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Variability of residual chlorine in swimming pool water and determination of chlorine consumption for maintaining hygienic safety of bathers with a simple mass balance model

Alvyn P. Berg, Ting-An Fang and Hao L. Tang

ABSTRACT

Trial-and-error chlorination as a conventional practice for swimming pool water disinfection may fail to consistently maintain the pool's residual chlorine within regulatory limits. This study explored the variability of residual chlorine and other common water quality parameters of two sample swimming pools and examined the potential of using a mass balance model for proactive determination of chlorine consumption to better secure the hygienic safety of bathers. A lightly loaded Pool 1 with a normalized bather load of 0.038 bather/m^3/day and a heavily loaded Pool 2 with a normalized bather load of 0.36 bather/m^3/day showed great variances in residual free and combined chlorine control by trial-and-error methods due to dynamic pool uses. A mass balance model based on chemical and physical chlorine consumption mechanisms was found to be statistically valid using field data obtained from Pool 1. The chlorine consumption per capita coefficient was determined to be 4120 mg/bather. The predictive method based on chlorine demand has a potential to be used as a complementary approach to the existing trial-and-error chlorination practices for swimming pool water disinfection. The research is useful for pool maintenance to proactively determine the required chlorine dosage for compliance of pool regulations.

Key words | chlorination, combined chlorine, disinfection, free chlorine, modeling, swimming pool

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INTRODUCTION

Swimming is considered a health-enhancing and relatively injure-free physical activity, and thus attracts people of all ages. In the United States, there are more than 368 million swimming visits each year in public areas, hotels and spas, and private residential homes (Tang *et al.* 2015). It is the fourth most popular recreational activity in the United States and the most popular recreational activity for children and teenagers (US Census Bureau 2012). However, swimming pool hygiene is of critical concern, because contamination brought into pools by bathers introduces biological and chemical health risks. For instance, a total of 81 recreational water–associated outbreaks affecting at least 1,326 persons were reported to Centers for Disease Control and Prevention (CDC) for 2009–2010 (Hlavsa *et al.* 2014). Thus, to conserve the beneficial aspects of this recreational activity, the swimming pool water must be effectively disinfected to prevent outbreaks of infectious illnesses.

Chlorination is the most common disinfection practice for inactivation of microbial pathogens. It typically involves the addition of chlorine in forms of chlorine (Cl_2) gas, calcium hypochlorite ($Ca(ClO)_2$) tablets, or sodium hypochlorite (NaClO) solution. Regardless of the original forms of chlorine, the chemicals dosed into the pools form

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hypochlorous acid (HClO), which dissociates into hydrogen ions (H^+) and hypochlorite ions (ClO^-). The sum of the concentrations of HClO, ClO^-, and aqueous Cl_2 is referred to as free chlorine. The sum of chloramines concentrations formed as a result of chlorine reaction with ammonia nitrogen is referred to as combined chlorine. The concentrations of residual chlorine in swimming pool water can fluctuate significantly, which imposes a problem for pool operation. On one hand, sufficient residual chlorine must be maintained to inactivate pathogens. On the other hand, keeping residual chlorine too high introduces side effects, such as irritant dermatitis and the formation of carcinogenic disinfection by-products at elevated concentrations in pool water (Tang & Xie 2016). To date, regulations on residual chlorine in swimming pool water show great variances in different countries and regions (Schmalz *et al.* 2011; Wang *et al.* 2014; Peng *et al.* 2016). For example, in Canada, regulations in Quebec require free chlorine between 0.8 and 2.0 mg/L (as Cl_2) (Tang *et al.* 2015). In France, the concentration of combined chlorine must not exceed 0.6 mg/L (Cimetiere & De Laat 2014). In the United States, the National Swimming Pool Foundation (NSPF) established free chlorine guidelines of 1 and 5 mg/L as lower and upper limits, respectively, and a combined chlorine guideline of 0.2 mg/L as the upper limit for pools (NSPF 2010). In addition, NSPF defines an ideal free chlorine range of 2–4 mg/L. It is important to note that these guidelines on residual chlorine are routinely exceeded in pools (Bradford 2014). According to CDC, approximately 1 in 10 (10.7% or 12,917 of 120,975) routine pool inspections identified pool disinfectant level violations, and almost 1 in 8 (12.1% or 13,532 of 111,487) routine pool inspections conducted during 2008 reported serious violations that resulted in immediate pool closure (CDC 2010). Thus, maintaining a required residual chlorine concentration in swimming pool water at all times for hygienic safety of bathers is both challenging and necessary, and represents an important area of research.

