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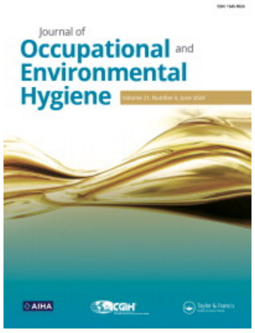

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REPORT

Estimating airborne trichloramine levels in indoor swimming pools using the well-mixed box model

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ABSTRACT

Exposure to airborne disinfection by-products, especially trichloramine (TCA), could cause various occupational health effects in indoor swimming pools. However, TCA concentration measurements involve specialized analysis conducted in specific laboratories, which can result in significant costs and time constraints. As an alternative, modeling techniques for estimating exposures are promising in addressing these challenges. This study aims to predict airborne TCA concentrations in indoor swimming pools using a mathematical model, the well-mixed box model, found in the IHMOD tool, freely available on the American Industrial Hygiene Association website. The model's predictions are compared with TCA concentrations measured during various bather load scenarios. The research involved conducting 2-hr successive workplace measurements over 16- to 18-hr periods in four indoor swimming pools in Quebec, Canada. TCA concentrations were estimated using the well-mixed box model, assuming a homogeneous mixing of air within the swimming pool environment. A novel approach was developed to estimate the TCA generation rate from swimming pool water, incorporating the number of swimmers in the model. Average measured concentrations of TCA were 0.24, 0.26, 0.14, and 0.34 mg/m^3 for swimming pools 1, 2, 3, and 4, respectively. The ratio of these measured average concentrations to their corresponding predicted values ranged from 0.51 to 1.30, 0.67 to 1.04, 0.57 to 1.14, and 0.68 to 1.49 for the respective swimming pools. In a worst-case scenario simulating the swimming pool at full capacity (maximum bathers allowed), TCA concentrations were estimated as 0.23, 0.36, 0.14, and 0.37 mg/m^3 for swimming pools 1, 2, 3, and 4. Recalculated concentrations by adjusting the number of swimmers so as not to exceed the recommended occupational limit concentration of 0.35 mg/m^3 gives a maximum number of swimmers of 63 and 335 instead of currently 80 and 424 for swimming pools 2 and 4, respectively. Similarly, for swimming pools 1 and 3, the maximum number of swimmers could be 173 and 398 (instead of the current 160 and 225, respectively). These results demonstrated that the model could be used to estimate and anticipate airborne TCA levels in indoor swimming pools across various scenarios.

KEYWORDS
Disinfection by products; mass emission rate; modeling; NCl_3; swimmer; worker exposure

Introduction

Despite recent developments in using non-chlorinated disinfectants for swimming pool water treatments (Richardson et al. 2007; Cheema et al. 2016; Semenov and Sakhno 2021; Shi et al. 2021), chlorination remains the prevalent method for disinfecting swimming pool water (Schets et al. 2020). The unintended reaction between the chlorine and nitrogen-containing organic matter, such as sweat, urea, and skin flakes, produces disinfection by-products (DBPs) (Ilyas et al. 2018; Yang et al. 2018; Tsamba et al. 2020).

The dominant airborne DBPs are trihalomethanes and chloramines (Weaver et al. 2009; Ahmadpour et al. 2022). Exposure to the most volatile chloramine (trichloramine [TCA]) has been associated with various health risks, especially for workers (Gouveia et al. 2019; Peng et al. 2020; Westerlund et al. 2022). Attendance in swimming pools with TCA concentrations higher than 0.2 mg/m^3 was correlated with ocular irritation, sore throat, and development of phlegm (Jacobs et al. 2007). Other studies have indicated that a high TCA level is associated with respiratory symptoms, red eyes, and

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airway reactivity (Fornander et al. 2013; Erkul et al. 2014). In addition, research showed that TCA exposure might affect the lower respiratory tract and increase the risk of developing asthma among swimming pool employees (Jacobs et al. 2007; Nordberg et al. 2012).

Various countries proposed recommendations to protect workers from TCA, with occupational exposure limits ranging from 0.2 mg/m^3 in Germany to 0.3 mg/m^3 in Sweden, and 0.35 mg/m^3 in British Columbia, Canada, in contrast to the World Health Organization's (WHO) recommended threshold limit value time-weighted average air concentration (TLV®-TWA) of 0.5 mg/m^3 (ANSES 2010; German Working Group on Indoor Guide Values of the Federal Environment Agency 2011; Swedish Work Environment Authority 2011; ANSES 2013; WorkSafeBC 2014). In addition, the French Agency for Environmental and Occupational Health Safety (AFSSET) recommends a maximum TCA level in the air of indoor swimming pools of 0.3 mg/m^3 (ANSES 2013).

