Review on the management of water quality for bio-mineral swimming pools in Western Europe

Julien G. Mahy[1,2,3,*], Frédéric Luizi[4]

[1] Department of Chemical Engineering – Nanomaterials, Catalysis and Electrochemistry (NCE), University of Liège, Allée du Six Août 11, 4000 Liège, Belgium

[2] Fonds de la Recherche Scientifique (FNRS), Rue d'Egmont 5, 1000 Bruxelles, Belgium

[3] Institut National de la Recherche Scientifique (INRS), Centre-Eau Terre Environnement, Université du Québec, 490, Rue de la Couronne, Québec (QC), G1K 9A9 Québec City, Canada

[4] Aquatic Science S.A., Zoning des Hauts Sarts, 3ème Avenue 1, 4040 Herstal, Belgium

*Corresponding author: Julien G. Mahy; email: julien.mahy@uliege.be; address: Allée du Six Août 11, 4000 Liège, Belgium

Abstract

In this review, we depict the state of the art concerning the water quality management of bio-mineral bathing pools, and compare these to traditional swimming pools. Bio-mineral pools use a combination of mechanic filtration, bio-filtration, and UV-treatment to disinfect the water. Studies in test tanks have shown that bio-filtration is effective in maintaining the water quality with regard to the treatment of organic pollution. Concerning biological risks, the bio-mineral pool relies on UV-treatment to degrade bacteria. Unlike chemical disinfectant treatments, UV disinfection does not lose its effectiveness in the event of high traffic in the pool. However, as only the water taken up by the filtration system is disinfected, it is essential that all the water in the pool is filtered. If the pool has a dead zone, its water is not disinfected and there is a risk of localized pathogen development.

As the development of bio-mineral pools spreads in Europe, legislation gradually follows. The health parameters measured differ slightly from one country to another, but there are constants: the measurement of *Escherichia coli*, *Enterococci,* and *Pseudomonas aeruginosa*. In terms of biological swimming pools, regulatory homogeneity across Europe does not exist. From these comparisons, Austrian legislation segmenting water quality into 4 categories ranging from "Excellent" to "Poor" represents legislation that combines health and safety with indications of possible malfunctions.

Next, a study of three real sites of bio-mineral pools is presented. It appears that, whatever the type of pool, bio-mineral filtration makes it possible to achieve performances comparable to those encountered in chlorinated swimming pools concerning the risks associated with fecal contamination and external pollution. On the other hand, when frequentation is high, as is the case in small pools used for aquafitness, monitoring the risks of inter-bather contamination, as illustrated by the presence of *Staphylococcus aureus*, reveals a recurring problem.

Knowing that this parameter is not evaluated in bathing waters in the natural environment and that numerous studies show that *Staphyloccocus aureus* are always detected, even on beaches, we propose the definition of three thresholds: i.e., 0 CFU/100 mL (threshold value in Wallonia) for water of excellent quality, less than 20 CFU/100 mL (threshold value in France) for water of very good quality, less than 50 CFU/100 mL (contribution of bathers by simple immersion) for good quality water, and more than 50 CFU/100 mL for poor quality water. This document could therefore be converted into a manual for operators on the use and management of bio-mineral baths.

Keywords: bio-mineral pool, European legislation, bathing parameters, swimming risks, bathing bacteria

1. Introduction

The first swimming pools appeared in antiquity, but it was really from the end of the 19th century that these started to develop. From the 1920s, many public swimming pools were created in developed countries and from the 1960s private pools appeared, a sign of wealth and luxury. Since then, many swimming pools have been constructed, both public and private.

In order to maintain clean water for swimming, cleaning systems were developed, with chlorine disinfection appearing in 1902 (Chowdhury et al., 2014). This chemical treatment is the most common disinfection system for both private and public swimming pools. Other chemical/physical agents can also be used, such as bromine, ozone, or UV radiation. These different techniques kill pathogens present in the water, but can nevertheless react with certain substances to produce disinfection by-products (Chowdhury et al., 2014; Karimi, 2020; Lu et al., 2013). These by-products can present a chemical risk to bathers (Carter et al., 2019; Chowdhury et al., 2014; Zhang et al., 2023).

Consequently, alternatives to chemical disinfection have been developed, in particular bio-mineral swimming pools. In this type of pool, there is no residual disinfectant; there is no disinfectant barrier between bathers. However, the water is disinfected at each filtration cycle. It is therefore disinfected but non-disinfecting water. In the specific case of bio-mineral bathing, the disinfection step is ensured by treatment with ultraviolet radiation which occurs without the addition of residual biocides and the particles in suspension are filtered by mechanical and biological filters which allow their elimination.

This review aims to present the state of the art of bio-mineral swimming pools and compare them with traditional swimming pools, with a focus on water disinfection and health issues. The review is divided into three parts: (i) the risks incurred when swimming; (ii) the state of European legislation on swimming in bio-mineral pools; and (iii) concrete examples of the microbiological parameters of swimming in a bio-mineral pool.

2. The health risks in traditional and bio-mineral swimming pools

The health risks for bathers in swimming pools come from two sources: chemical or biological risks. Good management of water quality in bio-mineral swimming pools requires complete control of risks. As recommendations are often based on the management of chlorinated swimming pools, comparative analyses of the characteristics of the two technologies are called for. A distinction is therefore made between disinfectant swimming pools (chlorinated swimming pools) and disinfected swimming pools (bio-mineral swimming pools).

2.1. Pools and artificial swimming pools

Within the meaning of French legislation, only pools equipped with disinfectant filtration can be called swimming pools. The official name of bio-mineral pools is “artificial pools with biological filtration”. To clearly mark the difference, it is appropriate to speak of swimming pools when referring to chlorinated swimming pools and of bathing pools to refer to disinfected but non-disinfecting swimming pools.

In swimming pools, the disinfectant (generally an active form of chlorine) is added and regulated in the closed circuit of swimming pool water treatment (Figure 1). Therefore, pool water is called disinfecting water; there is a disinfectant barrier between bathers.

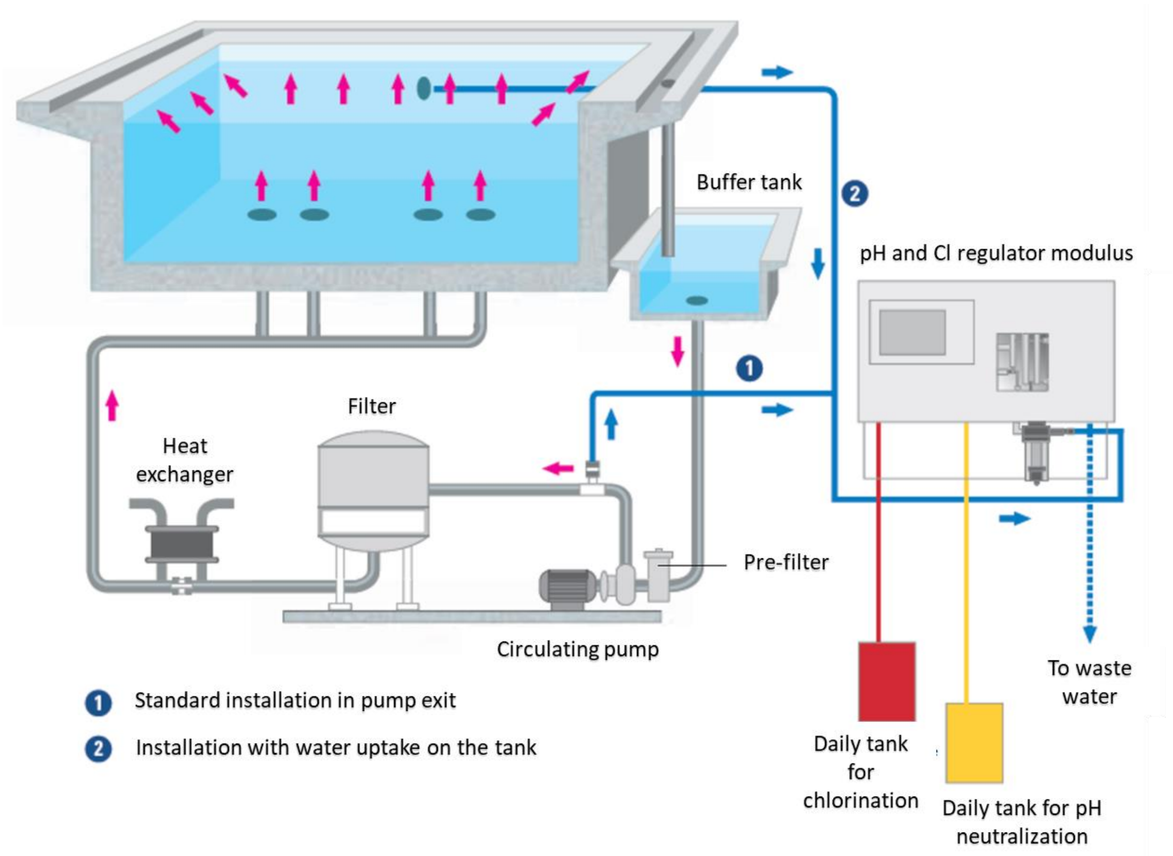

Figure 1: General scheme of a classical swimming pool (Association des Equipements Sportifs (AES), 2016)**.**

Artificial bathing pools, also called natural swimming pools, biological swimming pools, ecological swimming pools or, in the case that concerns us, bio-mineral swimming pools, do not contain residual disinfectant. There is no disinfectant barrier between bathers. However, the water is disinfected with each filtration cycle. It is therefore disinfected but non-disinfectant water.

In the specific case of bio-mineral pools, the disinfection stage is ensured by treatment with ultraviolet radiation combined with an advanced oxidation process (AOP) which occurs without the addition of residual biocides (Figure 2).

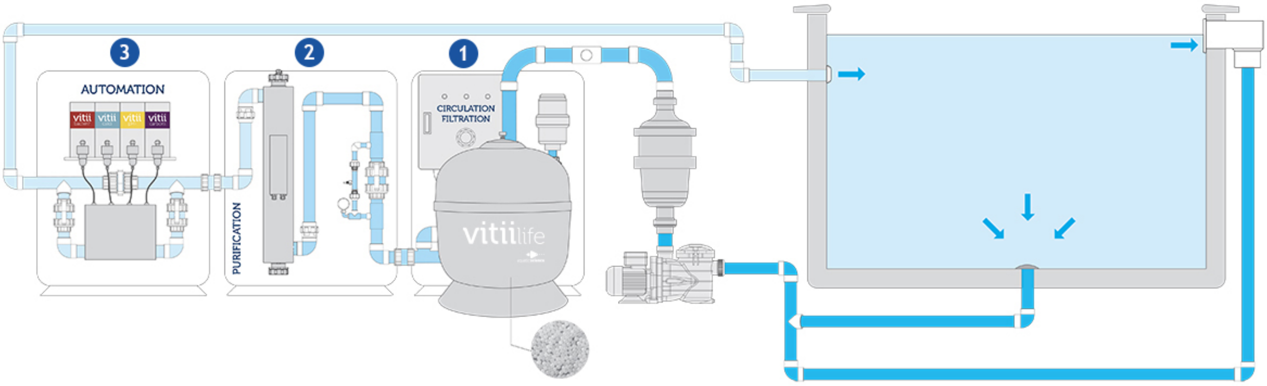

Figure 2: General scheme of a bio-mineral swimming pool (Aquatic Science, 2022b)**: (1) mechanical and biological filters, (2) UV reactor for disinfection, and (3) mineral and bacterial injections for the balance of the water.**

UV treatment is sometimes also used in chlorinated swimming pools, but most often with the aim of reducing the concentrations of by-products derived from chlorine (dechloramination) (Cheema, Kaarsholm, et al., 2017; Cheema, Manasfi, et al., 2017; Ilyas et al., 2018; Spiliotopoulou et al., 2015; Włodyka-Bergier et al., 2018, 2021; Yang et al., 2018; Zare Afifi et al., 2016) and not specifically to provide additional disinfection.

From the point of view of the management of organic pollution brought in by swimmers, in the swimming pool the material is oxidized by chlorine and mechanically filtered by the filters. This material is extracted during filter backwash cycles. In artificial swimming pools, such as bio-mineral pools, mechanical filtration is ensured by cyclones which allow the particles in suspension to be extracted from the hydraulic circuit in such a way that they do not degrade and do not enrich the water. The following biological filters harbor consortia of bacteria ensuring the degradation of organic matter and the nitrogenous load and its elimination in the form of nitrogen gas. This sequence of reactions leading to the elimination of organic nitrogen is known as the nitrogen cycle (Figure 3).