Operation of swimming pools generally involves constant recirculation of water (at an elevated temperature for heated pools) and unavoidable continual loading of anthropogenic organics from bathers. It is common for many pools to be used for several years before a total water replacement is conducted (Afifi & Blatchley III 2016). Thus, significant chlorine consumption arises from the reactions between chlorine and the bather load, which include sweat, urine, skin particles, hair, microorganisms, cosmetics, and other personal care products (Judd & Bullock 2003). Additionally, chlorine consumption could be promoted by UV exposure for outdoor pools, elevated temperature, and water agitation induced volatilization through an air–water interface (Weng & Blatchley III 2011; Weng *et al.* 2012; Chowdhurry *et al.* 2014). Therefore, the residual chlorine maintaining practice needs to consider the chlorine consumption mechanisms. This is important for compliance of pool regulations, reduction of disinfection byproducts formation, and economization of free chlorine usage.

The current residual chlorine maintaining practices can be classified into manual and automatic chlorine dosing, both of which are based on trial-and-error methods. Manual chlorine dosing is a conventional method for maintaining residual chlorine in small pools such as pools in private residential homes. The amounts of dosed tablet chlorine (i.e. $Ca(ClO)_2$) are empirically determined and the pool can be easily overdosed or insufficiently dosed. Automatic dosing reduces manpower and is more applicable to larger pools. It may use an oxidation-reduction potential (ORP) controller or a digital timer to turn on/off the chlorine dosing pumps. The ORP controller functions by measuring the ORP of the water, comparing it to a manually maintained set point, and adding chlorine if the measured ORP falls below the set point. An ORP controller may cease to control the residual chlorine if an undesirable reaction couple dominates the ORP of the water (Bradford 2014). Automatic feeding of chlorine on a digital timer may also fail during certain periods when the timer is not properly programmed to match the dynamic pool uses. Since the use of trial-and-error methods for residual chlorine control is reactive, it would be desirable to have an unconventional method that can proactively determine the chlorine consumption in swimming pools. This would help in reducing the occurrence of disinfectant level violations and better securing the hygienic safety of bathers. The objectives of this research, therefore, were to explore the variability of residual chlorine in swimming pools with different loads of bathers, and to present a method that can proactively determine the chlorine consumption in response to dynamic pool uses. Specifically, the study would employ a simple mass balance model to reflect the chlorine consumption mechanisms in swimming pools, and to obtain the model coefficients based on the field data. The research would improve existing understanding about chlorine consumption in swimming pools and help pool management determine required chlorine for compliance of pool regulations.

MATERIALS AND METHODS

Swimming pools under investigation

Two sample swimming pools in Indiana, Pennsylvania were selected for the investigation. Both pools were indoor heated pools and similar water temperatures (28.6 °C for Pool 1 and 29.8 °C for Pool 2 on average) were maintained throughout the experimental period. In addition, they had similar water ages, since the total water replacement had not been conducted for approximately one year. The notable differences of the two pools were the size, bather load and the chlorine dosing method. A description of the two pools is summarized in Table 1. Pool 1 contained 901 m^3 of water while the size of Pool 2 (492 m^3) was 55% of Pool 1. Pool 2, however, was heavily loaded with an average of 179 admitted bathers every day, which was approximately five times more than Pool 1. For the chlorine dosing method, Pool 1 used automatic dosing with an ORP controller (Hayward Model CAT 4000, Hayward Pool Products, New Jersey, USA) while Pool 2 used automatic dosing with a digital timer.

Figure 1 shows the schematic flow diagrams of the two pools. The recirculation waters (2 m^3/h) were both continuously filtered by diatomaceous earth pool filters, which can trap particles down to 3–5 μm. To compensate for the water loss during the pools' operation, make-up water was added to both pools periodically at 1.9 and 1.7% (estimations on daily basis), respectively. Pool 1 used tablet chlorine which was initially dissolved by the recirculating pool water with an Accu-Tab chlorination system (Axiall Corporation, Georgia, USA). The chlorine tablets, weighing 330 g each, were commercially available Accu-Tab blue calcium hypochlorite tablets with minimum 65% available chlorine.

Table 1 | Description of two heated indoor swimming pools under investigation

Parameter	Unit	Pool 1	Pool 2
Chlorinator		Automatic dosing with ORP control	Automatic dosing with digital timer control
Stock chlorine		Calcium hypochlorite tablets with 65% active ingredient	12.5% sodium hypochlorite solution
Pool size	m^3	901	492
Average daily bathers[a]		34	179
Total water change		Approx. 1 year	Approx. 1 year
Make-up water %	day^{-1}	1.9%	1.7%
Water temperature[a]	°C	28.6	29.8
Conductivity[a]	μS/cm	1128	7102
pH[a]		7.56	7.30
Alkalinity[a]	mg/L as $CaCO_3$	70	36
Free chlorine[a]	mg/L as Cl_2	2.43	1.35
Combined chlorine[a]	mg/L as Cl_2	0.57	1.19
Chloride[a]	mg/L	119	789
Nitrate[a]	mg/L	3.8	4.2

[a] Data presented are averages of samples analyzed during the 8-week investigation period.