Air sampling and TCA capture on impregnated quartz filters remain the common method for assessing the extent of air contamination in indoor swimming pools (Hery et al. 1995; Zwiener and Schmalz 2015; Wu et al. 2021; Ahmadpour et al. 2022). Samples are collected for a minimum of 2 hr with pumps and cassettes containing arsenic-impregnated filters, which are then sent to a laboratory to be analyzed by ion chromatography. The results will demonstrate airborne TCA's 2-hr average concentration in one [or few] locations inside swimming pools. However, several authors reported that TCA concentrations varied within a day and between days (Catto et al. 2012; Ahmadpour et al. 2022). To adequately represent exposure, it is thus necessary to take multiple sequential 2-hr samples. Nevertheless, exposure monitoring is restricted by the financial burden associated with sample collection and analysis.

Using models and estimations offers a viable strategy for disseminating information on contamination levels and effectively managing swimming pool facilities. Such approaches have demonstrated their ability to enhance decision-making processes (Jayjock et al. 2007; Spinazzè et al. 2019). Although some regression equations have been proposed to predict TCA concentrations from measurements of other parameters (Dyck et al. 2011; Saleem et al. 2019), obtaining these parameters is still complex and time-consuming. In other words, the few available studies provide equations that target advanced users who have experience in exposure estimation and who can solve the resulting mathematical equations.

Furthermore, numerous published studies have consistently shown that bather loads significantly impact airborne TCA concentrations in swimming pools, primarily due to the increased input of organic matter from sweat, urine, and other body fluids, which serves as a surrogate for chlorination reactions. Specifically, during periods of high attendance, such as weekends or school holidays, the TCA concentration tends to increase (Gabriel et al. 2019; Nitter and Hirsch Svendsen 2020; Lee and Blatchley 2022). Therefore, the equation must account for the influence of the number of swimmers as a key determinant.

The American Industrial Hygiene Association provided a free Microsoft Excel-based tool, IH MOD_2_0 (IHMOD), which features the well-mixed model (WMM) in a user-friendly application. IHMOD is a modeling tool used to estimate the concentrations of air pollutants or other airborne substances in industrial settings. Occupational hygienists are familiar with the IHMOD tool proposed for estimating occupational exposures. The WMM is one type of mathematical model that can be used within the IHMOD framework. While many different models are available for estimating airborne environmental contaminant levels (Turbulent Eddy diffusion, two zones, and near and midfield models), the WMM may be considered a simple model, with fewer parameters to estimate than some other models. It considers the input (contaminant generation rate) and the output (the dilution by ventilation) in a given physical environment. The WMM is a mathematical model assuming that the pollutants are well-mixed and uniformly distributed in the air (Ramachandran 2005; Jayjock et al. 2007; Arnold et al. 2017). Since the majority of TCA is released from a large source, the surface of the pool water, this provides the mixing condition that makes WMM the first approach selected. It makes fewer assumptions about the environment than some other models, and it has a high flexibility that could be used to estimate exposure levels for a range of different exposure scenarios, including modification in the ventilation system and variation on the generation rate in the presence of swimmers.

This study aims to use the WMM in predicting airborne TCA levels and assess its effectiveness. Full-scale tests were conducted in four indoor swimming pools, and air samples were collected for analysis. The IHMOD tool was employed to estimate TCA concentrations, considering different numbers of swimmers, and providing valuable insights into occupational exposure in indoor swimming pools.

Methods

Experimental tests

TCA samplings were carried out in four indoor swimming pools. A detailed overview of the swimming pools and the ventilation systems in the four swimming pools can be found in Table S1 (Supplementary material). In all four pools, ventilation was achieved through Constant Air Volume (CAV) systems. These selected swimming pools varied significantly in terms of facility size, with natatorium hall volumes ranging from 1312 m^3 to 13,556 m^3, water surfaces varying from 147 m^2 to 887 m^2, and total ventilation rates ranging from 169 m^3/min to 552 m^3/min. Sampling was conducted during the winter season, with a focus on maintaining closed doors and windows, ensuring that external influences were minimized.

In all the swimming pools, samplings were started 2 hr before opening and were continued nonstop until 2 hr after closing in three fixed sampling locations (A, B, and C) around the pool at 150 cm above the water surface (breathing zone) and less than one meter from the edges of the water. These locations were selected to be in proximity to the lifeguard chair while avoiding the direct influence of ventilation inlet or outlet. Daily variations in TCA levels were captured through a systematic collection of sequential 2-hr samples. In total, 99 samples were collected from these three locations in the four swimming pools.

TCA in the air was analyzed according to Hery's (Hery et al. 1995) adapted strategy previously presented by the author (Ahmadpour et al. 2022). Air samples for TCA measurements were pumped at a 0.75 l/min flow rate for 120 min through the separable cassette assembly consisting of a Teflon prefilter cassette connected by a Tygon tube to two-layer quartz fiber filters cassettes (Whatman Grade QMA 37-mm diameter). The quartz fiber filters were impregnated with a mixture of sodium carbonate (4.0 g/L) and diarsenic trioxide (0.4 g/L) to capture TCA from passing air in the form of chloride. These chlorides are measured and quantified by ion chromatography. All pumps (GilAir plus personal air sampling pumps) were calibrated before each session before sampling. Equipment details and collected results were previously published by the author (Ahmadpour et al. 2022).