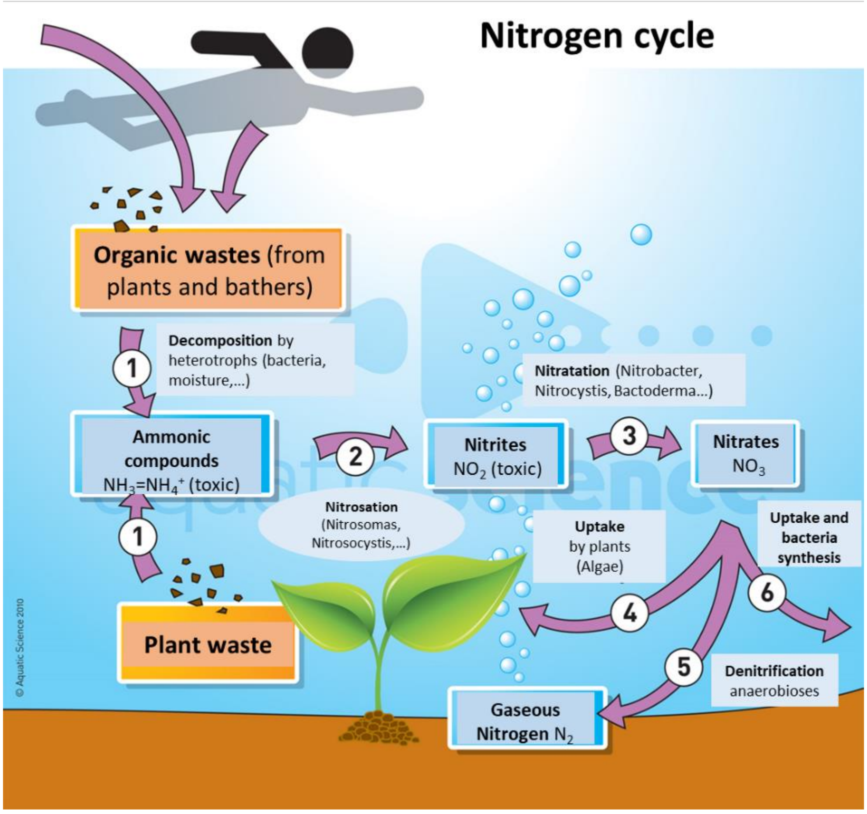

Figure 3: Nitrogen cycle of transformation and conversion.

This cycle takes place entirely inside the biological filters. The backwashing action of these filters removes dead bacteria, the mineral waste they have generated, and other suspended particles caught in the biofilm that they have formed on the substrates inside the filters.

In both swimming pools and bathing areas, the objective of filtration is to ensure the quality of the water for the health and safety of bathers.

More specifically, in a chlorinated swimming pool, the presence of bacteria indicating a health risk testifies to a limited functioning or even failure of the chlorination process. In such a case, the pool being a closed environment, there is a risk of bacterial accumulation/proliferation. It is this risk that must be avoided.

In a bio-mineral bath, as the water does not contain disinfectant, the presence of bacteria that would indicate a health risk in chlorinated pool water does not reflect the risk of accumulation, but rather reflects the contribution by bathers at the time of sampling. The risk of accumulation is circumscribed by ultra-violet (UV) disinfection and oxidation during each filtration cycle.

To assess the risk, as the analyses presented in Section 4 suggest, it is preferable to distinguish between possible accumulation and instantaneous contributions by bathers. The best way to do this is to measure prior to the operating period. If the values measured before access by bathers are high, this means that either the filtration is faulty or that there is a proliferation of bacteria in the pool. In both cases, the health risk is established and precautionary measures must be taken. On the other hand, if the bacteria thresholds are not exceeded, this confirms the proper functioning of the filtration system and proper maintenance of the pool. In this case, the risk of accumulation is avoided.

Within bio-mineral pools, the bacterial population is influenced in time and space by bathers in such a way that the environment close to each bather constitutes a micro-ecosystem in itself. As a result, a single one-off sample taken near a bather only very slightly reflects the health risk incurred by all the bathers frequenting an establishment.

In order to improve the strength of the data collected and allow bio-mineral pools to gain the trust and support of the control bodies, an in-depth reflection was carried out. It appears that demanding and well-configured self-checking techniques must be implemented to overcome the limitations of spot sampling. Evaluation of self-checking methods has shown that it is feasible to carry out analyses that are closer in time and better distributed in space in order to allow a detailed interpretation of the overall health quality of a swimming pool establishment.

2.2. How to adapt filtration to anthropogenic pollution

A swimming pool, whatever type it is, must legally be filled with mains water. As distribution water has undergone numerous controls and is drinkable, we start from the postulate that it cannot be the origin of a health risk for bathers, whether biological risk or chemical hazard. As a result, below we only consider the risks associated with the operation of pools open to the public. In the case of chemical risks, these arise from the addition of disinfectants and the resulting by-products. Like the quality of distribution water, the addition of disinfectants is controlled and legislation sets concentrations and monitoring measures to avoid direct risk (Gouvernement français, 1981). The main risks therefore come from the accumulation of derivative by-products. These are generated by the reaction of disinfection products with the material brought in by bathers. The risk is therefore directly linked to the contribution of bathers and the proper management of filtration. Biological risks also emanate from the contribution of bathers. In both cases, it is therefore essential that the filtration system is effective and as adapted as possible to the contribution of the bathers; we call this anthropogenic pollution (brought in by man).

2.2.1. Organic pollution

The organic anthropogenic pollution will depend on three factors: bather hygiene, their activity in the water, and the water temperature.

(i) Regarding hygiene, taking a shower before bathing significantly reduces the release of organic matter (perspiration, urine, feces, cosmetics, and other potential contaminants) (Lempart et al., 2018, 2020; Mazur et al., 2022; Wyczarska-Kokot et al., 2020) and passing through footbaths limits the release of *Pseudomonas aeruginosa* and papilloma virus that causes warts (Keuten et al., 2014).

(ii) The activity of bathers can be classified into three categories, rest, leisure activity, or intense activity. The most extensive knowledge on this subject comes from Maarten Keuten, a Dutch researcher who has carried out considerable research on the contributions of swimmers in swimming pools (Keuten et al., 2014). He demonstrated that the main organic fluid secretion of swimmers is perspiration and managed to precisely quantify these secretions. As shown in the figure below (Figure 4), he normalized the perspiration secretion in a swimming pool at 32°C in liters per m² of skin per hour. The unit on the abscissa represents the oxygen uptake in liters per minute, which depends on physical activity. Sweat production increases from 0.05 to 0.4 L/m²/h between rest and intense activity.

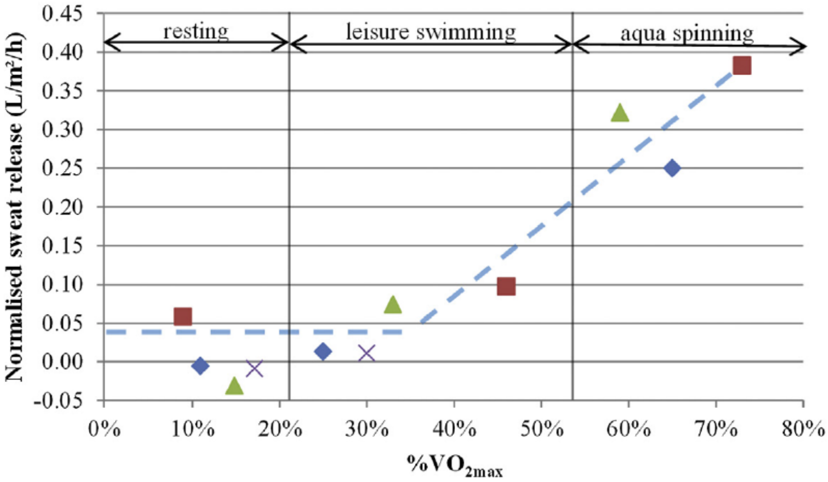

Figure 4: Evolution of the normalized sweat release as a function of the oxygen intake for different data from the literature. Reproduced from (Keuten et al., 2014) **with the permission of Elsevier.**

Knowing that an adult of average size (175.6 cm tall and 77.4 kg (Keuten et al., 2014)) has a skin surface that can be estimated at:

$$BSA = \frac{\sqrt{W\,x\,H}}{6} = 1.943\text{m}^2 \qquad (1)$$

Where BSA = body surface area (m²), W = weight (kg), and H = height (m)

We can consider that the maximum perspiration secretion is 0.78 L for a swimmer doing intense activity for one hour in water at 32°C.

(iii) In terms of temperature, the data given above (Figure 4) by Keuten et al. (Keuten et al., 2014) were compared with all the scientific literature in the field (Figure 5). There is a very significant increase in the sweat contribution of bathers above 29°C. At 32°C, the sweat secretion is double what it is at 29°C, whereas it does not vary between 25 and 29°C.

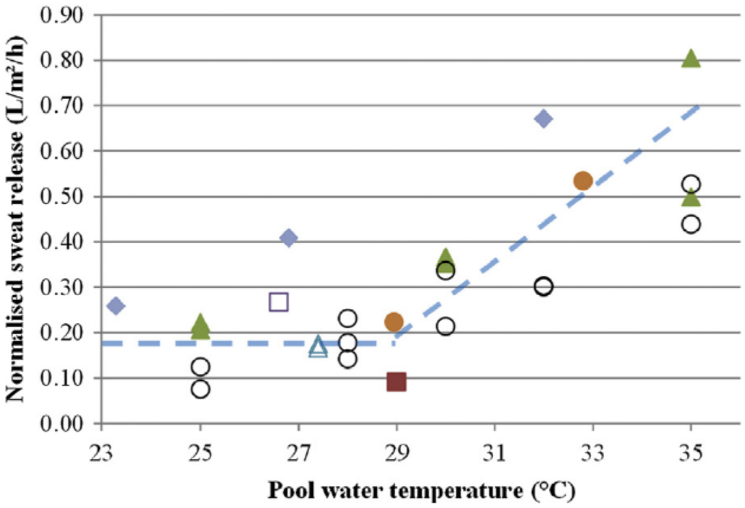

Figure 5: Evolution of the normalized sweat release as a function of the pool water temperature for different data from the literature. Reproduced from (Keuten et al., 2014) **with the permission of Elsevier.**

Based on the reference values set by the World Health Organization (WHO) (World Health Organization., 2006), the volume of perspiration translates to a quantity of nitrogen provided in the form of 68% urea, 18% ammonia, 5% amino acids, 1% creatine, and 8% other compounds for a total of 992 mg/L.

All of the above information, combined, leads to the conclusion that in an aquafitness pool, for example, the nitrogen secretion of bathers will be on average 774 mg per bath. This value corresponds well with the data generated by Seux et al. (Seux, 1988), who concluded a secretion of 860 mg of total nitrogen per bath. To this, Seux et al. (Seux, 1988) adds the urine secretion per bather, estimated between 25 and 60 mL, which corresponds to 215 mg of nitrogen. The high value was later confirmed by Erdinger et al. (Erdinger et al., 1997). These values are also confirmed by the body fluid analog defined by Judd and Bullock (Judd et al., 2003) and used in many studies since then (Hua et al., 2022; Peng et al., 2021).By adding an additional safety margin, the average secretion per swimmer taken into consideration to size a bio-mineral filtration system is 1,200 mg of nitrogen.

Phosphorus data are less detailed in the scientific literature. The main contribution comes from Schulz et al. (Schulz, 1981) who establishes a secretion of 0.55 mg from sweat to which is added 45 mg provided by urine. As a result, the average phosphorus secretion taken into consideration is 60 mg.

When sizing its bio-mineral filtration systems, Aquatic Science uses these anthropogenic pollution values and the operating scenarios to ensure a good match between the filtration capacity and each pool (Aquatic Science, 2022b).

2.2.2. Microbiological pollution

Bathers bring with them bacteria and various micro-organisms into the pool (Figure 6). These can be of fecal or non-fecal origin. Among the first category, there are viruses, protozoa and bacteria (an exhaustive list can be found in (AFSSET, 2009)).

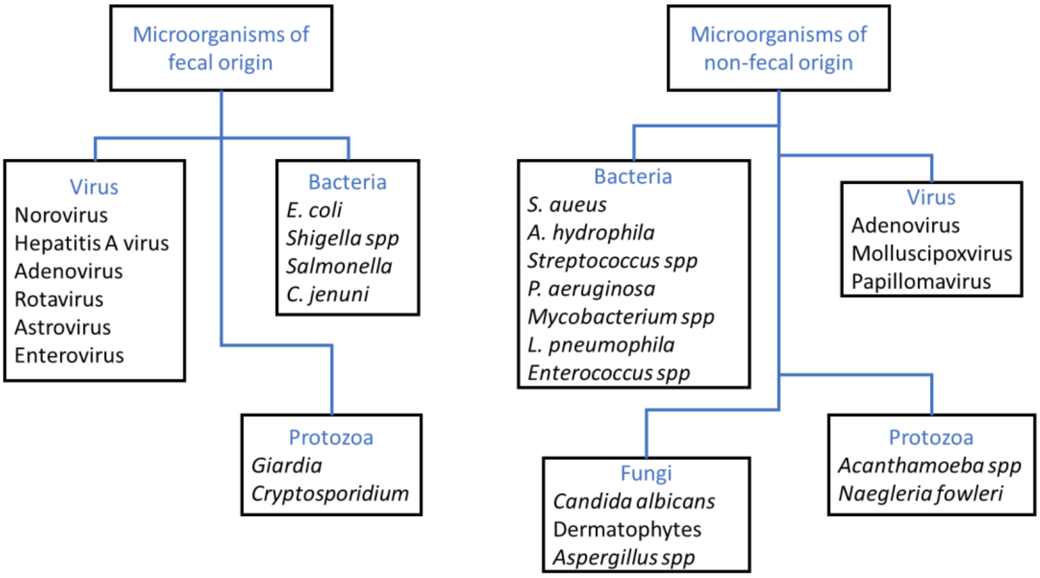

Figure 6: Bacteria classification of fecal or non-fecal origin.