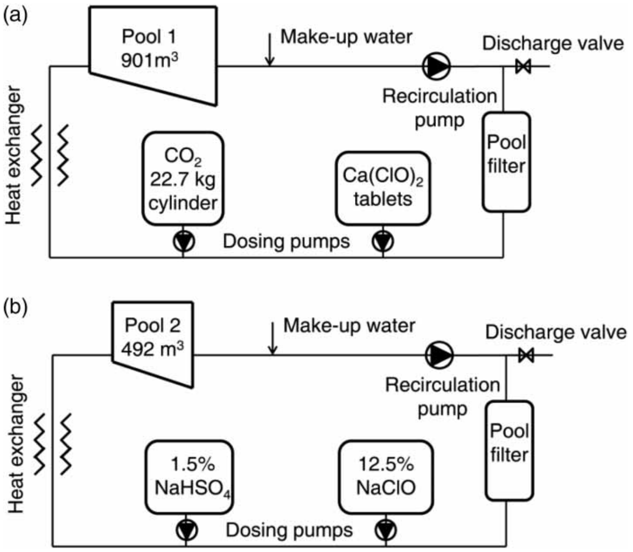

Figure 1 | Schematic flow diagrams of two heated indoor swimming pools (a) Pool 1 with automatic chemical dosing on an ORP controller, and (b) Pool 2 with automatic chemical dosing on a digital timer.

The application of ORP controller resulted in a tablet consumption rate of 36 tablets per month. The controller also regulated the dosing of CO_2 for pH control with a pH sensor, which depleted a 22.7 kg CO_2 gas cylinder every week. The set points of the controller were 7.5 pH and 650 mV ORP. Pool 2 used liquid chlorine at a NaClO concentration of 12.5%. A peristaltic metering pump (Stenner Pumps Model 85M5, Stenner Pump Company, Florida, USA) was operated on programmed cycles of 15 min on and 45 min relaxation for chlorine dosing, while the flow rates were adjustable from 16 to 322 liters per day by the pool maintenance staff. In addition, Pool 2 used a 1.5% sodium bisulfate ($NaHSO_4$) solution for pH control.

The sampling program

The study employed an 8-week comprehensive pool water sampling program in the summer of 2018. Grab water samples were taken from the same location and same depth near the surface of each pool on daily basis. Free chlorine and total chlorine were measured with the *N,N*-diethyl-*p*-phenylenediamine (DPD) method by a Hach DR/890 portable colorimeter (Hach Company, Colorado, USA). Combined chlorine was determined by the difference of the measured free and total chlorine. Chloride, pH, and conductivity were measured with Vernier chloride, pH, and conductivity probes (Vernier Software & Technology LLC, Oregon, USA), respectively. Nitrate was measured with a cadmium reduction method with the Hach DR/890 portable colorimeter. Alkalinity was measured with EPA method 310.1. The average values of these parameters are presented in Table 1. Considering that the number of bathers and chlorine residuals may vary substantially during a day, the 8-week comprehensive sampling program included the number of hours that had elapsed between any two samplings to increase the time accuracy by recording the exact time of each sampling event. Accurate bather counts during these periods were obtained from the pool management staff who kept a detailed log of daily admission.

Modeling

A statistical modeling approach was employed to simulate the variability of residual free chlorine. Of the 56 data sets (8 weeks × 7 days per week × 1 sample per day), 70% was chosen to initiate the regression with SigmaPlot (Systat Software Inc, Illinois, USA) and the remaining 30% was used to validate the corresponding regression results based on statistical requirements (Tang *et al.* 2011). The regression was based on a simple mass balance model (Equation (1)) that was used to describe the presence of chlorine in pool water:

$$\text{Chlorine Accumulation} = \text{Chlorine In} - \text{Chlorine Out} - \text{Chlorine Reacted} \quad (1)$$

The statistical modeling process examined the *p*-value of any not-yet-determined coefficient to test the hypothesis that the model coefficient was significantly different from zero, and the null hypothesis can be rejected if the *p*-value was less than 0.05. The Durbin–Watson statistic, a measure of serial correlation between the residuals, was used to test residuals for their independence of each other. If the residuals were not correlated when the independent variable was time, and the deviation between the observation and the regression line at one time were not related to the deviation at the previous time, the Durbin–Watson statistic would be 2. In addition, constant variance tests were performed by computing the Spearman rank correlation between the absolute values of the residuals and the observed value of the dependent variable. When this correlation was significant, the constant variance assumption may be violated, indicating a different model (i.e. one that more closely follows the pattern of the data) may be used, or a transformation of one or more of the independent variables may be used to stabilize the variance. Furthermore, the coefficient of determination (R^2) was used to measure how well the model described the data. An R^2 of one indicates that all the variability of dependent variables is addressed. The closer R^2 is to one, the better the model predicts the dependent variable.