The predictive model

The WMM with a constant generation rate was selected to predict TCA concentrations. The input parameters used in the WMM of the IH-MOD tool are shown in Table 1. Figure S1 (Supplementary material) presents a schematic representation of the basic parameters of the WMM. The *swimming pool supply/exhaust ventilation rate* (Q) and *natatorium hall volume (V)* are collected from questionnaire information filled out by swimming pool managers. Q was held constant throughout this study, as the participating swimming pools were equipped with mechanical CAV ventilation systems. *Contaminant concentration at time zero* (C_0) is the concentration of TCA we measured before the swimming pool starting time. We measured the concentrations for 2 hr in three locations in each swimming pool before the opening and used the arithmetic mean for parameter C_0 for the first phase. After that, we input the concentration of the previous 2 hr as a C_0 of the following 2 hr. For the *contaminant concentration in the air supply* (C_{in}) parameter, we measured a 2 hr-average airborne TCA concentration inside each swimming pool's ventilation system (inlet chamber), and we assumed that this concentration was constant for the modeling day. Figure S2 in the supplementary material shows the various sampling locations. The *loss mechanism value (KL)* represents the fraction of TCA that could be lost in each swimming pool due to various factors, such as settling, adherence to pool surfaces, or chemical transformation. We considered it zero for all swimming pools, as stable indoor environments were maintained under the controlled conditions of our study. The *maximum simulation time* (t) is the duration we wanted to predict the TCA concentration. For homogeneity and paring our results with experimental data, we ran each model for 120 min, equal to 2 hr of sampling. *Time at the end of generation* (t_{end}) is a parameter that addresses the time that TCA

Table 1. List of input parameters for the well-mixed model of the IH-MOD tool MMMMMMM.

Parameter name	Dimension	Symbol	Swimming Pool 1	Swimming Pool 2	Swimming Pool 3	Swimming Pool 4
Room supply/exhaust air rate	(m^3/min)	Q	432	170	552	768
Room volume	(m^3)	V	5736	1312	9200	13556
Contaminant concentration at time zero	(mg/m^3)	C_0	0.34	0.13	0.11	0.25
Contaminant concentration in air supply	(mg/m^3)	C_{in}	0.15	0.09	0.09	0.20
Loss mechanism value	(fraction/min)	K_l	0.00	0.00	0.00	0.00
Maximum time of simulation	(min)	T	120	120	120	120
Time at the end of generation	(min)	T_{end}	120	120	120	120
Contaminant mass emission rate	(mg/min)	G	10.91*	4.27*	14.55*	26.60*

*: These numbers present the Contaminant mass emission rate without swimmers.

generation is ended. The last parameter is the *contaminant mass emission rate* (mg/min). Generation rate (G) is the rate of TCA emissions from swimming pool water. Two TCA mass emission rates were calculated: first, we calculated the TCA mass emission rate for the swimming pool without swimmers (G_0), and then we adjusted TCA mass emission rates considering the presence of swimmers (G).

TCA mass emission rate without swimmers (G_0)

As previously published, the classic two-resistance theory considering the mass transfer coefficient could be applied to calculate G_0 from aqueous solutions (Lyman et al. 1990) (Guo and Roache 2003):

$$G_0 = S * K_{OL}(C_L - C_G/H) \quad (1)$$

where G_0 is the emission rate (µg/h), S is the source area (m^2), K_{OL} is the overall liquid phase mass transfer coefficient (m/h), C_L is the TCA concentration in the liquid (µg/m^3), C_G is the TCA concentration in air (µg/m^3), and H is the dimensionless Henry's constant [(µg/m^3) air/(µg/m^3) liquid]. For the swimming pool without swimmers, Schmalz et al. (2011) calculated the liquid phase mass transfer coefficient where $K_{OL} = 2{,}196 \times 10^{-2}$ (m/h) (Schmalz et al. 2011).

Sander et al. reported from the literature that the TCA Henry law constant for water as solvent (Hcp) is $9.9*10^{-4}$ mol m^{-3} pa^{-1} (Sander 2015). Next, taking into account the ideal gas assumption, the dimensionless Henry solubility constants (defined as c/c in equation 1) can be calculated from this formula (Sander 1999):

$$\begin{aligned} &H = R \times T \times Hcp \\ &H = 8.3\left(m^3pak^{-1}mol^{-1}\right) \times 298.15k \times 9.9 * 10^{-4}molm^{-3}pa^{-1} \\ &\mathbf{H = 2.44} \end{aligned} \quad (2)$$

Here, assumptions were made to give an order of magnitude of the expected TCA concentrations in water and air. Goeres et al. reported that in swimming pool water, TCA concentration is around 0.08 mg/L, so the TCA concentration in the liquid is $C_L = 8 \times 10^4$ µg/m^3 (Goeres et al. 2004). Regarding air concentration, we used the air concentration recommended to prevent the health effects of 0.3 mg/m^3: $C_G = 3 \times 10^2$ µg/m^3.

