based decision-making and improve the sustainability of thermal water management.

Conceptually, these interactions can be represented as a triangular balance between health benefits, safety requirements, and environmental sustainability, where optimal management strategies aim to maintain equilibrium among these three dimensions.

4.2. Innovations and Future Directions

Advances in analytical and monitoring technologies offer promising opportunities for improving risk assessment in thermal aquatic systems. Rapid microbiological detection methods, molecular diagnostics, and Next-generation sequencing approaches may enable earlier detection of microbial hazards. Similarly, high-resolution chemical screening techniques can facilitate the identification of CECs and DBPs in complex water matrices.

Predictive approaches based on environmental modeling and digital monitoring systems may further support proactive management strategies. Integrating sensor networks, real-time monitoring, and predictive modeling may allow operators to anticipate risk scenarios and optimize water treatment processes.

From a sustainability perspective, innovative technological solutions may help reduce the environmental footprint of thermal facilities. These include alternative disinfection strategies, optimized water recirculation systems, advanced filtration technologies, and energy-efficient infrastructure designs. Intelligent water management systems may also improve operational efficiency by optimizing water turnover rates and treatment intensity according to real-time conditions.

Improving energy efficiency represents another key priority. Integrating renewable energy sources, geothermal energy recovery systems, and heat-exchange technologies may reduce greenhouse gas emissions associated with thermal facility operation.

Despite increasing scientific interest, several knowledge gaps remain regarding the environmental and health implications of thermal water facilities. In particular, limited data are available on the occurrence and fate of emerging contaminants in thermal aquatic environments, as well as on the long-term ecological effects of wastewater discharges from spa infrastructures.

Another important gap concerns the lack of dedicated regulatory frameworks specifically addressing thermal water–supplied swimming pools. In many countries, thermal facilities are either regulated under spa medicine legislation or assimilated to conventional swimming pool standards, which may not adequately reflect the specific physicochemical and microbiological characteristics of thermal waters.

Future research should therefore focus on developing integrated monitoring strategies, standardized risk assessment frameworks, and evidence-based guidelines specifically tailored to thermal aquatic environments. In parallel, strengthening training programs for facility operators and public health professionals may help improve the implementation of sustainable and safe management practices.

5. Conclusion

Thermal water–supplied swimming pools represent a unique aquatic environment in which therapeutic benefits, public health protection, and environmental sustainability intersect. This review highlights that the management of these systems involves complex trade-offs between preserving the natural properties of thermal waters and ensuring adequate microbiological and chemical safety.

Current knowledge remains fragmented. Regulatory frameworks vary considerably across countries, while scientific data on chemical contaminants, disinfection by-products, and emerging pollutants in thermal pools remain limited. In addition, growing concerns regarding antimicrobial resistance and environmental sustainability further complicate the risk management landscape.

Addressing these challenges requires integrated and evidence-based strategies capable of balancing three key dimensions: health benefits, user safety, and environmental protection. Strengthening multidisciplinary research and developing harmonized regulatory approaches specifically tailored to thermal water facilities will be essential to support their sustainable and safe use in the future.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org, Figure S1: Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) Checklist.

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Abbreviations

The following abbreviations are used in this manuscript:

AMR	Antimicrobial resistance
ARGs	Antibiotic resistance genes
DBPs	Disinfection by-products
CECs	Emerging chemical contaminants
HAAs	Haloacetic acids
HGT	Horizontal gene transfer
LOD	Limit of detections
MDR	Multi-drug resistance
THMs	Trihalomethanes
PPCPs	Pharmaceuticals and personal care products
ROS	reactive oxygen species
SPs	Swimming pools

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