RESULTS AND DISCUSSION

Variability of water quality in the lightly loaded pool 1 with ORP controlled chlorine dosing

The number of daily admitted bathers in Pool 1 ranged from 0 to 350 with an arithmetic mean of 34 and a standard deviation of 58 (Figure 2(a)). The normalized bather load (the average daily admitted bathers divided by the pool size) was 0.038 bather/m^3/day. The pool was open to trainers and competition teams when the school was in session. During the summer months when the research was conducted, it accepted users of all ages from kids' basketball camps to university students to senior citizen aqua aerobics. It featured diurnal and weekly variations, since Tuesday and Thursday swim sessions only occurred in the mornings while the pool uses were generally lower than Monday, Wednesday, and Friday, and there was generally no swim on weekends. Under these scenarios, the pH and conductivity patterns demonstrated a trend of slight increase as shown in Figure 2(b). Note that a pH below 7.2 may cause damage to the filtration components and pool surface as well as bather discomfort due to corrosive water, while a pH above 7.8 may cause cloudy water, inefficient use of sanitizer, bather discomfort, and scaling on the pool surface, pipes, and filtration components. In addition, the correlation between pH and disinfection by-products formation

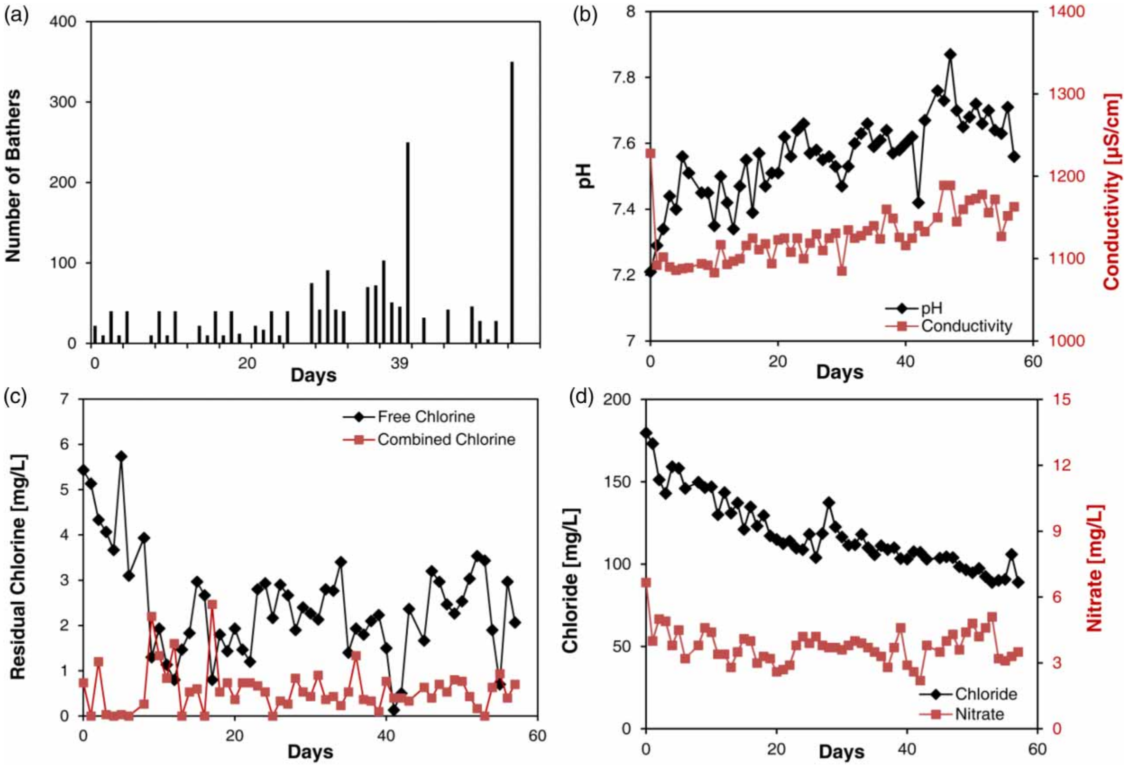

Figure 2 | Variability of common pool water quality parameters in Pool 1 with (a) number of admitted bathers on daily basis; (b) pH and conductivity values; (c) residual free and combined chlorine; and (d) chloride and nitrate concentrations.

in swimming pool water has been reported (Hansen *et al.* 2013). The study revealed that pH was largely maintained in an optimum range with an average pH of 7.56 in Pool 1. The slight increasing trend of conductivity could be ascribed to the release of ionizable amino acids and other anthropogenic substances from bathers.