All together:

$$\begin{aligned} &G = S * K_{OL}(C_L - [C_G/H]) \\ &G = S * \ 2.19 \times 10^{-2} * \left(8 \times 10^4 - \left[3 \times 10^2/2.44\right]\right) \\ &G(\mu g/h) = S(m^2) * 1735.9(\mu g.m^{-2}/h) \\ &G(mg/min) = S(m^2) * 0.029(mg.m^{-2}/min) \end{aligned} \quad (3)$$

In this equation, S represents the source area (m^2) corresponding to the surface of the pool water. Finally, TCA mass emission rates without swimmers (G_0) will be:

$$G_0(mg/min) = \text{Pool water surface} * 0.029 \quad (4)$$

TCA mass emission rate with swimmers (G)

Jacobs et al. (2007) demonstrated that visitor numbers were significantly associated with TCA levels. More specifically, the increase of 50 bathers was associated with a 0.40 mg/m^3 increase in TCA air level (Jacobs et al. 2007). The number of swimmers is a key parameter driving the contamination of pool water by DBPs (Aggazzotti et al. 1995; Chu and Nieuwenhuijsen 2002; Bessonneau et al. 2011). Lochner et al. modified the ASHRAE recommendation by mentioning that a public school swimming pool may have 50% more emissions than a swimming pool with no activity (unused swimming pool) (Lochner and Wasner 2017).

Bradford et al. showed that one bather in 1 h of normal swimming exudes 0.410 g of organic-N, mostly as urea (0.345 g urea and 0.084 g NH_3—N) (Bradford 2014). Converting this rate to a per-minute basis, each swimmer contributes approximately 0.00683 g of organic nitrogen during a 1-min period, equivalent to 6.83 mg/min. The percentage of organic nitrogen in swimming pool water that converts to airborne TCA can vary depending on several factors, such as water conditions and disinfection methods. However, studies have generally suggested that a small fraction of organic nitrogen, typically less than 1%, may be converted to airborne TCA in swimming pools. The assumption that 1% of the organic nitrogen is converted to TCA is considered realistic due to the gradual accumulation of TCA over time and the understanding that the conversion reaction is irreversible and consecutive. These assumptions provide a reasonable basis for estimating the contribution of organic nitrogen to TCA levels in the swimming pool environment (Soltermann et al. 2015). Considering this last item, each swimmer will add 0.0683 mg/min to the TCA emission rate.

By this modification, the new equation will be:

$$G(\mathrm{mg/min}) = G_0(\mathrm{mg/min}) + 0.0638 * N_s \quad (5)$$

The variable “Ns” in Equation 5 corresponds to the average number of swimmers reported during each 2-hr sampling period. Table S2 (supplementary material) presents the swimmer numbers recorded during each 2-hr sampling period in the four indoor swimming pools that have been used in equation 5.

Application of the model

First, the model’s outputs (2-hr TCA concentrations) were compared to experimental data from four indoor swimming pools. The principal approach for evaluating the model’s predictive performance involved computing the estimated concentrations and comparing them with the measured concentrations for each 2-hr interval in every swimming pool. In conjunction with the predictive-to-measurement concentration ratio, we employed graphical comparisons of model estimates and measured data utilizing bars and scatter plots. The objective was to assess the precision of the estimation. The input parameters utilized for this purpose are provided in Table 1. In addition to the measure of the predictive-to-measurement concentration ratio, a scatter plot of the predicted and measured concentrations was provided, and statistical indexes were calculated according to the criteria proposed by the ASTM Standard 5157 − 97. The correlation coefficient (r), regression slope (b), and regression intercept (a) were assessed, along with the Normalized Mean Square Error (NMSE) and the Fractional Bias (FB). The criteria presented in Table S5 (Supplementary material), proposed by ASTM, were used for assessing the general agreement between predicted and measured concentrations and assessing bias in the mean of predicted values.

Second, to evaluate the model’s generalizability, two independent published studies reported TCA concentrations (Lévesque et al. 2015; Nitter and Hirsch Svendsen 2020) were incorporated into the model framework, and the model-to-measured ratios were also calculated. The two studies for inclusion in the analysis were selected based on the availability of information regarding the input parameters.

Third, the model was employed to simulate the TCA concentration under two exposure scenarios in the four swimming pools. The first scenario represents the worst-case scenario when the maximum bather load was present. The second scenario represents modification when the ventilation system remained inactive overnight.

In this study, the data analyses involved both descriptive reports and analytical calculations. To accomplish these analyses, Excel software (version 2019) and SPSS software (version 27) were employed.

Results

Model predictive performance testing

Results of the four swimming pools’ TCA measured concentrations or those estimated from models are shown graphically in Figure 1, and the ratio between concentrations is presented in Table 2 and Figure 2. The arithmetic means of measured TCA concentrations were 0.24 mg/m^3, 0.26 mg/m^3, 0.14 mg/m^3, and 0.34 mg/m^3 in swimming pools 1, 2, 3, and 4, respectively. In all swimming pools, the arithmetic means of the TCA concentrations were lower than the recommended level of 0.35 mg/m^3 proposed in British Columbia, Canada. Swimming pools experimentally measured levels showed temporal variations in TCA concentration (Figure 1). In general, the variation in TCA concentrations showed the same daily trend on the experimental results and model prediction levels.