Among all the microorganisms that can be encountered in swimming pools, the pathogens most frequently implicated in sporadic cases or epidemic outbreaks in France, as example country leader in Europe, are listed in Table 1. In other countries, same pathogens are also responsible for epidemic outbreaks as collected in (Barna et al., 2012; Bonadonna et al., 2019; Gromicko, 2023; Hassanein et al., 2023).

Table 1: The pathogens most frequently implicated in sporadic cases or epidemic outbreaks in France.

Micro-organism	Origin (H=human: A=animal)	Mode of contami-nation	Associated pathologies	Population group at risk	Link with bathing waters
Pseudomonas aeruginosa	Hydrotelluric (biofilms), fecal (H,A), skin mucosa (H,A)	Respiratory contact	Ottitis, folliculitis, urinary or respiratory infection, conjunctivitis	Children, elderly, immunodeficient persons or those with mucovisidosis	(World Health Organization ., 2006)
Shigella sp.	Fecal (H)	Fecal-oral	Gastro-enteritis	Young children	(World Health Organization ., 2006)
Crypto-sporidium spp	Fecal (H, A), hydrotelluric (oocytes)	Contact, fecal-oral	Acute gastro-enteritis, chronic for immunodeficient patients and potentially lethal for some at-risk populations	Children, elderly or immunodeficient persons	(Coupe et al., 2006; Graczyk et al., 2007; Karanis et al., 2007; World Health Organization ., 2006)
Giardia duodenalis	Fecal (H,A)	Fecal-oral	Gastro-enteritis	All	(Coupe et al., 2006; Graczyk et al., 2007;

					Karanis et al., 2007; World Health Organization., 2006)
Adenovirus	Fecal (H,A)	Fecal-oral, respiratory mucosa	Gastro-enteritis, conjunctivitis, acute respiratory disease	Immunodeficient persons	(World Health Organization., 2006)
Calicivirus (incl. norovirus)	Fecal (H,A)	Fecal-oral	Gastro-enteritis	All	(World Health Organization., 2006)
Enterovirus	Fecal (H)	Fecal-oral, respiratory	Respiratory disease, skin infection, heart disease, meningitis	Children	(World Health Organization., 2006)

We note that among the pathogens frequently present in swimming pools, all are of fecal origin with the exception of *Pseudomonas aeruginosa* which are generally found in lawns bordering certain outdoor swimming pools.

It is interesting to note that protozoa are listed among the pathogens encountered in swimming pools while they are not among the indicator organisms. For example, numerous studies have revealed that *Cryptosporidium* oocysts are frequently observed in chlorinated swimming pools (Coupe et al., 2006; Graczyk et al., 2007; Karanis et al., 2007; World Health Organization., 2006). An exhaustive study showed that they were present in 7.7% of hotel swimming pools and in 33.3% of swimming pools frequented by schools for an overall average of 16.7% (Xiao et al., 2017). The presence of these pathogens being sporadic, other bacteria have been selected to play the role of indicators of contamination and dysfunction of disinfection (Coupe et al., 2006; Graczyk et al., 2007; Karanis et al., 2007; World Health Organization., 2006). The indicators of the sanitary quality of water reflecting fecal contamination are generally *Escherichia coli* and *Enteroccocus spp* (World Health Organization., 2006). Regarding pathogens of non-fecal origin, the indicators of the sanitary quality of water are generally *Pseudomonas aeruginosa* and *Staphylococcus aureus* (World Health Organization., 2006).

These bacteria that are indicative of a health risk, described as "indicator bacteria", are almost always brought in by the various routes of contamination. In this sense, they play their role as indicators well. For example, Elmir et al. (Elmir et al., 2007) demonstrated that healthy carrier swimmers bring on average 5.5×10^5 colony-forming units (CFU) of *Enterococcus* and 6.1×10^6 CFU of *Staphylococcus aureus*. These results reinforced older studies such as those by Robinton et al. (Robinton et al., 1966) and Smith et al. (Smith et al., 1993).

Taking the French legislation relating to artificial bathing as a reference, which provides for a dilution factor of the potential for inter-bather contamination, each bather must have a minimum of 10 m^3 of water. If we consider that the bacteria brought in by a bather are dispersed in a homogeneous way in the whole of the volume of water available to them, in periods of maximum frequentation, the average contribution related to the measurement of the quality of the water of bathing will be 65 CFU/100 mL of *Staphyloccocus aureus* and 6 CFU/100 mL of *Enterococcus* on average per healthy carrier. Knowing that for *Staphyloccocus aureus*, 20% of adults are healthy carriers and 60% occasional carriers, the expected average levels will be around 13 to 52 CFU/100 mL, i.e., greater than all the regulations in force for the quality of swimming pool water (Kluytmans et al., 1997).

As with organic pollution, usage scenarios must be carefully considered. The calculation summarizing the contributions by bathers assumes a homogeneous distribution of the contribution of each. However, this will never be the case. It is easy to imagine that the close proximity of a bathing couple, for example, locally creates very different situations. The place of sampling, attendance, and the type of activity in progress at the time of sampling will influence the representativeness of the sample on the overall assessment of the health risk. However, it is important to define an overall risk in order to adapt the size and calibration of disinfection systems and to set up an appropriate operation.

2.3. Impact of swimming pool type on the contents of organic pollutants entering the water - A comparative study at the "Centre Scientifique des Techniques du Bâtiment" (CSTB) in Nantes

In swimming pools, the size of the filters is calibrated to the filtration rate, which ensures treatment of the entire volume of water in a maximum time depending on the basin size and local legislation (European Standards, 2012). As organic matter brought in by bathers reacts with the disinfectant to form by-products, accumulation is possible. Washing the filters makes it possible both to maintain their performance and also to renew the water so as to reduce the concentrations of by-products. The consumption of disinfectants will therefore depend on the load of bathers and the contribution of anthropogenic pollution.

In artificial pools such as bio-mineral pools, the absence of disinfectant means that there is no accumulation of by-products. Analyses carried out on a pool with bio-mineral filtration that had been in operation for 6 years in Belgium showed that, without changing the water, there was no accumulation and that the oils in sun creams were degraded by bacteria. On the other hand, there could be accumulation of organic matter likely to promote algal and bacterial development. The combined role of mechanical filtration and biological filtration is to ensure the elimination of this material to prevent its accumulation.

To remove any ambiguity on this question, Aquatic Science commissioned a comparative study at the Center Scientifique des Techniques du Bâtiment (CSTB) in Nantes. This center has an indoor experimental pool (shown in Figure 7), the characteristics of which are listed in Table 2.

Table 2: Characteristics of the indoor experimental pool at the CSTB.

Characteristic	Value
Useful volume (m^3)	42.24
Length (m)	8
Width (m)	4
Depth (m)	1.32
Temperature (°C)	27 ± 3
Number of body fluid analogue injections	4
Buffer tank (m^3)	4
Water flow ($m^3.h^{-1}$)	15 to 40
Renewal rate (h) to filter the total volume of water	1 to 3
Water treatment	Sand filter, chlorine-based disinfection, pH regulation

In a complementary way, a mechanical device of artificial swimmers makes it possible to reproduce the real water mixing conditions of several swimmers (see Figure 7) as well as the organic pollution brought in by the latter in the form of an organic liquid called body fluid analogue (BFA). The composition of the added BFA is based on the formulation proposed by Judd et al. (Judd et al., 2003).

Figure 7: Picture of the indoor pool at the CSTB.

For the test to be carried out under realistic bathing attendance conditions, the maximum daily attendance (MDA) defined by French legislation was used as a benchmark (Gouvernement français, 2019). This MDA is fixed by decree according to the following formula:

$$MDA = (V_{total} + V_{recycled} + V_{new}) / 10 \qquad (2)$$

Where V_{total} is the total volume accessible to swimmers (expressed in cubic meters); $V_{recycled}$ is the volume of water recycled and treated during the daily bathing operating period (expressed in cubic meters), which is equivalent to the filtration rate multiplied by the number of opening hours; V_{new} is the volume of new water brought into the bathing area during the daily operating period for bathing (expressed in cubic meters).

For example, a swimming pool such as that of the CSTB, open from 8 a.m. to 8 p.m., filtered with a flow rate of 25 m^3/h can accommodate:

$MDA = (42 + (12 * 25)) / 10 = 34$ persons

The same pool, open from 10 a.m. to 7 p.m., filtered at 15 m^3/h can accommodate:

$MDA = (42 + (9 * 15) / 10 = 18$ persons

The decree provides that these figures can be doubled by decision of the Director General of the Regional Health Agency (ARS) at the request of the person responsible for bathing management. In the examples above, the authorized attendance therefore increases to 68 and 36 people respectively.

In this context, the comparative study carried out was based on attendance ranging from 18 to 54 people per day (CSTB Recherche, 2018). The same attendance was simulated for the two conditions, one where the swimming pool operated with its standard filtration-chlorination system and one where a Vitii bio-mineral filtration (Aquatic Science, 2022b) system was installed. During the "chlorinated" test, the average water temperature during the tests was 29.6°C, the air was 27.2°C, and the relative humidity 62.8%. During the "bio-mineral" test, the average water temperature was 29.5°C, the air 27.1°C, and the relative humidity 63.8%.

During the chlorinated condition (Figure 8) there is a slight increase in the concentration of total organic carbon (TOC) in the water due to the introduction of organic pollution from swimmers into the pool. A significant increase in the trichloramine concentration in the air is observed after 2 days of operation with an increase from 0.005 to 0.13 mg/m^3 to reach 0.29 mg/m^3 on the 7th day of the experiment. Knowing that the French Agency for Food, Environmental and Occupational Health & Safety (ANSES) proposes a maximum value of trichloramine in the air of 0.3 mg/m^3 in its 2010 report (AFSSET, 2012), this threshold was reached in 7 days.

For its part, the combined chlorine value remained below the concentration of 0.6 mg/L required by the decree of April 7, 1981 (Gouvernement français, 1981) with a maximum value of 0.4 mg/L.

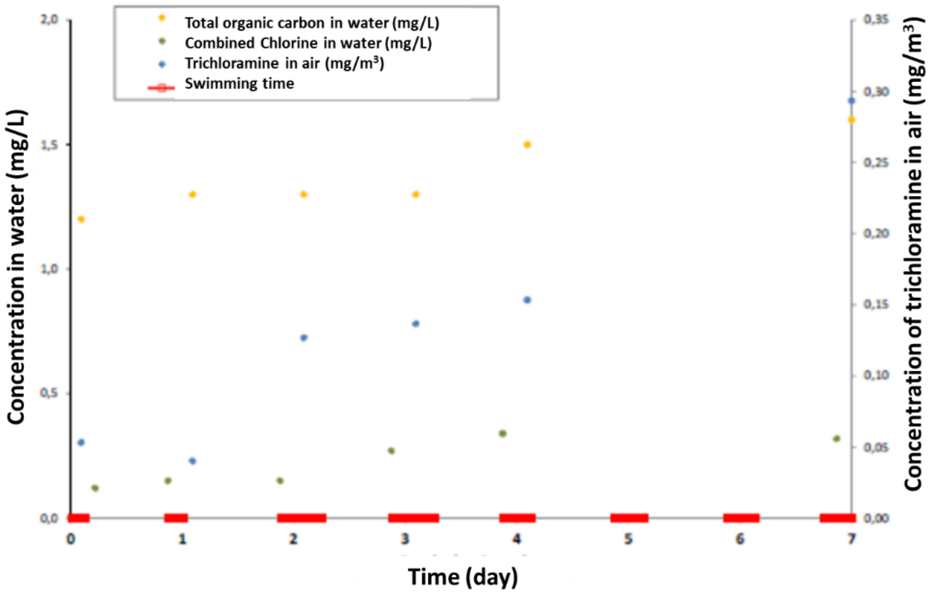

Figure 8: Evolution of different chemical concentrations over 7 days for a classical chlorinated pool system.

In the bio-mineral condition, none of the measured values showed any variation throughout the experiment (Figure 9). The TOC and the concentrations of calcium, magnesium, nitrates, phosphates, the complete alkalimetric title (CAT), and the hydrometric title (HT) did not change significantly. This high stability of the water parameters during the bio-mineral condition was also observed when no new water supply was added. In contrast, during the chlorinated experiment, 30 L of new water per bather was added.

Finally, product consumption was very different between the two conditions. During the chlorine experiment, 4.62 L of sodium hypochlorite at 48% and 0.99 L of 35.3% sulfuric acid were used. At the same time, the consumption of products (minerals and bacteria) during the bio-mineral experiment was only 0.47 L, i.e., a quantity of over 10 times less product.