With ORP controlled chlorine dosing, the residual free chlorine fluctuated between 0.13 and 5.73 mg/L (as Cl_2) with an arithmetic mean of 2.43 and a standard deviation of 1.16 (Figure 2(c)). There were a total of 29 out of 56 data points (52%) in the optimum free chlorine range of 2–4 mg/L and 48 out of 56 data points (86%) in compliance with the NSFP limit between 1 and 5 mg/L. The residual combined chlorine fluctuated between 0 and 2.47 mg/L (as Cl_2) with an arithmetic mean of 0.57 and a standard deviation of 0.50. There were a total of 11 out of 56 data points (20%) in compliance with the NSPF limit of 0.2 mg/L and 34 out of 56 data points (61%) in compliance with the French pool limit of 0.6 mg/L. These results indicated that there was certainly room to improve the trial-and-error chlorination method, reduce the fluctuations of residual chlorine, and better maintain the hygienic safety of bathers in Pool 1. In addition to residual chlorine, chloride and nitrate are generally considered as indicators of pool water quality, as they have a potential to accumulate in pool water (E *et al.* 2016). However, such accumulations were not observed during the 8-week frame of investigation period in Pool 1. The chloride concentration decreased steadily from 180 to 89 mg/L, and the nitrate concentration fluctuated around an approximate baseline of 3.8 mg/L (Figure 2(d)). The non-accumulation of chloride and nitrate could be ascribed to the partial water replacement as a result of daily make-up water addition. The input or exchange of pool water with fresh water during the investigation period controlled the accumulation of stable ions well.

Variability of water quality in the heavily loaded pool 2 with timer controlled chlorine dosing

The number of daily admitted bathers in Pool 2 ranged from 0 to 318 with an arithmetic mean of 179 and a standard deviation of 94 (Figure 3(a)). The normalized bather load was 0.36 bather/m^3/day, which was approximately 10 times higher than that of the lightly loaded Pool 1. The pool was open to the general public with pool membership or daily passes. The bathers also showed a weekly pattern, as the pool visits on weekends were generally less than weekdays. Figure 3(b) shows the pH and conductivity significantly increased under the high loading scenario. The pH had increased from 7.0 to the optimum range around 7.5 as the 8-week sampling program approached the end, since the pool maintenance staff strived to maintain the pool water quality by manually adjusting the feed rate of dosing pumps. Water cloudiness was often observed, indicating the deterioration of water quality as Pool 2 continuously accepted bathers. The conductivity increased from a level of 6700 to 7500 μS/cm as a result of anthropogenic ionizable substances released from bathers.

With timer controlled chlorine dosing, the residual free chlorine fluctuated between 0.03 and 5.40 mg/L (as Cl_2) with an arithmetic mean of 1.35 and a standard deviation of 1.16 (Figure 3(c)). There were a total of 8 out of 56 data points (14%) in the optimum free chlorine range of 2–4 mg/L and 28 out of 56 data points (50%) in compliance with the NSFP limit between 1 and 5 mg/L. The residual combined chlorine fluctuated between 0 and 1.67 mg/L (as Cl_2) with an arithmetic mean of 1.19 and a standard deviation of 0.35. There were a total of 2 out of 56 data points (4%) in compliance with NSPF limit of 0.2 mg/L and 3 out of 56 data points (5%) in compliance with the French pool limit of 0.6 mg/L. The results indicated the chlorine maintenance practice on Pool 2 was unsatisfactory due to the significant numbers of limit violations. Although the pool maintenance staff periodically adjusted the feed rate of the chlorine dosing pump to higher settings as soon as the water turned cloudy and the free chlorine became low, there was an approximate waiting period of 24 hours for complete water mixing and recovery of residual chlorine level. Overdoses and insufficient doses were frequently observed in this scenario, which increased the health risks of bathers. Improvements in residual chlorine maintenance practices were therefore needed. Similar to Pool 1, the accumulations of chloride and nitrate were not observed during the 8-week frame of investigation period in Pool 2, due to the contribution of partial water replacement. The chloride concentration decreased steadily from a level of 1200 to 650 mg/L, and the nitrate concentration fluctuated around an approximate baseline of 4.2 mg/L (Figure 3(d)).