The ratio between the concentration predicted by WMM and the average value of the measured concentrations ranged from 0.51 to 1.49. Ratios of the 2-hr measured concentrations in comparison to those predicted ranged from 0.51 to 1.30, 0.67 to 1.04, 0.57 to 1.14, and 0.68 to 1.49 for swimming pools 1, 2, 3, and 4, respectively (Table 2 and Figure 2). This means that the TCA levels estimated by the WMM differ by a maximum factor of two from the full-scale sampling results taken in the swimming pools. Phase one (concentration before the swimmer’s presence) of the estimated level in indoor swimming pool 1 was half of the experimentally measured results (ratio = 0.51). Further investigations revealed that this swimming pool had turned off the ventilation system during the night, which explains the higher initial concentration of TCA in this pool.

Model and experimentally measured TCA level comparison based on literature data

In a study by Nitter and Hirsch Svendsen (2020), airborne TCA concentrations in a swimming pool were measured twice daily, from 6 AM to 9 AM and 3 PM to 6 PM, with reported swimmer numbers ranging from 0 to 60. In this study, the modified WMM was utilized to estimate the corresponding 3-hr TCA

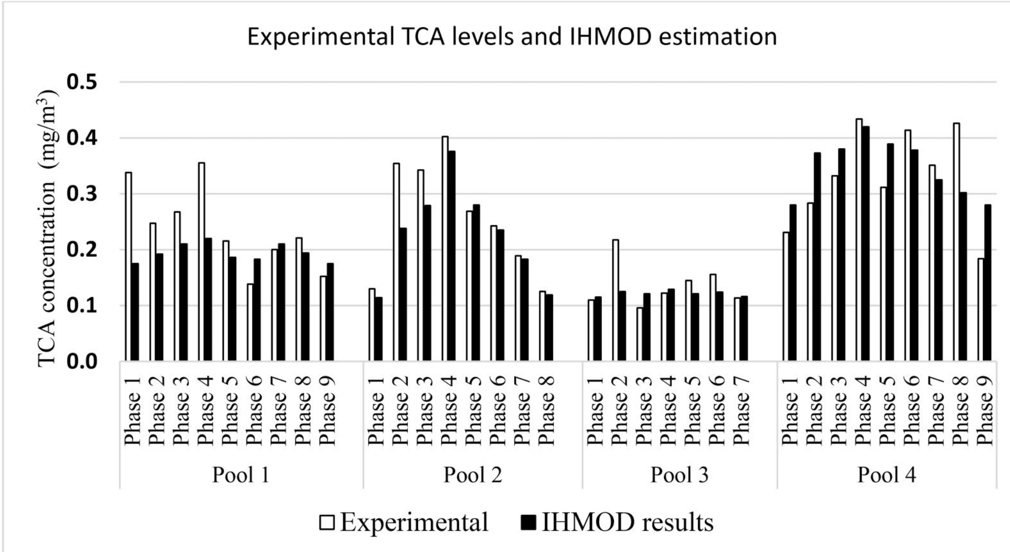

Figure 1. Experimental TCA levels (sampling from swimming pools) and IHMOD estimation. The demonstrated field levels show the geometric mean of TCA concentration from three simultaneous sampling in three locations of swimming pools.

Table 2. Model predictive performance testing.

Sample	Swimming Pool 1	Swimming Pool 2	Swimming Pool 3	Swimming Pool 4
1	0.51*	0.88	1.03	1.15
2	0.77	0.67	0.57	1.28
3	0.78	0.81	1.14	1.09
4	0.62	0.93	1.02	0.93
5	0.86	1.04	0.83	1.19
6	1.30	0.97	0.79	0.88
7	1.03	0.97	1.02	0.92
8	0.88	0.95	N.A	0.68
9	1.15	N.A	N.A	1.49
MIN	0.51	0.67	0.57	0.68
MAX	1.30	1.04	1.14	1.49

*= The ventilation system was deactivated during nighttime.

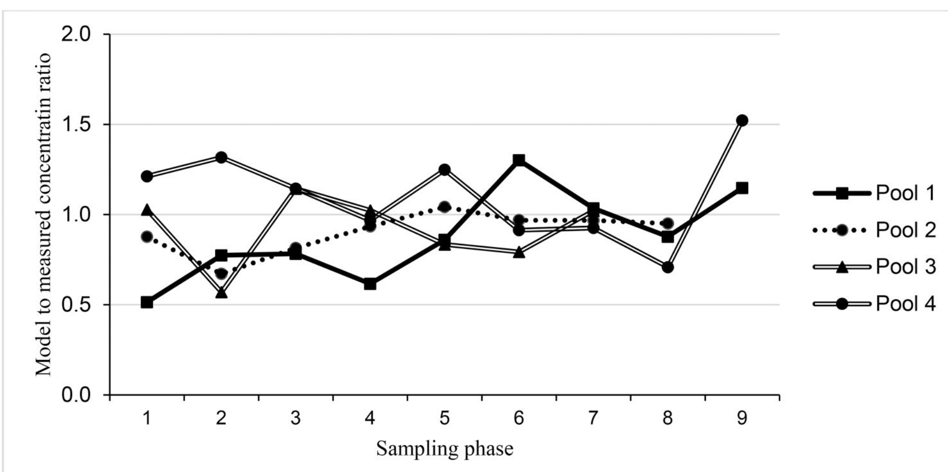

Figure 2. Schematic presentation of the model-to-measured concentration ratio of airborne TCA levels in 4 contributed swimming pools.