These test conditions have shown that Aquatic Science's well-sized Vitii bio-mineral filtration system (Aquatic Science, 2022b) was perfectly capable of controlling organic matter and maintaining constant water quality without adding new water and without the accumulation of potentially toxic by-products. On the other hand, the chlorine condition showed that the organic matter secretion by swimmers generated an estimated chlorine consumption of 15 mg/Cl_2/mg C (Tsamba et al., 2020). All this chlorine reacts with organic matter to form many disinfection by-products, generating a significant chemical risk for bathers (Carter et al., 2017). These risks range from lung disease to decreased fertility following exposure in young children (Nickmilder et al., 2011; Rosenman et al., 2015).

As a conclusion to this section, it is reasonable to say that, unlike disinfectant pools, bio-mineral filtration does not generate chemical risks for bathers.

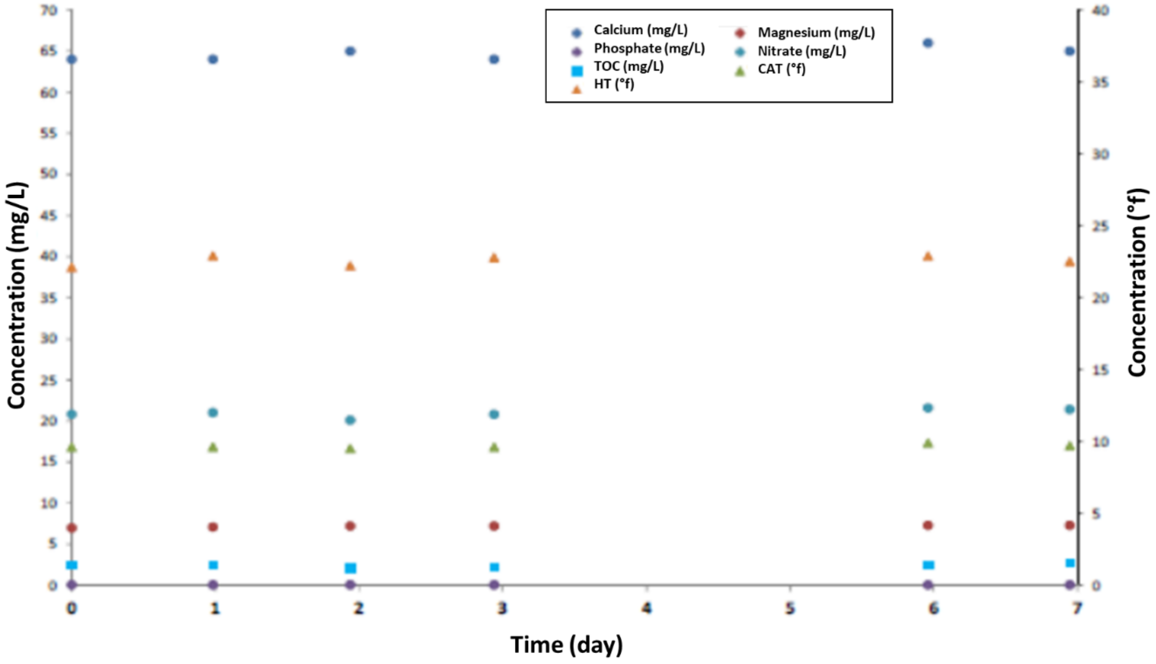

Figure 9: Evolution of different chemical concentrations over 7 days for a pool with bio-mineral filtration.

2.4. Impact of pool type on microbiological pollution

As detailed in Section 2.1, the microbiological risk is treated by the disinfectant in swimming pools and by UV radiation in artificial swimming pools with bio-mineral filtration. In swimming pools, this leads to antagonism between attendance levels and the effectiveness of disinfection. The more bathers there are, the more their organic inputs will neutralize chlorine and therefore less active chlorine will be available to disinfect the water (Fernandez, 2016; Zhang et al., 2023). Furthermore, the addition of more disinfectant is not an option insofar as the neutralization of chlorine by organic inputs generates disinfection by-products posing a chemical risk for bathers (Carter et al., 2019). In summary, the more bathers there are, the higher the chemical risk and the less effective the disinfection (Carter et al., 2019; Zhang et al., 2023).

Added to this is the fact that chlorine, the most commonly-used disinfectant, is only slightly effective against certain pathogens, including, among the most common, the protozoan *Cryptosporidium spp*. That said, in general, cases of contamination in swimming pools are very low compared to the number of people practicing sports or leisure swimming (Bonadonna et al., 2019; Dallolio et al., 2013). The standards applied for water disinfection are fully operational (Barna et al., 2012).

In artificial bathing, less knowledge is available on the effectiveness of measures taken to ensure the sanitary quality of water. The risk incurred by bathers is different from that incurred in a chlorinated pool (Casanovas-Massana et al., 2013; Shoults et al., 2021), here ultraviolet radiation combined with an advanced oxidation process (AOP) ensures powerful reduction of the various pathogens encountered in swimming pools (Ekowati et al., 2019; Shoults et al., 2021).

Table 3 shows the UV dose expressed in mJ/cm² required for a 99.99% reduction in exposed microorganisms. The cited references illustrate the highest doses listed in the perpetual inventory maintained by the International UV Association (Abshire et al., 1981; Blatchley III et al., 2016; Bounty et al., 2012; Chang et al., 1985; Clauß, 2006; Gerba et al., 2002; Linden et al., 2009; Malayeri et al., 2018; Nwachuku et al., 2005; Park et al., 2011; Qian et al., 2004; Shin et al., 2005; Thurston-Enriquez et al., 2003; Wilson, 1992).

Table 3: UV dose (in mJ/cm²) required for a 99.99% reduction in exposed microorganisms.

Micro-organism	**Strain**	**UV lamp type**	**UV dose (mJ/cm^2) for 99.99% elimination**	**References in bathing waters**
Pseudomonas aeruginosa	ATCC 9027	Low pressure	17.0	(Abshire et al., 1981)
	ATCC 27853	Low pressure	3.1	(Clauß, 2006)
	NCTC 10662	Low pressure	5.0	(Blatchley III et al., 2016)
Shigella sp.	*S. dysenteriae*	Low pressure	2.8	(Wilson, 1992)
	S. sonnei	Low pressure	6.5	(Chang et al., 1985)
Cryptosporidium spp	-	Low and medium pressure	6.0	(Qian et al., 2004)
Giardia duodenalis	-	Low and medium pressure	3.4	(Qian et al., 2004)
Adenovirus	Type 1	Low pressure	138	(Nwachuku et al., 2005)
	Type 2 A549 cell line	Low pressure	168	(Linden et al., 2009)
	Type 2 ATC VR-846	Low pressure	206	(Bounty et al., 2012)
Calicivirus (including *Norovirus*)	*CRFK cell line*	Low pressure	30	(Thurston-Enriquez et al., 2003)
	ATCC CCL-94	Low pressure	26	(Park et al., 2011)
Enterovirus	*Coxsackievirus* BGM cell line – B3	Low pressure	33	(Gerba et al., 2002)
	Coxsackievirus BGM cell line – B4	Low pressure	24	(Shin et al., 2005)

In addition to this list of pathogens most frequently responsible for infections in swimming pools, Table 4 shows the same values for the indicator bacteria.

Table 4: UV dose (in mJ/cm²) required for a 99.99% reduction in indicator organisms.

Micro-organism	Strain	UV lamp type	UV dose (mJ/cm²) for 99.99% elimination	References in bathing waters
Escherichia coli	ATCC 11229	Low pressure	8.4	(Chang et al., 1985)
	ATCC 700891	Low pressure	13.0	(Quek et al., 2008)
Enterococcus spp.	*S. dysenteriae*	Low pressure	2.8	(McKinney et al., 2012)
	E. faecium	Low pressure	13.0	(Moreno-Andrés et al., 2016)
	E. Faecalis	Low pressure	14.0	(Abshire et al., 1981)
Pseudomonas aeruginosa	ATCC 9027	Low pressure	17.0	(McKinney et al., 2012)
	01	Low pressure	6.3	(Chang et al., 1985)
Staphylococcus aureus	ATCC 25923	Low pressure	10.0	(Chang et al., 1985)

The UV dose emitted during disinfection is calibrated to ensure a minimum of 25 mJ/cm² and an optimum of 40 mJ/cm² so that none of the pathogens or indicator bacteria undergo a reduction of less than 4-log (99.99%). Only certain adenoviruses will be weakly affected by this disinfection treatment (McKinney et al., 2012; Moreno-Andrés et al., 2016; Quek et al., 2008).

Unlike disinfectant treatment, UV disinfection does not lose its effectiveness in the event of high traffic. On the other hand, as only the water taken up by the filtration system is disinfected, it is essential that all the water in the pool is taken up. If the pool has a dead zone, its water is not disinfected and there is a risk of localized pathogen development.

Although public biological and bio-mineral swimming pools are multiplying in Europe (>150), there is no legislative consensus concerning health and safety management. In addition, standards vary greatly from region to region and from country to country. As a result, water quality management is put into perspective in relation to the oldest and most complete standards, with a focus on the situation in France, a reference country and leader of the European swimming pool market (Fairland, 2022).

In Austria, since 2015, a specific standard has been in operation (Austrian law, 2015). It defines bacterial thresholds to classify water as "Excellent", "Very good", "Good" and "Poor" on the basis of three bacteriological parameters expressed in the form of concentrations in colony forming units per 100 mL (CFU/100 mL) for the bacterium *Escherichia coli*, for the bacterial genus *Enterococcus,* and for the bacterium *Pseudomonas aeruginosa* (Abshire et al., 1981). In other regions, a fourth indicator is frequently measured, the bacterium *Staphylococcus aureus*. As this is not the case in Austria, we do not have a reference value for this parameter. Furthermore, as 20% of individuals have been shown to be permanent carriers of *Staphyloccocus aureus* (Kluytmans et al., 1997), 60% are intermittent carriers, and only 20% of adults are non-carriers, it is inevitable that these bacteria will temporarily find their way into pool water before being filtered out. This will be more prevalent for a swimming pool frequented by children, who are carriers in 60% of cases. For this parameter, we therefore only indicate the threshold value defined in French legislation and we provide it as the threshold for excellent to good quality.

In order not to confuse the risk of potential accumulation with the bacteria brought in by bathers, reference can also be made to the European Directive of February 15, 2006 on the quality of bathing water in the natural environment (lakes, rivers, etc.) (Parlement Européen, 2006). However, this Directive only sets thresholds for so-called “good” water quality for 2 indicators.

Table 5 summarizes this data and shows that, by defining categories of water quality, the Austrian legislation has already taken account of this Directive and the reflection proposed in this document.

Table 5: Austrian water quality parameters for bacteria concentrations (Austrian law, 2015) **in water for bathing in natural environments.**

Parameter (CFU/100 mL)	Excellent water	Very good water	Good water	Poor water	Directive 2006/7/CE
E. coli	<25	26-100	101-1000	>1000	>1000
Enterococcus	<15	16-50	51-400	>400	>400
P. aeruginosa	0	1<25	25<100	>100	
Staphylococcus aureus	<20	>20			

When an analysis reveals that all the parameters correspond to "Excellent" quality water, this reflects the perfect functioning of the filtration system, so no corrective action is to be taken. In all other cases where analysis reveals that the water is not "Excellent" for all the parameters, corrective action must be taken. Action is recommended when the water is of "Very Good" quality, is important when the water is of "Good" quality, and is essential if the water is of "Poor" quality.

The results of analyses of the quality of bathing water for systems equipped with bio-mineral filtration for three reference cases are presented in Section 4, which demonstrate that it is appropriate to define protocols for the sanitary management of water quality, suitable for defined categories of water quality.

3. Summary of standards applicable to biological pools in Europe

3.1. Introduction

The title of this section can be confusing. According to the French Public Health Code, for example, a swimming pool is defined as “an establishment or part of an establishment which includes one or more artificial pools used for bathing or swimming activities” (article D1332-1). Up to this point in the definition, there is nothing to distinguish a so-called “traditional” swimming pool from a so-called “biological” swimming pool. In the following article of the Code, the notion of disinfection is introduced and, in article D-1332-4, clarity is made on the specification of "traditional" swimming pools whose water must be "filtered, disinfected” and disinfectant used.

As the main characteristic of a biological swimming pool is to not use disinfectant products, an essential difference appears. Figure 10, published by ANSES in (AFSSET, 2009), illustrates the sequences that make it possible to clearly distinguish between the different places for bathing or swimming.

