Comparative study of fecal bacterial decay models for the simulation of plumes of submarine sewage outfalls

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ABSTRACT

In the literature, analytical models have been shown to be extremely useful for estimating the decay rates of coliform as fecal indicator microorganisms, providing reliable predictions of bathing conditions in coastal and continental waters. Although a number of different formulations have been developed in the literature, each one may only be suitable for specific environments, and no comparison between these methods has ever been carried out. In the present article, a comparative analysis of bacterial decay models, calculated by eight different formulations, was performed in coastal outfall plumes, considering identical environmental conditions of solar radiation, temperature and salinity. A statistical approach was applied to identify the differences in means and in behaviors of the results obtained in the various simulations. The results indicate good agreement between bacterial decay rates calculated with at least four methods that were considered more reliable, and at least one of the models was shown to be suitable for estimating bacterial decay rates under nighttime conditions, considering only the combined influences of temperature and salinity. Moreover, under daytime conditions, it provides consistent decay rates when compared with measurements taken in the field.

Key words | coliform, die-off kinetics, modeling, salinity, solar radiation

INTRODUCTION

Fecal bacteria originating from human and animal feces disposed of in the aquatic environment, whether treated or not (George et al. 2002), constitute important sources for environmental contamination of the aquatic environment (Faust 1976; Weiskel et al. 1996). In the Achères wastewater treatment plant (Ile de France) the efficiency of the treatment is elevated, varying between 44.54 and 93.19%, depending on the season (George et al. 2002). However, the treated waters present coliform concentrations as high as $2.47 \times 10^7$ most probable number (MPN) 100 mL$^{-1}$ (average), much higher than the 500 MPN 100 mL$^{-1}$ established for coastal water by the European Union regulations (European Union 2006). In seawater, the behavior of fecal bacteria depends on several processes related to their physiologic characteristics, and their survival in aquatic systems is affected by both biotic and abiotic factors. Biotic factors such as grazing and abiotic factors such as solar radiation, water salinity and temperature, oxygen availability, sedimentation rates, pH and nutrient levels (Sinton et al. 1999; Muela et al. 2008) may induce growth or decay of the fecal bacteria. Among these factors, the effects of solar radiation and salinity levels are particularly important in the inactivation of Escherichia coli and the survival of the bacteria, interfering with DNA replication and the amino acids synthesis regulation (Sinton et al. 1999; Chandran & Mohamed-Hatha 2005). Studies on the kinetics of plasmolysis and deplasmolysis of suspensions of Escherichia coli cells, in response to osmotic stress (salinity), have been carried out and probably will clarify osmotic resistance and consequent survival in the aquatic environment (Hubert et al. 2005; Xu et al. 2010). This survival in freshwater and in
The marine environment can vary, from some minutes to several days, according to the environmental conditions and the bacteria’s ability to make changes in the morphology and physiology of their own cells.

Submarine outfalls have been employed to dispose of urban effluents, due to the high capacity for dilution and decay of organic matter in the open ocean. However, the environmental impact evaluation of these facilities in coastal areas relies heavily on bacterial decay kinetics that have been studied by several laboratories worldwide carrying out in situ and in vitro studies. Even though it is a complex task, due to the inter-relationship between environmental factors, over the past years some authors have been able to establish mathematical relations between bacterial decay and variations in salinity, temperature, solar radiation and grazing.

In the present work fecal indicator bacteria decays were determined and compared using various formulations presented in the literature, under identical environmental conditions. The use of real field data allowed the evaluation of the application of each method with respect to varying environmental conditions.

**COLIFORM BACTERIA DECAY KINETICS**

Coliform bacteria are used to indicate the sanitary quality of water. As stated above, once outside the intestines of humans or other warm-blooded animals, the bacteria population reaches a more hostile environment and starts to die off. The reduction in initial concentration of bacteria is driven by a combination of factors, such as initial dilution, dispersion (as in conservative behavior), and decay, which contribute to the non-conservative behavior of coliform bacteria. Neglecting the diffusive and advective terms of the mass conservation equation, it reduces to:

\[
\frac{\partial C}{\partial t} = kC
\]

(1)

By integrating and solving the above equation a first-order decay equation is obtained, where \( C \) = time concentration; \( C_0 \) = initial concentration; \( k \) = bacterial decay rate and \( t \) = time:

\[
C = C_0 e^{-kt}
\]

(2)

In numerical modeling studies the decay rates \( k \) are also expressed by the parameter \( T_{90} \), which corresponds to the time required to reduce the bacterial population by 90% of its original amount. In this case the previous equation can be written as:

\[
0.1 C_0 = C_0 e^{-kT_{90}} \quad T_{90} = \frac{2.3}{k}
\]

(3)

Many factors including solar radiation (photo-oxidation), temperature, salinity, sedimentation and predation affect this decay rate. UV photo-oxidation is the most important agent in causing the mortality of bacteria. The mechanism of damage induced by solar radiation was thoroughly studied by Chamberlin & Mitchell (1978).