concentrations. The input data are presented in Table S3 (Supplementary material), while the measured and estimated concentrations are presented in Table 3. The model-to-measured concentration ratios were 0.7 and 0.8 in the absence and presence of 60 swimmers, respectively.

Table 3. IH MOD model estimation of TCA levels and reported experimental results in studiesM.

Article name	Nitter and Hirsch Svendsen 2020		Lévesque et al.2015		
Study condition	No swimmer	60 swimmers	ACH = 1	ACH= 1.5	ACH = 2
Reported concentration in the article (mg/m^3)	0.2	0.3	0.5	0.42	0.30
Estimated TCA concentrations (mg/m^3)	0.14	0.25	0.52	0.33	0.27
Model/measured concentration ratio	0.70	0.83	1.05	0.77	0.90

Table 4. IH MOD model estimation of airborne TCA levels in maximum bather load condition.

Swimming *Pool number*	Swimming pool 1	Swimming pool 2	Swimming pool 3	Swimming pool 4
Maximum number of swimmers allowed	160	80	225	424
Estimated TCA concentrations (mg/m^3)	0.23	0.36	0.14	0.37
Maximum number of swimmers TCA< 0.35 mg/m^3	173*	63	398*	335

*: Calculations for swimming pools with estimated TCA concentrations not exceeding 0.35 mg/m^3 are provided solely for the purpose of comparison.

Table 5. TCA concentration under different ventilation system capacity.

	Estimated initial TCA concentrations (mg/m^3)			
Ventilation condition	Swimming Pool 1	Swimming Pool 2	Swimming Pool 3	Swimming Pool 4
Ventilation system with current (100%) capacity	0.17	0.11	0.12	0.28
Ventilation system with 50% capacity at night	0.21	0.34	0.14	0.36
Ventilation system deactivation at night (off)	0.62	0.58	0.52	0.76

In a study conducted by Lévesque et al. (2015), TCA levels were measured in indoor swimming pools under different ventilation configurations categorized as air changes per hour (ACH) ACH $\leq$1, 1 <ACH <2, and ACH $\geq$2 (Lévesque et al. 2015). WMM was employed to estimate the airborne TCA concentration in these three ventilation scenarios. The necessary input data were obtained from the article and are presented in Table S3 (Supplementary material), while the measured and estimated concentrations can be found in Table 3. The model-to-experimental ratios were determined as 1.05, 0.77, and 0.90 for the ACH = 1, ACH = 1.5, and ACH = 2 scenarios, respectively.

TCA concentration estimation under maximum bather loads

Table 4 presents the TCA concentrations estimated using the WMM considering the maximum bather load. The model results demonstrated that in the two swimming pools (swimming pool numbers 2 and 4); full-capacity swimmer attendance would lead to TCA concentrations higher than the recommended level of 0.35 mg/m^3 (British Columbia-Canada). Recalculated concentrations by adjusting the number of swimmers so as not to exceed the recommended limit concentration of 0.35 mg/m^3 gives a maximum of swimmers of 63 and 335 instead of currently 80 and 424 for swimming pools 2 and 4, respectively (Table 4). Likewise, in the case of swimming pools 1 and 3, the maximum capacity for swimmers could be 173 and 398, respectively, compared to the current 160 and 225.

Estimation of TCA concentration under varied ventilation systems (supply/exhaust air rates)

The WMM also allows us to estimate the TCA concentrations under different ventilation configurations. In swimming pool 1, the ventilation system was off during the night. This ventilation strategy was carried out for energy-saving purposes. The WMM could be used to anticipate and quantify the TCA accumulation assuming a stoppage of the ventilation during the night in the four swimming pools.

The estimated airborne TCA levels in the early morning are presented in Table 5, considering modifications to the ventilation system during the nighttime period (6 h). As anticipated, the highest concentrations were observed when the ventilation system was completely stopped throughout the night, reaching 0.62, 0.58, 0.52, and 0.76 mg/m^3 for swimming pools 1, 2, 3, and 4, respectively. It is important to emphasize that there were no swimmers present during the periods when ventilation was deactivated. However, reducing ventilation to 50% resulted in a significant decrease in the anticipated concentrations.