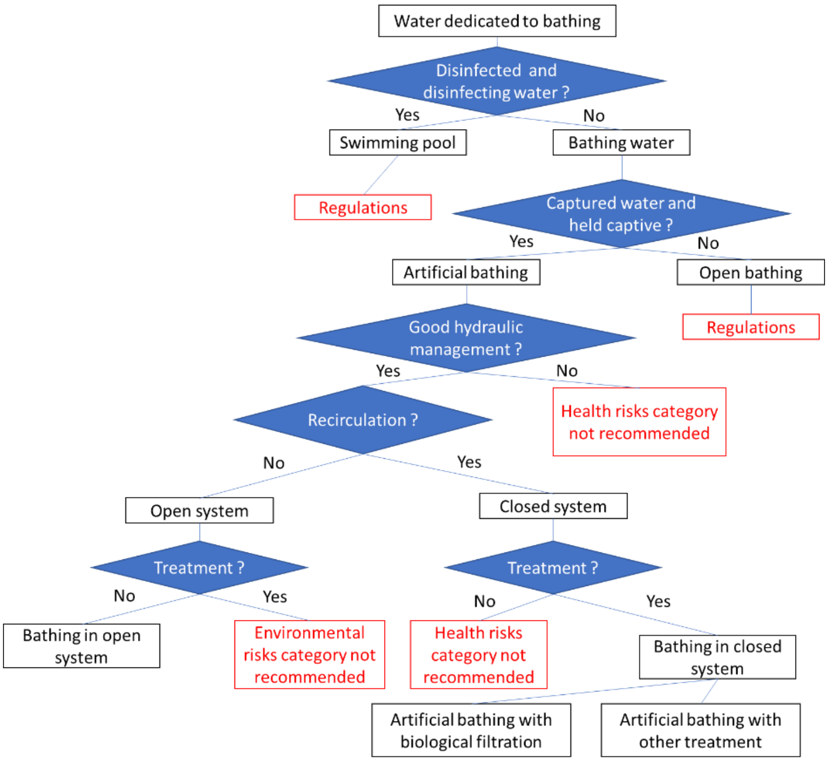

Figure 10: Sequence scheme to distinguish between the different places for bathing or swimming, translated from (AFSSETfsset, (2009)**.**

When the water is not disinfecting (e.g., chlorine-treated), it is officially necessary to speak of bathing. In the case of developed places, we refer to artificial bathing. Then, good hydraulic management, a closed system, and the use of efficient filtration leads to the definition of artificial bathing with treatment by biological filtration. The activity of Aquatic Science is located squarely in this category of bathing place. That being said, in everyday language the first part of the definition of the swimming pool prevails, i.e., one or more artificial pools used for bathing or swimming activities.

To mark the distinction, if the term swimming pool is used, it will be followed by "with biological filtration". Alternatively, the term bathing is used. The first pools of this type accessible to the public date to the 1980s in Germany and Austria (Couleur Nature, 2022). These pools with biological filtration are subject to local permissions, as was the first such pool installed in Combloux, France in 2002 (Delohen, 2012).

These pioneering facilities were well-received by the public, but also had limitations in terms of operation, positioning them in a segment of activities that is not very comparable to that of traditional swimming pools. All resorted to biological filtration by lagooning. This approach makes it difficult to heat water, equip indoor establishments, accommodate a large audience, etc. This has led professionals in the sector in France under the aegis of their association (UNEP) to distinguish two sub-categories of swimming pools with biological filtration. In concrete terms, this resulted in the publication of two professional rules:

- C.C.10-R0 (July 2013) – Design and construction of biological pools with intensive filtration (Thepaut et al., 2013)

- C.C.9-R0 (December 2017) – Design and construction of artificial swimming pools with biological filtration (Esser et al., 2017)

The technology developed by Aquatic Science falls into the so-called "intensive" category, which offers a real alternative to traditional swimming pools. In this case, the biological filtration is no longer done by lagooning, but in three stages comprising mechanical filtration, bacterial filtration, and disinfection by oxidizing UV. In addition to these filtration stages, the mineral balance of the water is maintained. We then distinguish a sub-category of swimming pools with biological filtration, namely swimming pools with bio-mineral filtration.

The first swimming pool with bio-mineral filtration accessible to the public was installed in Belgium in 2012 (Aquatic Science, 2022a). The largest in size and attendance to date is in the Paris region and accommodates up to 900 people per day in a volume of water of 1300 m³.

The regulatory framework in which these various pools with biological filtration have evolved over the years can be summarized as briefly presented in the next section.

3.2. The microbiological/bacteriological quality parameters of biological swimming pool waters

The health parameters measured differ slightly from one country to another, but constants emerge: the measurement of *Escherichia coli*, *Enterococci,* and *Pseudomonas aeruginosa* (Gouvernement flamand, 2019; Switzerland law, 2016; Walloon law (Belgium), 2013). The transposition of the standards applied to traditional pools to biological pools can be summarized and applied as follows:

- *Escherichia coli*

In traditional swimming pools, *E. coli* is a control germ indicator of recent fecal contamination, which reflects a decrease in the effectiveness of the disinfection treatment and the potential presence of other pathogenic germs. The main risk associated with the presence of *E. coli* concerns gastroenteritis and the risk of urinary tract infections (Barna et al., 2012; Gromicko, 2023).

In a bio-mineral pool, disinfection is ensured by treatment based on ultraviolet (UV) radiation with additional oxidation such as photocatalytic UV. The UV dose required for the elimination of 99.99% of *E. coli* is 7.2±2.55 mJ/cm² according to the synthesis of 48 studies carried out by Malayeri et al. (Malayeri et al., 2018). The combination of the impoverishment of the medium in order to limit bacterial proliferation, a UV treatment delivering a minimum of 25 mJ/cm² and a hydraulic circuit making it possible to treat the entire volume of water repeatedly in accordance with the legislation makes it possible to limit the contribution of bacteria by swimmers.

Bio-mineral filtration technology is therefore perfectly suited to controlling the risk associated with the release of fecal bacteria by swimmers.

- *Enterococcus*

Enterococci are bacteria that usually appear in the form of chains. These are opportunistic pathogens causing sepsis, urinary tract infections, or abdominal infections of intestinal origin. They are the cause of more than 10% of nosocomial infections (AFSSET, 2009, 2012). For a very long time, *Enterococci* were classified within the genus *Streptococcus*, until 1984, when an analysis of the genome indicated that it was more appropriate to create the genus *Enterococcus* (AFSSET, 2009, 2012). As their name suggests (enteric + shell), *Enterococci* are part of the commensal flora and are found in particular in the digestive and genitourinary tracts. The ecology of *Enterococci* is different from that of *Streptococci* and their adaptation to the intestinal environment, where they are normally commensal minorities, gives them several properties that are different from *Streptococci*; In particular, they are more resistant in outdoor environments. As with *E. coli* bacteria, their presence in water is an indicator of fecal pollution.

The most common ailments are (AFSSET, 2009, 2012):

- urinary tract infections and abdominal abscesses where they are found alone or in association with *E. coli* bacteria;
- peritonitis;
- secondary infections of surgical wounds, especially abdominal ones, responsible for abscesses;
- slow or subacute endocarditis (5 to 10% especially in elderly men) which can lead to bacteremia and septicemia.

In 2004 (AFSSET, 2009, 2012), *Enterococcus spp.* took the place of the fecal coliform group for the new French federal standard for the quality of bathing water at public beaches, as this indicator is considered to be representative of many other fecal pathogens and, in particular, is found in wastewater.

The two species most frequently encountered in human pathology are *Enterococcus faecium* and *Enterococcus faecalis*, which can cause infections in weakened patients. They are opportunistic pathogenic bacteria.

The dose required to achieve a 4-log reduction (99.99%) of these two bacteria is respectively 13 mJ/cm² (McKinney et al., 2012) and 12 to 14 mJ/cm² (Chen et al., 2016; Moreno-Andrés et al., 2016). Oxidizing UV treatment delivering a minimum of 25 mJ/cm² is therefore perfectly suited to eradicating these bacteria.

- *Pseudomonas aeruginosa* (from (Zini et al., 2010))

Pseudomonas aeruginosa is an abundant ubiquitous bacterium in soils, plants, and water. It is distinguished by its great adaptability (the strains require very few nutrients), by its ability to survive for several months in water or even to multiply there, and by its ability to colonize humans. Under laboratory conditions, its optimum temperature for growth is 37°C, but the bacterium can multiply up to a temperature of 42°C (Husson et al., 2000).

Water is the natural reservoir of *P. aeruginosa*. Some authors consider that its presence constitutes an indicator of contamination of surface water, domestic wastewater, and agricultural effluents (de Vicente et al., 1988; Geldreich, 1996; Warburton et al., 1994). The concentration of *P. aeruginosa* in surface water receiving wastewater and runoff can vary between 1 to 10,000 cells/100 mL (Geldreich, 1996). Its concentration in river water, near urban runoff sites, can be significant and vary from 100 to 1000 cells/100 mL (Alonso et al., 1989). Unlike bio-mineral pools, in other swimming pools and bathing areas whose water is not chlorinated, the concentration of *P. aeruginosa* can exceed 1,000 cells/100 mL (Mena et al., 2009). In bathing waters, the number of *P. aeruginosa* is correlated with the number of bathers (Seyfried et al., 1984). This germ, adapted to the water environment, is able to very quickly colonize wet surfaces (walls and bottom of basins), to spread throughout the installation (filters, pumps, pipes, etc.) and to colonize biofilms (Mena et al., 2009).

Among the bacteria of the genus *Pseudomonas*, *P. aeruginosa* is the species most commonly associated with human pathologies. In addition to the fact that it is the cause of nosocomial infections in subjects whose immunity is weakened (it represents 10% of hospital nosocomial infections), *P. aeruginosa* is recognized as being responsible for infections during swimming in recreational waters. (Mena et al., 2009). The infectious dose is difficult to establish because it varies according to the strain and the mode of transmission: orally, it would be around 10^8 CFU in mice and 10^{10} CFU in humans; by inhalation, the LD50 in mice is estimated at 2.7×10^7 CFU, which suggests a relatively high infectious dose in humans; via the dermal route, this is not known (Mena et al., 2009).

To achieve a 4-log reduction (99.99%) of *Pseudomonas aeruginosa,* the UV dose required is 3.1 to 6.2 mJ/cm² (Blatchley III et al., 2016; Clauß, 2006). Again, the photocatalytic UV treatment delivering a minimum of 25 mJ/cm² is therefore highly suitable for eradicating these bacteria.

3.3. Regulations region by region

In terms of biological swimming pools, there is no regulatory homogeneity across Europe. The tables below summarize the situation in the regions where specific legislation has either been published or is under specific examination, in order of importance from the point of view of the number of equipped swimming pools.

In France, the legislative framework has recently evolved. Since 2006 and the referral to AFSSET (now ANSES) relating to the health risks associated with artificial bathing, recommendations had been given to the Regional Health Agencies (ARS). A certain margin of maneuver was left to their discretion. This was particularly the case for the levels of *Pseudomonas aeruginosa* which varied according to the bathing size between 10 and 100 CFU/100 mL. The situation has been clarified since the entry into force on April 15, 2019 of a decree and its implementing orders (Gouvernement français, 2019). The standards applied can be summarized as shown in Table 6:

Table 6: Water quality parameters for bacteria concentrations in France (Gouvernement français, 2019)**.**

Parameters/norm	France	
	Acceptable	Poor
Escherichia coli (in CFU/100 mL)	<100	>500
Enterococcus (in CFU/100 mL)	<40	>200
Pseudomonas aeruginosa (in CFU/100 mL)		>100

In Wallonia, the oldest bio-mineral swimming pool has been in operation since the end of 2012. It has been the subject of a permission. This remains the reference document, which has since been applied to other establishments open to the public. Its operating permit has evolved over time and has led to a reduction in the limits of microbiological parameters. The limits of the first and the second allowed are listed in Table 7 as the limits of excellent or poor water quality.

Table 7: Wallonia water quality parameters for bacteria concentration (Walloon law (Belgium), 2013)**.**

Parameters/norm	Wallonia		
	Excellent	Acceptable	Poor
Escherichia coli (in CFU/100 mL)	<50	50<…<500	>500
Enterococcus (in CFU/100 mL)	<20	20<…<200	>200
Pseudomonas aeruginosa (in CFU/100 mL)			

In Austria, a specific standard was published on the subject in June 2015 (Austrian law, 2015) (Table 5). In Flanders, legislation exists concerning swimming ponds (zwemvijvers) (Gouvernement flamand, 2019). A more comprehensive and demanding bill is, however, being drafted. In Table 8, the values given under the headings “Poor, Acceptable, and Very Good” correspond to the limit values and recommended values for swimming ponds. The limit values of the new legislation in preparation are indicated under the heading "Bio Pool".

Table 8: Flanders water quality parameters for bacteria concentration (Gouvernement flamand, 2019)**.**

Parameters/norm	Flanders			
	Excellent	Acceptable	Poor	Bio Pool
Escherichia coli (in CFU/100 mL)	<1000	1000<…<2000	>2000	>100
Enterococcus (in CFU/100 mL)	<400	400<…<700	>700	>50
Pseudomonas aeruginosa (in CFU/100 mL)				>10

In Switzerland (Switzerland law, 2016), according to the ordinance relating to so-called "biologically regenerated" bathing waters, a single maximum threshold has been set for three indicator bacteria (Table 9).

Table 9: Switzerland water quality parameters for bacteria concentration (Switzerland law, 2016)

Parameters/norm	Switzerland	
	Excellent	Poor
Escherichia coli (in CFU/100 mL)	<100	>100
Enterococcus (in CFU/100 mL)	<50	>50
Pseudomonas aeruginosa (in CFU/100 mL)	<10	>10

It emerges from these comparisons that the Austrian legislation segmenting water quality into 4 categories ranging from "Excellent" to "Poor" combines both health and safety and indicators of possible malfunctions.