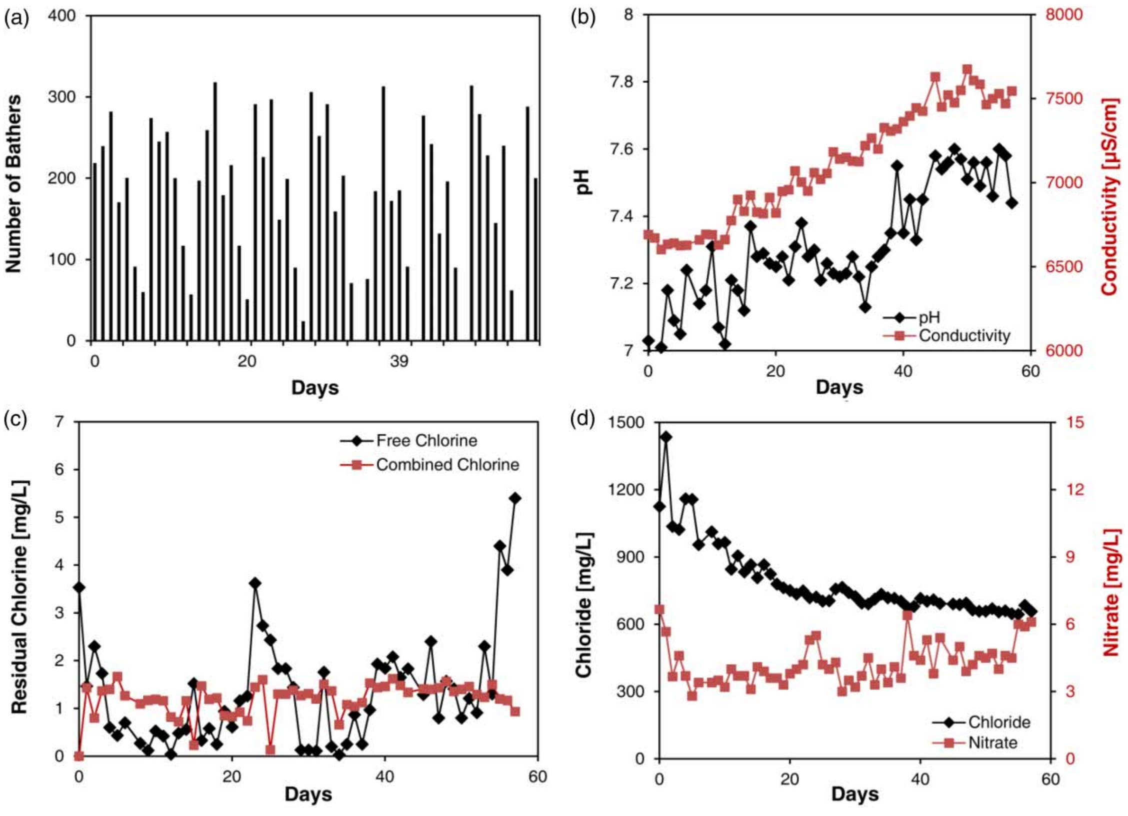

Figure 3 | Variability of common pool water quality parameters in Pool 2 with (a) number of admitted bathers on daily basis; (b) pH and conductivity values; (c) residual free and combined chlorine; and (d) chloride and nitrate concentrations.

The chlorine mass balance model development

The study of variability in the above two sections has implied the limitations of reactive trial-and-error methods in maintaining the residual chlorine in optimum ranges and determining the required chlorine dosage for pool water. In this section, we explore the possibility of using a simple chlorine mass balance model for such purposes. The model should consider the daily number of bathers so that it could proactively respond to dynamic pool uses. The processes that influence the chlorine concentrations in pool water include: (1) addition of new chlorine from an external source; (2) consumption of chlorine through chemical reactions with nitrogenous and other anthropogenic pollutants from bathers (Wojtowicz 2001); and (3) natural loss of chlorine physically through partial water replacement and water agitation induced volatilization by bathers. An example of the second process was the reaction between chlorine and urea, a final product of protein metabolism and the main nitrogenous compound introduced by bathers. Urea has been found to react with chlorine slowly and has large free chlorine demand (De Laat *et al.* 2011). In the simple mass balance model, we interpreted the term '*Chlorine Reacted*' as a combination of the second and third processes, which included both chemical and physical changes to the chlorine. Since both the second and third processes were found to be correlated with number of bathers (Dyck *et al.* 2011; Florentin *et al.* 2011), we used $k \times n$ to describe the overall free chlorine consumption by the second and third processes, where k was the per capita free chlorine consumption rate constant in mg Cl_2/bather and n was the number of bathers on any given day. Additionally, the term '*Chlorine Out*' was neglected, considering there were no apparent water discharges from the pools. Therefore, Equation (1) became:

$$\Delta Cl_2 = a - kn \tag{2}$$

where ΔCl_2 was the change in free chlorine amount in mg Cl_2 and a was the added free chlorine amount in mg Cl_2. The free chlorine change (ΔCl_2) was determined by the difference in residual free chlorine between any two closest sampling events. The chlorine addition (a) was determined by the flow rate of chlorine dosing pump and the concentration of chlorine stock solution maintained by the pool management staff. Since the recirculation pumps of the two pools operated at flow rates of 2 m^3/min, it took no more than 7.5 hours to have the pools well mixed. Considering the mixing (equilibrium) time of 7.5 hours was well below the time differences of any closest two sampling events on daily basis (which were above 20 hours), development of a simple mass balance model was not limited by the time it took to reach equilibrium after chlorine addition. The sampling program was designed in such a way that development of a mass balance model is possible.

The k value was the only not-yet-determined coefficient of the mass balance model while all other parameters were obtained experimentally from this research. The statistical modeling process with 70% of the field data returned with different k values for the two pools as shown in Table 2. Pool 1 was found to have a lower k value (4120 mg Cl_2/bather) compared to Pool 2 (11,030 mg Cl_2/bather), suggesting the chlorine consumption coefficient by bathers may vary across different pools. Judd & Black (2000) reported a specific chlorine demand of 2800 mg Cl_2/bather through bench scale trials using simulated pool water with body fluid analogues. The value was lower than the obtained model coefficients in this study, which could be ascribed to the real pool water scenarios and the regression with combined chemical and physical chlorine consumption mechanisms. The results of statistics tests are also included in Table 2. The p-values were less than 0.05, indicating k was significantly different from zero and was statistically valid to be listed as a model coefficient. Modeling with field data from Pool 1 passed the Durbin–Watson test, indicating the residuals were not correlated with time. Additionally, it passed the constant variance test, suggesting the default constant variance assumption was statistically valid. On the other hand, Pool 2 failed both of the above-mentioned statistics tests. A possible explanation was that the simple mass balance model was able to describe chlorination scenarios in a pool with sufficient residual free chlorine only. Since Pool 2 was heavily loaded with bathers while insufficiently chlorinated most of the time, the obtained free chlorine consumption data in this study could not accurately represent the actual potential of free chlorine demand of the water.

Table 2 | Chlorine consumption per capita coefficient (k) of the two pools determined by the simple mass balance model

Pool	Coefficient *k*	*p*-value	Durbin–Watson statistic	Constant variance test
Pool 1	4120	0.0422	2.0469 (Passed)	$p = 0.1295$ (Passed)
Pool 2	11030	<0.0001	1.1210 (Failed)	$p < 0.0001$ (Failed)

Prediction of residual free chlorine with the mass balance model

While the mass balance model was used to predict the residual free chlorine in Pool 1 on a daily basis, it was found that the model was able to capture the rising and declining trends of free chlorine concentrations well (Figure 4(a)). To compare the actual and predicted residual free chlorine data in further detail, graphical analyses of regression and verification results were employed. As shown in Figures 4(b) and 4(c), the 45° lines depicted the hypothetic free chlorine predictions that were precisely equal to the actual values. The R^2 values were calculated between the predicted data and the 45° lines. Both the regression R^2 and verification R^2 values were greater than 0.97, demonstrating that the mass balance model provided a good fit to the actual chlorine data. The results suggest that it is possible to proactively determine the chlorine dosage with the mass balance model based on the predictive number of bathers and the chlorine consumption per capita coefficient. This is complementary to the existing trial-and-error chlorination practices, which are reactive and sometimes fail in maintaining residual chlorine within regulatory limits. The pros and cons of trial-and-error and predictive chlorination practices are summarized in Table 3. Despite the beneficial aspects of the predictive chlorination method, in order to achieve better disinfection of pool water for the hygienic safety of bathers, good projection on the daily number of bathers and use of a sound chlorine consumption per capita coefficient are needed.