Model predictive performance

Figure 3 displays a scatter plot comparing measured and predicted airborne TCA concentrations in indoor swimming pools. The correlation coefficient is 0.81

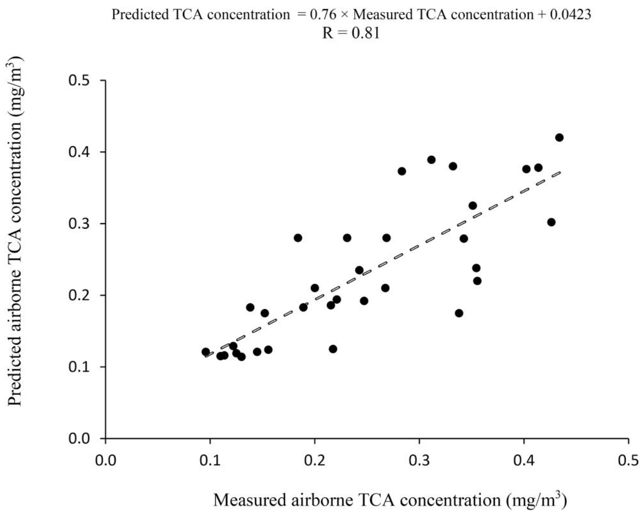

Figure 3. Scatter plot of measured and predicted airborne TCA levels in indoor swimming pools.

and the regression slope is 0.76 with a regression intercept of 0.04. Criteria used to judge the performance of the model according to ASTM criteria are presented in the Supplementary material (Table S5). Overall, ASTM criteria indicate a good agreement between the predicted and measured TCA concentrations. However, a slight underestimation of the model is highlighted by the value of the regression line and the FB criteria.

Discussion

Results demonstrated that the model could be used to estimate and anticipate airborne TCA levels in indoor swimming pools across various scenarios. WMM proves to be a robust and practical choice, providing valuable insights to evaluate and mitigate health risks for workers and swimmers.

The first assumption of the WMM is that the room is perfectly mixed during the modeling. Our study demonstrates that this assumption is acceptable for estimating indoor pool TCA levels for two reasons. First, the concentrations at the three locations (A, B, and C) were similar throughout the study in all four pools (Supplementary material Table S4). Second, TCA measurements carried out at the air extraction point of the ventilation system were similar to those taken at the three sampling points around the pool (Supplementary material Table S4). This consistency confirms that the well-mixed model is suitable for estimating TCA levels.

A second important element of the WMM concerns the estimation of the emission rate. Equations 4 and 5 present a novel approach to estimating the TCA generation rate based on the two film theories. This approach is aligned with previous research. Schmalz et al. utilized an adapted two-film theory method for estimating TCA generation in indoor swimming pools. However, the Schmalz method considers only the influence of the liquid phase in the calculation. This approximation can be done only for substances slightly soluble in water with a high Henry's law constant. Indeed, in these situations, the mass transfer coefficient is primarily controlled by the liquid film resistance, and the rate of mass transfer at the gas-liquid interface is largely determined by how easily these gases can move through the liquid film, rather than their solubility in the liquid (Lyman et al. 1990; Rumble 2017). Overall, whether using the two-film theory (equation 5) or an adapted one-film theory considering only the liquid film resistance, the estimates of TCA flux from water to air for swimming pools will yield similar results, with a generation rate of $1.8 * 10^{-3}$ $g{\cdot}h^{-1}{\cdot}m^{-2}$ and $1.74 * 10^{-3}$ $g{\cdot}h^{-1}{\cdot}m^{-2}$ for Schmalz et al. (2011) and Equation 5, respectively.

By definition, the calculation of the emission rate based on the two-film theory is a conceptual model. However, the subsequent formulation in Equation 5 introduces a coefficient derived from experiments or sampling data, aligning with the empirical model approach. It should be noted that conceptual and empirical frameworks are not mutually exclusive; rather, they are often used synergistically to provide a more comprehensive understanding of a particular subject matter (Bullock et al. 2006). Consequently, the emission rate proposed in equation 5 could be defined as a "postulated" emission factor.

Validation of exposure assessment models involves comparing estimated exposures from the model with the dataset of measurement data (Fransman 2017; Schlüter et al. 2022). A recent review study has revealed that most of the studies using mathematical models were performed in laboratory settings, with only limited utilization of workplace measurements (Abattan et al. 2021). This could indicate a potential bias in validating models under real-world conditions. The present study, conducted in real-world conditions, filled the gaps and emerged as a robust approach.

The model-to-measured concentration ratio is a valuable metric for assessing the accuracy of exposure models. According to the published studies, the acceptable range for this ratio is generally considered to be between 0.5 to 2.0 (Spinazzè et al. 2019; Ramachandran 2022; Schlüter et al. 2022). This range serves as a criterion to evaluate the model's accuracy in predicting actual concentrations. A ratio below 0.5

suggests an underestimation of measured concentrations, which may indicate undetected health risks. Conversely, a ratio above 2.0 indicates an overestimation, potentially leading to unnecessary control measures and resource allocation. Ensuring that the model-to-measured concentration ratio falls within this acceptable range is crucial for reliable predictions of occupational exposure. In our study, we found that the model-to-measured concentration ratio ranged from 0.51 to 1.49, which falls within the acceptable range and suggests the reliability of our model in predicting occupational exposure to TCA in indoor swimming pool environments. Furthermore, the alignment of statistical parameters with the ASTM D5157 standard criteria also demonstrates a strong correspondence between the predicted and measured TCA concentrations.