The question of the release by bathers of *Staphyloccocus aureus* is, however, not resolved by the threshold value of the Austrian legislation. Only release by bathers during immersion in water, before the water has time to be filtered, can lead to this threshold being exceeded if bathing density corresponds to the maximum authorized in France. As we have seen, the release by swimmers can reach 52 CFU/100 mL without the proper functioning of the filtration being incriminated.

4. Summary of analysis results – Example of 3 public swimming pools

4.1. Introduction

In order to properly position the strengths and weaknesses of the technology in the context of maintaining the sanitary quality of bathing waters, three representative bathing scenarios (two in France and one in Belgium) are detailed below.

For these three infrastructures in operation before the publication of the French decree relating to biological bathing (April 2019) (Gouvernement français, 2019), a detailed analysis of the health control reports carried out by the reference laboratories was undertaken. These data are therefore completely objective and reliable.

4.2. Summary of data collected from three bio-mineral pools in France and Belgium

These three pools correspond to three different use scenarios, making them very representative of the diversity of infrastructures.

Bathing pool A is a fine example of a large-volume outdoor communal swimming pool, it belongs to a French public school. At the other end of the spectrum of swimming pools, bathing pool B is a French aquafitness pool. It is a small heated indoor swimming pool frequented by a large number of bathers. Bathing pool C is intermediate because it is heated, indoors, but successively very popular for recreational activities (aquabike, baby swimmers, etc.) and little used for relaxation and care activities; it is a Belgian aquafitness pool.

4.3. Bathing pool A

The characteristics of this pool are summarized in Table 10.

Table 10: Characteristics of the pools A, B, and C.

Parameters	Bathing pool A	Bathing pool B	Bathing pool C
Opening date	July 2016	December 2018	December 2012
Capacity	1,700 m³	50 m³	50 m³
Filtration rate	635 m³/h	from 70 to 105 m³/h	35 m³/h
Maximum instantaneous attendance (MIA)	170 people	5 people	Unlimited
Maximum daily attendance (MDA)	1100 people	110 people	Around 120 people per week
Hydraulic characteristics	- Discharge network distributed over the entire shallow depth - A bottom suction circuit via large bottom drains -An overflow channel along the entire length of the pool for surface recovery	- Discharge network distributed on one side of the swimming pool - A suction circuit from the bottom by 2 bottom drains - Distribution of skimmer on 2 sides of the pool for surface suction	- Discharge network distributed on one side of the swimming pool - A bottom suction circuit via 1 bottom drain - Distribution of skimmer on the opposite side to the pool discharge for surface suction
Thermal characteristics	- Water heating by a few °C to allow comfortable outdoor use from mid-May to mid-September - Large shallow beach actively contributing to water warming.	- Heat pump to maintain the water temperature between 29 and 32°C	- Heat pump to maintain the water temperature between 28 and 30°C
Games and accessories	- 5 pentaglides in operation a few hours a day - 90 m³/h slide in operation a few hours a day.	- Addition of equipment for the practice of Aquagym such as Aquabikes	- Addition of equipment for the practice of Aquagym such as Aquabikes

Average water temperature	24.50±2.50°C with a maximum at 29.40°C (n=32)	28.60±2.30°C with a maximum at 32.10°C (n=29)	29.70±1.10°C with a maximum at 31.20°C (n=85)
Transparency	background visible in 100% of cases (n=32)	background visible in 100% of cases (n=29)	Not measured
Average pH	8.05±0.37, i.e., pH which is always basic (n=32)	7.90±0.30, i.e., pH which is always basic (n=14)	7.92±0.17, i.e., pH which is always basic (n=85)

In addition to these water parameters, the bacteriological parameters had the following results (Table 10):

Table 10: Bacteriological parameters measured for bathing pool A.

Bathing pool A	***E. coli***	***Enterococcus***	***P. aeruginosa***	***S. aureus***
Number of samples	32	32	32	32
Mean count (CFU/100 mL)	1	0	4	0
Standard deviation	4	0	16	0
“Excellent water” threshold	32	32	28	32
% of samples	100.00%	100.00%	87.50%	100.00%
“Very good water” threshold	0	0	2	0
% of samples	0.00%	0.00%	6.25%	0.00%
“Good water” threshold	0	0	1	0
% of samples	0.00%	0.00%	3.13%	0.00%
% “poor water”	0.00%	0.00%	0.00%	0.00%

Table 10 shows us that none of the 32 samples was non-compliant for bacteria. That said, 2 analyses revealed the presence of fecal bacteria, *E. coli*, but in sufficiently low numbers so that it does not affect the quality of the water. In addition, 4 analyses revealed the presence of *Pseudomonas aeruginosa*. Two of these analyses contained less than 25 CFU/100 mL of this bacterium and one analysis a concentration between 25 and 100 CFU/100 mL, i.e., the value defined for “good” water.

4.4. Bathing pool B

The characteristics of this pool are summarized in Table 10. In addition to these water parameters, the bacteriological parameters had the following results (Table 11):

Table 11: Bacteriological parameters measured for bathing pool B.

Bathing pool B	***E. coli***	***Enterococcus***	***P. aeruginosa***	***S. aureus***
Number of samples	30	30	30	30
Mean count (CFU/100 mL)	3	3	28	15
Standard deviation	7	12	7	34
"Excellent water" threshold	29	27	24	16
% of samples	96.67%	90.00%	80.00%	53.33%
"Very good water" threshold	1	2	4	10
% of samples	3.33%	6.67%	13.33%	33.33%
"Good water" threshold	0	1	1	1
% of samples	0.00%	3.33%	3.33%	3.33%
% "poor water"	0.00%	0.00%	3.33%	10.00%

Table 11 reveals the presence of *Staphyloccocus aureus* in almost 50% of the samples reaching problematic levels in 10% of cases. It is noted that attendance is generally much higher (up to 3-4 times) than the maximum instantaneous attendance (MIA) at the time the samples are taken.

As detailed in other sections of this document, *Staphylococcus aureus* is a bacterium for which 20% of the adult population are permanent carriers and 60% intermittent carriers (Kluytmans et al., 1997). In a relatively low volume of water per bather and with abundant attendance, the release by bathers is therefore sufficient to reach the maximum threshold without there being any bacterial development in the pool.

To fully define the context for which attendance becomes excessive compared to non-disinfectant technology, an action plan is being implemented for this bathing area. A follow-up of the bacterial contribution by the swimmers will be carried out thanks to samples taken several times a day. It will be possible to monitor whether there is an accumulation over time and whether operating constraints must be imposed to avoid this accumulation of *Staphylococcus aureus*. The UV treatment applied is calibrated to ensure the death of these bacteria with an efficacy greater than 99.99%.

4.5. Bathing pool C

The characteristics of this pool are summarized in Table 10. In addition to these water parameters, the bacteriological parameters had the following results (Table 12):

Table 12: Bacteriological parameters measured for bathing pool C.

Bathing pool C	*E. coli*	*Enterococcus*	*P. aeruginosa*	*S. aureus*
Number of samples	91	90	15	93
Mean count (CFU/100 mL)	28	3	6	49
Standard deviation	120	7	9	142
"Excellent water" threshold	79	84	7	70
% of samples	86.81%	93.33%	46.67%	75.27%
"Very good water" threshold	8	6	8	4
% of samples	8.79%	6.67%	53.33%	4.30%
"Good water" threshold	3	0	0	5
% of samples	3.30%	0.00%	0.00%	5.38%
% "poor water"	0.00%	0.00%	0.00%	15.05%

Table 12 reveals a frequent problem of excessive presence of *Staphyloccocus aureus* in 15% of the samples. In this specific case, a problem of water contamination following a failure of the water heating circuit had been identified. Several consecutive analyses revealed this problem before it could be perfectly localized and treated. This does not explain all the overruns, but illustrates the relevance of the indicator.

As for bathing pool B, to fully define the context for which attendance becomes excessive compared to non-disinfectant technology, an action plan is being implemented for this bathing area. A follow-up of the bacterial contribution by the swimmers will be carried out thanks to samples taken several times a day. It will be possible to monitor whether there is an accumulation over time and whether operating constraints must be imposed to avoid this accumulation of *Staphylococcus aureus*. The UV treatment applied is calibrated to ensure the death of these bacteria with an efficacy greater than 99.99%.

5. Conclusions and perspectives

In this review, we have illustrated the state of the art concerning bio-mineral swimming pools and compared it to traditional swimming pools. Bio-mineral swimming pools use a combination of mechanical filtration, bio-filtration, and UV-treatment to disinfect the water. There is no chemical addition to the water, it is not disinfectant. Within bio-mineral pools, the bacterial population is influenced in time and space by bathers in such a way that the environment close to each bather constitutes a micro-ecosystem in itself. As a result, a single one-off sample taken near a bather only very slightly reflects the health risk incurred by all the bathers frequenting an establishment. The analysis of the water quality needs to be different to a traditional swimming pool.

Two main risks exist in a pool: chemical (only organic pollution for the bio-mineral pool) and biological risks, both of which are linked to the bathers. We call this anthropogenic pollution. Contrary to a traditional swimming pool, no risk is associated to chemicals such as chlorine in a bio-mineral pool as no chemical treatments are added. Organic pollution levels depend on three factors: bather hygiene, activity of the bathers, and the water temperature. The biological pollution can be of fecal or non-fecal origin. Studies in test tanks have shown that bio-filtration is well-adapted to maintaining the quality of the water concerning the treatment of organic pollution. This type of filtration clearly avoids the many chlorine by-products present in classical swimming pools, which can lead to many chemical risks for the bathers. Concerning the biological risks, the bio-mineral pool relies on UV-treatment to degrade bacteria. Unlike disinfectant treatments, UV disinfection does not lose its effectiveness in the event of high traffic in the pool. On the other hand, as only the water taken up by the filtration system is disinfected, it is essential that all the water in the pool is filtered. If the pool has a dead zone, its water is not disinfected and there is a risk of localized pathogen development.

As these bio-mineral pools are spreading across Europe, legislation is gradually following. The health parameters measured differ slightly from one country to another, but constants emerge: the measurement of *Escherichia coli*, *Enterococci*, and *Pseudomonas aeruginosa*. In terms of biological swimming pools, there is no regulatory homogeneity across Europe. The Tables presented in this review summarize the situation in the regions where the number of bio-mineral pools is the highest. From these comparisons, it is apparent that the Austrian legislation segmenting water quality into 4 categories ranging from "Excellent" to "Poor" combines both health and safety and indicators of possible malfunctions.

Then, a study of three real sites of bio-mineral pools was presented. Bacteria used as indicators of bathing water quality can be broken down into three categories: fecal pollution indicators, external pollution indicators, and inter-bather contamination indicators.

It appears that, whatever the type of swimming pool, bio-mineral filtration makes it possible to achieve performances comparable to those encountered in chlorinated swimming pools concerning the risks associated with fecal contamination and external pollution. On the other hand, when frequentation is high, as is the case in small swimming pools used for Aquafitness, monitoring the risks of inter-bather contamination as illustrated by the presence of *Staphylococcus aureus* reveals a recurring problem. The simple addition of these bacteria by bathers during their immersion is enough to exceed the threshold value before the UV + bio-filtration system (Figure 2) has been able to disinfect the water and reduce the presence of these bacteria.

Knowing that this parameter is not evaluated in bathing waters in the natural environment, and that numerous studies show that *Staphyloccocus aureus* are always detected even on beaches (Goodwin et al., 2012; Thapaliya et al., 2017; Topić et al., 2021), we propose the definition of three thresholds, i.e., 0 CFU/100 mL (threshold value in Wallonia) for water of excellent quality, less than 20 CFU/100 mL (threshold value in France) for water of very good quality, less than 50 CFU/100 mL (contribution of bathers by simple immersion) for good quality water, and more than 50 CFU/100 mL for poor quality water.

Combined with the Austrian regulations, these various thresholds lead to the proposal shown in Table 13.

Table 13: Proposed water quality parameters for bacteria concentrations

Parameter	Excellent water	Very good water	Good water	Poor water	Directive 2006/7/CE (Parlement Européen, 2006)
E. coli (CFU/100 mL)	<25	26-100	101-1000	>1000	>1000
Enterococcus (CFU/100 mL)	<15	16-50	51-400	>400	>400
P. aeruginosa (CFU/100 mL)	0	1<25	25<100	>100	
Staphylococcus aureus (CFU/100 mL)	0	0<20	20<50	>50	

For each of the thresholds and for each parameter, actions to be taken to return to excellent water quality are described. This document could therefore be converted into an operator manual for the management and use of bio-mineral bathing pools.

Acknowledgements

J.G.M. is grateful to F.R.S.-F.N.R.S for his postdoctoral fellowship (chargé de recherche). J.G.M. is grateful to the Rotary for a District 2160 grant, to the University of Liège and the FNRS for financial support for a postdoctoral stay in INRS Centre Eau, Terre, Environnement in Québec, Canada.