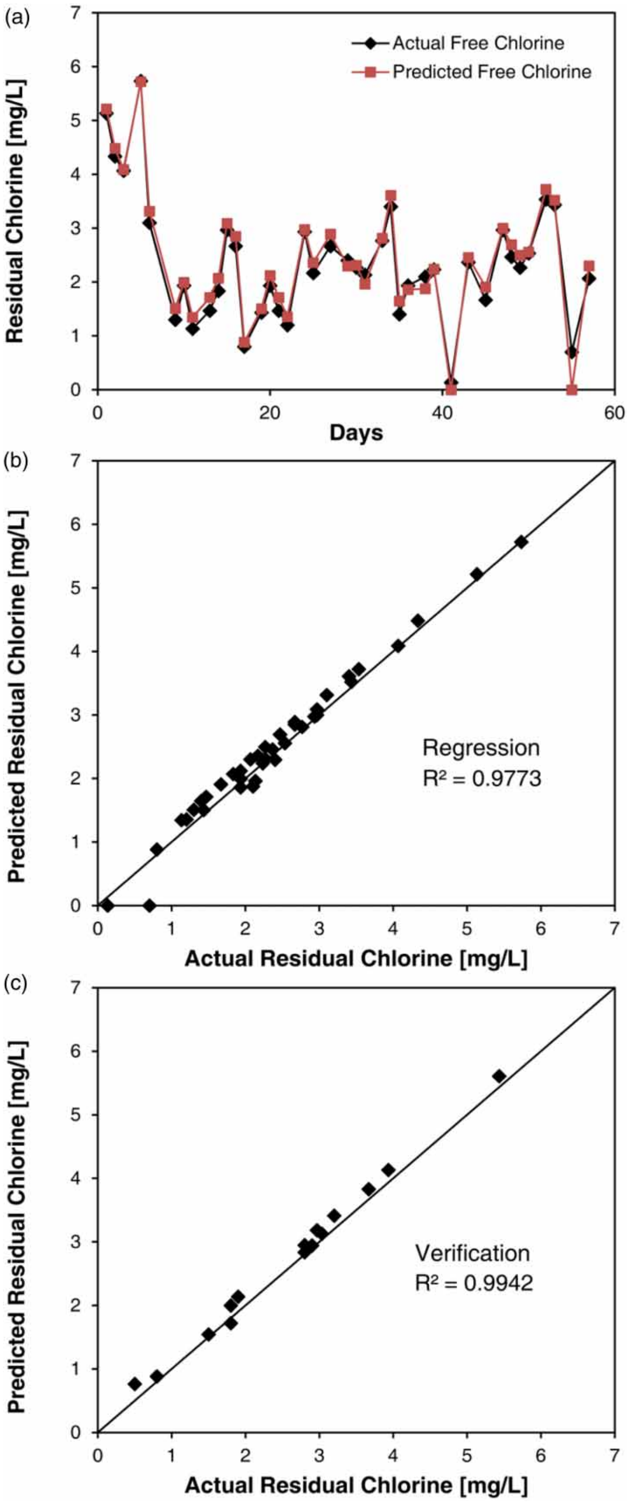

Figure 4 | Comparison of actual and model predicted residual free chlorine in Pool 1: (a) Time series comparison, (b) Regression R^2 with 70% field data, and (c) Verification R^2 with 30% remaining field data.

Table 3 | Pros and cons of trial-and-error and predictive chlorination practices

Chlorination practice	Pros	Cons
Manual, dynamic feed on experience	Less costly	For small pools only; difficult to maintain residual chlorine
Automatic, dynamic feed on ORP controller	Less manpower	May fail to maintain residual chlorine at all times
Automatic, dynamic feed on timer	Less manpower	May fail to maintain residual chlorine at all times
Predictive, dynamic feed on chlorine demand	For both small and large pools; easy to maintain residual chlorine	Requires projections on the daily number of bathers and use of a sound chlorine consumption per capita coefficient

CONCLUSIONS

This study explored the variability of residual chlorine and other common water quality parameters in two sample swimming pools and examined the potential of using a mass balance model for proactive determination of chlorine consumption in pool water. The ORP controlled lightly loaded Pool 1 with a normalized bather load of 0.038 bather/m^3/day and the timer controlled heavily loaded Pool 2 with a normalized bather load of 0.36 bather/m^3/day were both found to have flaws in maintaining the residual chlorine within the regulatory limits, suggesting a need for improvement in chlorination practices due to dynamic pool uses. A mass balance model based on chemical and physical chlorine consumption mechanisms was found to be statistically valid using field data obtained from Pool 1. The chlorine consumption per capita coefficient was determined to be 4120 mg/bather. The model predictions were able to catch the rising and declining trends of residual free chlorine well and had high regression and verification R^2 values. Thus, the model has potential to be used as a complementary approach to the existing trial-and-error chlorination methods for swimming pool water disinfection. The research is useful for pool maintenance to proactively determine the required chlorine dosage for compliance of pool regulations.

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