It should be noted that this study utilized data from 2-hr samples conducted in four indoor swimming pools in the "normal" situation. Estimating worst-case scenarios (maximum number of swimmers present) was done. Indeed, considering the ethical considerations of conducting studies under maximum swimmer numbers or in non-ventilated indoor swimming pool conditions, the implementation of this model emerges as a reliable tool for predicting worst-case TCA concentrations.

Besides, this finding represents a significant advancement in assisting swimming pool managers dealing with elevated airborne TCA levels in evaluating the impact of raising the proportion of fresh air before investing in ventilation system modifications. Such an approach facilitates calculating costs and the prudent selection of the optimal percentage of fresh air. One possible scenario is to upgrade the swimming pool ventilation system to meet the minimum recommendations set by ASHRAE. The ASHRAE standard 62.1 (ASHRAE Applications Handbook section on natatoriums) determined that a minimum of 0.48 cfm/ft (2.4 L/s. m^2) of outdoor air is required in the breathing zone around the water surface (7.6 cm–183 cm above the floor) (ASHRAE 2016). The minimum ventilation rate specified by ASHRAE was intended to ensure acceptable air quality in average swimming pools using chlorine as the primary disinfectant; however, ASHRAE also recommends adjusting these guidelines to account for activity levels and air distribution requirements (Lochner and Wasner 2017).

Although different formulas are used to calculate the maximum number of bathers in indoor swimming pools, they generally yield similar results. The International Swimming Pool and Spa Code and similar regulations recommend a comparable calculation method. According to Quebec regulations, the maximum number of bathers allowed in indoor swimming pools, both on the deck and in the water, should be calculated based on granting 1.4 m^2 of surface area in the shallow area and 2.2 m^2 in the deep area (Government of Quebec 2013). While no specific regulations govern indoor swimming pool air contamination, the primary focus is on regulating temperature (ranging from 23 °C for competition swimming pools to 33 °C for children's pools) and humidity (50% RH in winter and 60% RH in summer). Numerous studies have highlighted the influence of swimmers on airborne DBPs. Our study's estimations indicate that the maximum bather load should be reevaluated to prevent contamination of the swimming pool air by DBPs.

The model demonstrated its capability to predict airborne TCA concentrations in the presence of varying numbers of swimmers. Furthermore, it serves as a valuable tool for predicting exposure levels during specific events, such as competitions, where swimmers are present in large numbers for short durations. Additionally, for swimming pool managers who are hesitant about increasing the performance of the ventilation system and its potential impact on TCA exposure, this tool can effectively predict the effects of such modifications. By providing these predictions, the model assists managers in making informed decisions regarding ventilation system enhancements and ultimately contributes to the overall control of TCA exposure in indoor swimming pool environments.

In this study, the TCA generation rate in indoor swimming pools was calculated and presented. The calculations were conducted under the assumption of constant physio-chemical conditions, specifically temperature and partial pressure. However, it is important to note that further studies are required to refine this equation by incorporating temperature as a variable. Considering the influence of temperature on TCA generation is crucial for a more accurate estimation of airborne TCA levels in different indoor swimming pool environments such as hot tubs and water parks. Future research in this area will contribute to a better understanding of the factors affecting TCA formation and facilitate the development of more precise predictive models.

Finally, we employed a deterministic modeling approach to estimate TCA concentrations. While this deterministic approach served our research objectives by providing the estimates of TCA levels, we acknowledge its limitations in fully presenting the variability and uncertainty present in this complex environment. Probabilistic modeling approaches like Monte Carlo simulations (which are accessible through IH MOD_2_0) could be used to quantitatively account for risk in pool decision-making projects.

Conclusion

In conclusion, this study demonstrates the potential of the WMM as a valuable resource for predicting and estimating airborne TCA concentrations in indoor swimming pools. By utilizing a mathematical model, WMM, and incorporating the number of swimmers, the model provides realistic estimations of TCA concentrations. The comparison between measured and predicted concentrations in various bather load scenarios indicates a reasonable agreement, further supporting the model's reliability. The WMM proves its efficacy in predicting the impact of ventilation system modifications on TCA concentrations, providing valuable insights for control measures and mitigation strategies. These findings highlight the importance of employing modeling techniques to overcome the challenges associated with costly and time-consuming TCA concentration measurements in specialized laboratories. Moreover, this research underscores the significance of real large-scale measurements in indoor swimming pools to validate exposure assessment models and account for the unique complexity and variability of these environments.

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Disclosure statement of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors confirm no conflicts of interest associated with this publication.

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Data availability

The corresponding author can provide the data supporting the findings of this study upon reasonable request.

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