Author contributions

Julien G. Mahy and Frédéric Luizi: conceptualization, methodology, writing – original draft, writing – review & editing, investigation, formal analysis, supervision, funding acquisition, project administration.

Data availability statement

The raw/processed data required to reproduce these findings cannot be shared at this time as these are part of an ongoing study.

Funding

No funding was obtained for this study.

Compliance with ethical standards

Conflict of interest: The authors declare that they have no conflicts of interest.

References

Abshire, R. L., & Dunton, H. (1981). Resistance of Selected Strains of Pseudomonas aeruginosa to Low-Intensity Ultraviolet Radiation. *APPLIED AND ENVIRONMENTAL MICROBIOLOGY*, *41*(6), 1419–1423. Retrieved from https://journals.asm.org/journal/aem

AFSSET. (2009). *Risques sanitaires liés aux baignades artificielles - Evaluations des risques sanitaires*. Retrieved from www.afsset.fr

AFSSET. (2012). *Évaluation des risques sanitaires liés aux piscines Partie I : piscines réglementées*.

Alonso, J. L., Garay, E., & Hernandez, E. (1989). MEMBRANE FILTER PROCEDURE FOR ENUMERATION OF PSEUDOMONAS AERUGINOSA IN WATER. *Water Research*, *23*(12), 1499–1502.

Aquatic Science. (2022a). *Notre histoire - Aquatic Science*. Retrieved from https://www.aquatic-science.com/notre-histoire/

Aquatic Science. (2022b). *Vitii*. Retrieved from https://vitii.be/

Association des Equipements Sportifs (AES). (2016). *Vade-Mecum 2016 des piscines belges*. Retrieved from https://www.aes-asbl.be/vade-mecum-piscines/

Austrian law. (2015). *ÖNorm M 6230 (2015) Badegewässer – Anforderungen an die Wasserqualität, Untersuchung und Bewertung*. Retrieved from https://www.bdb.at/Service/NormenDetail?id=627895

Barna, Z., & Kádár, M. (2012). The risk of contracting infectious diseases in public swimming pools. A review. *Annali Dell'Istituto Superiore Di Sanita*, *48*(4), 374–386. doi: 10.4415/ANN_12_04_05

Blatchley III, E. R., Oguma, K., & Sommer, R. (2016). Comment on the 'UV disinfection induces a VBNC state in Escherichia coli and Pseudomonas aeruginosa. *IUVA News*, 12–16.

Bonadonna, L., & La Rosa, G. (2019). A review and update on waterborne viral diseases associated with swimming pools. *International Journal of Environmental Research and Public Health*, *16*(2). doi: 10.3390/ijerph16020166

Bounty, S., Rodriguez, R. A., & Linden, K. G. (2012). Inactivation of adenovirus using low-dose UV/H2O2 advanced oxidation. *Water Research*, *46*(19), 6273–6278. doi: 10.1016/j.watres.2012.08.036

Carter, R. A. A., Allard, S., Croué, J. P., & Joll, C. A. (2019). Occurrence of disinfection by-products in swimming pools and the estimated resulting cytotoxicity. *Science of the Total Environment*, *664*, 851–864. doi: 10.1016/j.scitotenv.2019.01.428

Carter, R. A. A., & Joll, C. A. (2017). Occurrence and formation of disinfection by-products in the swimming pool environment: A critical review. *Journal of Environmental Sciences (China)*, *58*, 19–50. doi: 10.1016/j.jes.2017.06.013

Casanovas-Massana, A., & Blanch, A. R. (2013). Characterization of microbial populations associated with natural swimming pools. *International Journal of Hygiene and Environmental Health*, *216*(2), 132–137. doi: 10.1016/j.ijheh.2012.04.002

Chang, J. C. H., Ossoff, S. F., Lobe, D. C., Dorfman, M. H., Dumais, C. M., Qualls, R. G., & Johnson, J. D. (1985). UV Inactivation of Pathogenic and Indicator Microorganisms. *APPLIED AND ENVIRONMENTAL MICROBIOLOGY*, *49*(6), 1361–1365.

Cheema, W. A., Kaarsholm, K. M. S., & Andersen, H. R. (2017). Combined UV treatment and ozonation for the removal of by-product precursors in swimming pool water. *Water Research*, *110*, 141–149. doi: 10.1016/j.watres.2016.12.008

Cheema, W. A., Manasfi, T., Kaarsholm, K. M. S., Andersen, H. R., & Boudenne, J. L. (2017). Effect of medium-pressure UV-lamp treatment on disinfection by-products in chlorinated seawater swimming pool waters. *Science of the Total Environment*, *599–600*, 910–917. doi: 10.1016/j.scitotenv.2017.05.008

Chen, P. Y., Chu, X. N., Liu, L., & Hu, J. Y. (2016). Effects of salinity and temperature on inactivation and repair potential of Enterococcus faecalis following medium- and low-pressure ultraviolet irradiation. *Journal of Applied Microbiology*, *120*(3), 816–825. doi: 10.1111/jam.13026

Chowdhury, S., Al-hooshani, K., & Karanfil, T. (2014). Disinfection byproducts in swimming pool: Occurrences, implications and future needs. *Water Research*, *53*, 68–109. doi: 10.1016/j.watres.2014.01.017

Clauß, M. (2006). Higher effectiveness of photoinactivation of bacterial spores, UV resistant vegetative bacteria and mold spores with 222 nm compared to 254 nm wavelength. *Acta Hydrochimica et Hydrobiologica*, *34*(6), 525–532. doi: 10.1002/aheh.200600650

Couleur Nature. (2022). *Histoire de la piscine naturelle : une vision écologique de la baignade*. Retrieved from https://www.couleur-nature-piscine.fr/couleur-nature/actus-presse/histoire-de-la-piscine-naturelle-une-vision-ecologique-de-la-baignade

Coupe, S., Delabre, K., Pouillot, R., Houdart, S., Santillana-Hayat, M., & Derouin, F. (2006). Detection of Cryptosporidium, Giardia and Enterocytozoon bieneusi in surface water, including recreational areas: A one-year prospective study. *FEMS Immunology and Medical Microbiology*, *47*(3), 351–359. doi: 10.1111/j.1574-695X.2006.00098.x

CSTB Recherche. (2018). *Study on biomineral pools asked by Aquatic Science*. Retrieved from https://recherche.cstb.fr/fr/publications/

Dallolio, L., Belletti, M., Agostini, A., Teggi, M., Bertelli, M., Bergamini, C., Chetti, L., & Leoni, E. (2013). Hygienic surveillance in swimming pools: Assessment of the water quality in Bologna facilities in the period 2010-2012. *Microchemical Journal*, *110*, 624–628. doi: 10.1016/j.microc.2013.07.013

de Vicente, A., Aviles, M., Borrego, J. J., & Romero, P. (1988). Die-off and survival of Pseudomonas aeruginosa in freshwater. *Zentralblatt Fur Bakteriologie, Mikrobiologie Und Hygiene. Serie B, Umwelthygiene, Krankenhaushygiene, Arbeitshygiene, Praventive Medizin*, *185*(6), 534–547. Retrieved from http://europepmc.org/abstract/MED/3131996

Delohen, P. (2012). Une baignade biologique de 10 000 m2. *Le Moniteur*. Retrieved from https://www.lemoniteur.fr/article/une-baignade-biologique-de-10-000-m2.1446409

Ekowati, Y., Ferrero, G., Farré, M. J., Kennedy, M. D., & Buttiglieri, G. (2019). Application of UVOX Redox® for swimming pool water treatment: Microbial inactivation, disinfection byproduct formation and micropollutant removal. *Chemosphere*, *220*, 176–184. doi: 10.1016/j.chemosphere.2018.12.126

Elmir, S. M., Wright, M. E., Abdelzaher, A., Solo-Gabriele, H. M., Fleming, L. E., Miller, G., Rybolowik, M., Peter Shih, M. T., Pillai, S. P., Cooper, J. A., & Quaye, E. A. (2007). Quantitative evaluation of bacteria released by bathers in a marine water. *Water Research*, *41*(1), 3–10. doi: 10.1016/j.watres.2006.10.005

Erdinger, L., Kirsch, F., & Sonntag, H. G. (1997). Potassium as an indicator of anthropogenic contamination of swimming pool water. *Zentralblatt Fur Hygiene Und Umweltmedizin= International Journal of Hygiene and Environmental Medicine*, *200*(4), 297–308.

Esser, D., Jost, G., Vallee, V., Dumas, C., & Thévenin, P.-A. (2017). Conception et réalisation de baignades artificielles avec filtration biologique (C.C.9-R0). *Travaux d'aménagement et d'entretien Des Constructions Paysagères*. Retrieved from www.julietteberny.com

European Standards. (2012). *DIN 19643-1 - Treatment of water of swimming pools and baths*. Retrieved from https://www.en-standard.eu/din-19643-1-treatment-of-water-of-swimming-pools-and-baths-part-1-general-requirements/

Fairland. (2022). *France Remains the Leading Private Swimming Pool Market in Europe with Extraordinary Growth*. Retrieved from https://www.fairland.com.cn/allnews/france-remains-the-leading-private-swimming-pool-market-in-europe-with-extraordinary-growth.html

Fernandez, R. (2016). *Final Report Summary - POOLSAFE (A novel swimming pool water treatment for the detection and elimination of excess cyanuric acid.)*. European Commission. Retrieved from https://cordis.europa.eu/project/id/604884/reporting

Geldreich, E. E. (1996). *Microbial quality of water supply in distribution systems*. CRC Lewis Publishers.

Gerba, C. P., Gramos, D. M., & Nwachuku, N. (2002). Comparative inactivation of enteroviruses and adenovirus 2 by UV light. *Applied and Environmental Microbiology*, *68*(10), 5167–5169. doi: 10.1128/AEM.68.10.5167-5169.2002

Goodwin, K. D., McNay, M., Cao, Y., Ebentier, D., Madison, M., & Griffith, J. F. (2012). A multi-beach study of Staphylococcus aureus, MRSA, and enterococci in seawater and beach sand. *Water Research*, *46*(13), 4195–4207. doi: 10.1016/j.watres.2012.04.001

Gouvernement flamand. (2019). *3 MAI 2019. - Arrêté du Gouvernement flamand modifiant divers arrêtés en matière d'environnement et d'agriculture*. Loi Flamande. Retrieved from Moniteur Belge - Belgisch Staatsblad (fgov.be)

Gouvernement français. (1981). Décret n°81-324 du 7 avril 1981 fixant les normes d'hygiène et de sécurité applicables aux piscines et aux baignades aménagées. In Loi Française. Retrieved from https://www.legifrance.gouv.fr/loda/id/LEGITEXT000006063476/2011-09-27/#:~:text=Les%20eaux%20coulant%20sur%20les,par%20l%27eau%20des%20bassins.&text=La%20capacit%C3%A9%20d%27accueil%20de%20l%27%C3%A9tablissement%2C%20fix%C3%A9e%20par,%C3%AAtre%20affich%C3%A9e%20%C3%A0%20l%27entr%C3%A9e.

Gouvernement français. (2019). Arrêté du 15 avril 2019 relatif à la fréquentation, aux installations sanitaires et au règlement intérieur des baignades artificielles. In Loi francaise. Retrieved from https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000038383188

Graczyk, T. K., Sunderland, D., Tamang, L., Lucy, F. E., & Breysse, P. N. (2007). Bather density and levels of Cryptosporidium, Giardia, and pathogenic microsporidian spores in recreational bathing water. *Parasitology Research*, *101*(6), 1729–1731. doi: 10.1007/s00436-007-0734-1

Gromicko, N. (2023). *Pool Water Pathogens*. Retrieved from https://www.nachi.org/pool-water-pathogens.htm

Hassanein, F., Masoud, I. M., Fekry, M. M., Abdel-Latif, M. S., Abdel-Salam, H., Salem, M., & Shehata, A. I. (2023). Environmental health aspects and microbial infections of the recreational water: Microbial Infections and Swimming pools. *BMC Public Health*, *23*(1). doi: 10.1186/s12889-023-15183-z

Hua, P., Chen, Y., & Zhang, J. (2022). Modeling the formation of disinfection byproducts in chlorinated swimming pool water: Role of body fluid analog. *Water Supply*, *22*(9), 7337–7351. doi: 10.2166/ws.2022.296

Husson, M. O., Hamze, M., Verhille, S., & Izard, D. (2000). Pseudomonas et burkholderia. In Précis de bactériologie clinique (pp. 1259–1283). Eska Paris.

Ilyas, H., Masih, I., & Van Der Hoek, J. P. (2018). An exploration of disinfection by-products formation and governing factors in chlorinated swimming pool water. *Journal of Water and Health*, *16*(6), 861–892. doi: 10.2166/wh.2018.067

Judd, S. J., & Bullock, G. (2003). The fate of chlorine and organic materials in swimming pools. *Chemosphere*, *51*(9), 869–879. doi: 10.1016/S0045-6535(03)00156-5

Karanis, P., Kourenti, C., & Smith, H. (2007). Waterborne transmission of protozoan parasites:A worldwide review of outbreaks and lessons learnt. *Journal of Water and Health*, *5*(SUPPL. 1), 1–18. doi: 10.2166/wh.2006.002

Karimi, B. (2020). Formation of disinfection by-products in the swimming pool water treated with different disinfection types. *Desalination and Water Treatment*, *175*, 174–181. doi: 10.5004/dwt.2020.24887

Keuten, M. G. A., Peters, M. C. F. M., Daanen, H. A. M., de Kreuk, M. K., Rietveld, L. C., & van Dijk, J. C. (2014). Quantification of continual anthropogenic pollutants released in swimming pools. *Water Research*, *53*, 259–270. doi: 10.1016/j.watres.2014.01.027

Kluytmans, J., van Belkum, A., & Verbrugh, H. (1997). Nasal Carriage of Staphylococcus aureus: Epidemiology, Underlying Mechanisms, and Associated Risks. *Clinical Microbiology Reviews*, *10*(3), 505–520. Retrieved from http://cmr.asm.org/

Lempart, A., Kudlek, E., & Dudziak, M. (2020). The potential of the organic micropollutants emission from swimming accessories into pool water. *Environment International*, *136*. doi: 10.1016/j.envint.2019.105442

Lempart, A., Kudlek, E., Lempart, M., & Dudziak, M. (2018). The presence of compounds from the Personal Care Products group in swimming pool water. *Journal of Ecological Engineering*, *19*(3), 29–37. doi: 10.12911/22998993/85377

Linden, K. G., Shin, G. A., Lee, J. K., Scheible, K., Shen, C., & Posy, P. (2009). Demonstrating 4-log adenovirus inactivation in a medium-pressure UV disinfection reactor. *Journal / American Water Works Association*, *101*(4). doi: 10.1002/j.1551-8833.2009.tb09876.x

Lu, P., Yuan, T., Feng, Q., Xu, A., & Li, J. (2013). Review of swimming-associated Cryptosporidiosis and cryptosporidium oocysts removals from swimming pools. *Water Quality Research Journal of Canada*, *48*(1), 30–39. doi: 10.2166/wqrjc.2013.036

Malayeri, A. H., Mohseni, M., Cairns, B., & Bolton, J. R. (2018). Fluence (UV dose) required to achieve incremental log inactivation of Bacteria, Protozoa, Viruses and Algae. *International UV Association*.

Mazur, D. M., & Lebedev, A. T. (2022). Transformation of Organic Compounds during Water Chlorination/Bromination: Formation Pathways for Disinfection By-Products (A Review). *Journal of Analytical Chemistry*, *77*(14), 1705–1728. doi: 10.1134/S1061934822140052

McKinney, C. W., & Pruden, A. (2012). Ultraviolet disinfection of antibiotic resistant bacteria and their antibiotic resistance genes in water and wastewater. *Environmental Science and Technology*, *46*(24), 13393–13400. doi: 10.1021/es303652q

Mena, K. D., & Gerba, C. P. (2009). *Reviews of Environmental Contamination and Toxicology Vol 201* (D. M. Whitacre, Ed.; Vol. 201). Boston, MA: Springer US. doi: 10.1007/978-1-4419-0032-6

Moreno-Andrés, J., Romero-Martínez, L., Acevedo-Merino, A., & Nebot, E. (2016). Determining disinfection efficiency on E. faecalis in saltwater by photolysis of H2O2: Implications for ballast water treatment. *Chemical Engineering Journal*, *283*, 1339–1348. doi: 10.1016/j.cej.2015.08.079

Nickmilder, M., & Bernard, A. (2011). Associations between testicular hormones at adolescence and attendance at chlorinated swimming pools during childhood. *International Journal of Andrology*, *34*(5 PART 2). doi: 10.1111/j.1365-2605.2011.01174.x

Nwachuku, N., Gerba, C. P., Oswald, A., & Mashadi, F. D. (2005). Comparative inactivation of adenovirus serotypes by UV light disinfection. *Applied and Environmental Microbiology*, *71*(9), 5633–5636. doi: 10.1128/AEM.71.9.5633-5636.2005

Park, G. W., Linden, K. G., & Sobsey, M. D. (2011). Inactivation of murine norovirus, feline calicivirus and echovirus 12 as surrogates for human norovirus (NoV) and coliphage (F+) MS2 by ultraviolet light (254 nm) and the effect of cell association on UV inactivation. *Letters in Applied Microbiology*, *52*(2), 162–167. doi: 10.1111/j.1472-765X.2010.02982.x

Parlement Européen. (2006). European Directive of February 15, 2006 on the quality of bathing water in the natural environment. In Législation européenne. Retrieved from https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2006:064:0037:0051:EN:PDF

Peng, F., Yang, F., Lu, Y., Li, H., & Yang, Z. (2021). Formation of disinfection byproducts during chlorination of mixed nitrogenous compounds in swimming pools. *Science of the Total Environment*, *754*. doi: 10.1016/j.scitotenv.2020.142100

Qian, S. S., Donnelly, M., Schmelling, D. C., Messner, M., Linden, K. G., & Cotton, C. (2004). Ultraviolet light inactivation of protozoa in drinking water: A Bayesian meta-analysis. *Water Research*, *38*(2), 317–326. doi: 10.1016/j.watres.2003.10.007

Quek, P. H., & Hu, J. (2008). Indicators for photoreactivation and dark repair studies following ultraviolet disinfection. *Journal of Industrial Microbiology and Biotechnology*, *35*(6), 533–541. doi: 10.1007/s10295-008-0314-0

Robinton, E. D., & Mood, E. W. (1966). A quantitative and qualitative appraisal of microbial pollution of water by swimmers: A preliminary report. *Journal of Hygiene*, *64*(4), 489–499. doi: 10.1017/S0022172400040808

Rosenman, K. D., Millerick-May, M., Reilly, M. J., Flattery, J., Weinberg, J., Harrison, R., Lumia, M., Stephens, A. C., & Borjan, M. (2015). Swimming facilities and work-related asthma. *Journal of Asthma*, *52*(1), 52–58. doi: 10.3109/02770903.2014.950428

Schulz, L. (1981). *Nährstoffeintrag in seen durch badegäste*.

Seux, R. (1988). Evolution de la pollution apportée par les baigneurs dans les eaux de piscines sous l'action du chlore. *Journal Français d'hydrologie*, *19*(2), 151–167. Retrieved from https://doi.org/10.1051/water/19881902151

Seyfried, P. L., & Cook, R. J. (1984). Otitis externa infections related to Pseudomonas aeruginosa levels in five Ontario lakes. *Canadian Journal of Public Health/Revue Canadienne de Sante'e Publique*, 83–91.

Shin, G. A., Linden, K. G., & Sobsey, M. D. (2005). Low pressure ultraviolet inactivation of pathogenic enteric viruses and bacteriophages. *Journal of Environmental Engineering and Science*, *4*(SUPPL. 1). doi: 10.1139/s04-036

Shoults, D. C., Li, Q., Petterson, S., Rudko, S. P., Dlusskaya, L., Leifels, M., Scott, C., Schlosser, C., & Ashbolt, N. J. (2021). Pathogen performance testing of a natural swimming pool using a cocktail of microbiological surrogates and QMRA-derived management goals. *Journal of Water and Health*, *19*(4), 629–641. doi: 10.2166/WH.2021.015

Smith, B. G., & Dufour, A. P. (1993). Effects of the microbiological quality of recreational waters: A simulation study. *American Society for Microbiology 93rd General Meeting: May 16–20 1993; Atlanta, GA*.

Spiliotopoulou, A., Hansen, K. M. S., & Andersen, H. R. (2015). Secondary formation of disinfection by-products by UV treatment of swimming pool water. *Science of the Total Environment*, *520*, 96–105. doi: 10.1016/j.scitotenv.2015.03.044

Switzerland law. (2016). *Ordonnance du DFI sur l’eau potable et l’eau des installations de baignade et de douche accessibles au public (OPBD) – 16 décembre 2016 – n°817.022.11*. Retrieved from https://www.fedlex.admin.ch/eli/cc/2017/153/fr

Thapaliya, D., Hellwig, E. J., Kadariya, J., Grenier, D., Jefferson, A. J., Dalman, M., Kennedy, K., DiPerna, M., Orihill, A., Taha, M., & Smith, T. C. (2017). Prevalence and Characterization of Staphylococcus aureus and Methicillin-Resistant Staphylococcus aureus on Public Recreational Beaches in Northeast Ohio. *GeoHealth*, *1*(10), 320–332. doi: 10.1002/2017GH000106

Thepaut, G., Balestra, D., Gerard, J.-C., Laurent, J.-L., Luizi, F., Grosbellet, C., & Ruaud, M. (2013). Conception et réalisation de baignades biologiques avec filtration intensive (C.C.10-R0). *Travaux d’aménagement et d’entretien Des Constructions Paysagères*. Retrieved from http://www.entreprisesdupaysage.org/base-documentaire/regles-professionnelles/149-Regles-professionnelles-finalisees/.

Thurston-Enriquez, J. A., Haas, C. N., Jacangelo, J., Riley, K., & Gerba, C. P. (2003). Inactivation of feline calicivirus and adenovirus type 40 by UV radiation. *Applied and Environmental Microbiology*, *69*(1), 577–582. doi: 10.1128/AEM.69.1.577-582.2003

Topić, N., Cenov, A., Jozić, S., Glad, M., Mance, D., Lušić, D., Kapetanović, D., Mance, D., & Lušić, D. V. (2021). Staphylococcus aureus—an additional parameter of bathing water quality for crowded urban beaches. *International Journal of Environmental Research and Public Health*, *18*(10). doi: 10.3390/ijerph18105234

Tsamba, L., Cimetière, N., Wolbert, D., Correc, O., & le Cloirec, P. (2020). Body fluid analog chlorination: Application to the determination of disinfection byproduct formation kinetics in swimming pool water. *Journal of Environmental Sciences (China)*, *87*, 112–122. doi: 10.1016/j.jes.2019.06.009

Walloon law (Belgium). (2013). *Arrêté du Gouvernement wallon déterminant les conditions sectorielles relatives aux bassins de natation couverts et ouverts utilisés à un titre autre que purement privatif dans le cadre du cercle familial, lorsque la surface est supérieure à 100 m2 et la profondeur supérieure à 40 cm (M.B. 12.07.2013)*. Retrieved from http://environnement.wallonie.be/legis/pe/pesect070.html

Warburton, D. W., Bowen, B., & Konkle, A. (1994). The survival and recovery of Pseudomonas aeruginosa and its effect upon salmonellae in water: methodology to test bottled water in Canada. *Canadian Journal of Microbiology*, *40*, 987–992. Retrieved from www.nrcresearchpress.com

Wilson, B. (1992). Coliphage MS-2 as a UV water disinfection efficacy test surrogate for bacterial and viral pathogens. *Proc. of the AWWA Water Quality Technology Conference. Toronto, Ont., AWWA, 1992*.

Włodyka-Bergier, A., & Bergier, T. (2018). Impact of UV disinfection on potential of personal care products components on chlorination by-products formation in swimming pool water. *Desalination and Water Treatment*, *134*, 65–75. doi: 10.5004/dwt.2018.22655

Włodyka-Bergier, A., & Bergier, T. (2021). Impact of low-pressure uv lamp on swimming pool water quality and operating costs. *Energies*, *14*(16). doi: 10.3390/en14165013

World Health Organization. (2006). *Guidelines for safe recreational water environments - Volume 2: Swimming pools and similae environments*. Geneva: World Health Organization Press.

Wyczarska-Kokot, J., Lempart-Rapacewicz, A., Dudziak, M., & Łaskawiec, E. (2020). Impact of swimming pool water treatment system factors on the content of selected disinfection by-products. *Environmental Monitoring and Assessment*, *192*(11). doi: 10.1007/s10661-020-08683-7

Xiao, S., Yin, P., Zhang, Y., & Hu, S. (2017). Occurrence of cryptosporidium and giardia and the relationship between protozoa and water quality indicators in swimming pools. *Korean Journal of Parasitology*, *55*(2), 129–136. doi: 10.3347/kjp.2017.55.2.129

Yang, L., Chen, X., She, Q., Cao, G., Liu, Y., Chang, V. W. C., & Tang, C. Y. (2018). Regulation, formation, exposure, and treatment of disinfection by-products (DBPs) in swimming pool waters: A critical review. *Environment International*, 1039–1057. doi: 10.1016/j.envint.2018.10.024

Zare Afifi, M., & Blatchley, E. R. (2016). Effects of UV-based treatment on volatile disinfection byproducts in a chlorinated, indoor swimming pool. *Water Research*, *105*, 167–177. doi: 10.1016/j.watres.2016.08.064

Zhang, D., Dong, S., Chen, L., Xiao, R., & Chu, W. (2023). Disinfection byproducts in indoor swimming pool water: Detection and human lifetime health risk assessment. *Journal of Environmental Sciences (China)*, *126*, 378–386. doi: 10.1016/j.jes.2022.05.003

Zini, S., & Lagriffoul, A. (2010). *Note complémentaire au rapport « Risques sanitaires liés aux baignades artificielles » se rapportant à la valeur limite en Pseudomonas aeruginosa*. Maisons-Alfort.