**EFFECTS OF SOLAR RADIATION ON OUTFALL PLUMES**

Considering that the proposal of this study was to predict bacterial decay rates in waste-field formation by ocean outfalls, some simplifications were made.

For the purpose of comparing different models, estimates of solar radiation that reaches the earth’s surface were calculated with the formulations presented by Martin et al. (1999), which consider the effects of latitude, season of the year, hour of the day, cloud cover, and concentration of suspended particles.

Assuming solar radiation is the main input parameter of bacterial decay models, it is necessary to establish its intensity according to plume depth as illustrated in Figure 1.
There is an exponential light extinction with depth, given by:

\[ I = I_0 \exp(-K_e Z) \]  

(4)

where \( I \) = solar radiation at depth \( Z \); \( I_0 \) = solar radiation on the water surface; \( K_e \) = light extinction coefficient (m\(^{-1}\)).

According to Carvalho et al. (2006), it is difficult to precisely evaluate the light extinction coefficient \( (K_e) \) in the water column, because it varies considerably with the density of organisms and suspended and dissolved materials. In order to obtain a rough estimate of the light extinction coefficient, Secchi depth can be used, considering that this parameter is routinely obtained in oceanographic surveys for primary productivity studies. The light extinction coefficient \( K_e \) was calculated by:

\[ K_e = \frac{1.8}{Z_s} \]  

(5)

where \( Z_s \) is the Secchi depth.

Assuming that the effluent plume is uniformly mixed across its entire thickness \( H \) (Figure 1), the average solar radiation within the plume (\( \bar{I} \)) was adopted. Integrating Equation (4), which represents the light intensity at any point inside the plume, we obtain:

\[ \bar{I} = \frac{I_0}{HK_p} \left[ 1 - e^{-K_pH} \right] \]  

(6)

where \( \bar{I} \) is the average solar radiation within the plume (MJ m\(^{-2}\)), \( K_p \) is the light extinction along the thickness of the plume (m\(^{-1}\)), \( I_{TP} \) is the solar radiation at the top of the plume and is given by:

\[ I_{TP} = I_0 e^{-K_e Z} \]  

(7)

By replacing \( I_{TP} \) in the previous equation, we obtain the average solar radiation between the top and the bottom of the plume situated at any depth:

\[ \bar{I} = \frac{I_0}{HK_p} e^{-K_e Z} \left[ 1 - e^{-K_pH} \right] \]  

(8)

**DESCRIPTION OF COLIFORM BACTERIAL DECAY MODELS**

According to Christoulas & Andreadakis (1995) the use of coliform as an index of the degree of pathogenicity of water had been questioned because some viruses have greater resistance than coliforms to a variety of environmental conditions. However, viral infections have seldom been identified in waters presenting colimetry lower than specifications of regulations. The reduction in coliform concentration from \( 10^8 \) MPN 100 mL\(^{-1}\) in unmixed sewage to \( 10^2 \) MPN 100 mL\(^{-1}\) in bathing waters is sufficient to reduce the number of pathogens to levels below the epidemiological limit of infection. Thus, the use of coliform remains suitable, constituting a practical basis for the design of ocean disposal systems (Christoulas & Andreadakis 1995).

In the sequence, a comparative analysis of the coliform bacterial decay models is presented. All equations consider the average light intensity within the plume.

**Model proposed by Bellair et al. (1977)**

Bellair et al. (1977) determined fecal coliform (FC) decay rates based on field studies, carried out in coastal waters of Sydney, Australia. In their work, \( T_{90} \) values varied significantly throughout the day, from a maximum of 40 h during the night-time to 1.9 h just before noon. The relationship obtained between \( T_{90} \) values and solar radiation, was given by:

\[ T_{90} = 3.4 \bar{I}^{-0.42} \]  

(9)

where \( \bar{I} \) represents the average solar radiation within the plume (MJ m\(^{-2}\)), and the \( T_{90} \) value is given in hours.

The experiments varied from dark to sunlight and overcast conditions with water temperature range of 18.5–26 °C. No mathematical relationships were established between decay rates, salinity and temperature variations during the night-time. However, in these conditions, field experiments showed \( T_{90} \) values of around 40 h for temperature ranges between 18 and 26 °C.

**Model proposed by Chamberlin & Mitchell (1978)**

Chamberlin & Mitchell (1978), based on field studies under sunlight conditions, proposed a model that assumed that the coliform bacterial decay rate in aquatic environments is directly proportional to the light intensity, which decreases exponentially with depth. That rate was given by:

\[ k = k_1 \bar{I} \]  

(10)

where \( k_1 \) is the empirical coefficient of proportionality, which constitutes the light sensitivity to photo-oxidation.
of a specific organism (cm² cal⁻¹), and \( J \) is the average solar radiation within the plume (cal cm⁻² h⁻¹), as established in Equation (8). Chamberlin & Mitchell (1978) presented proportionality coefficients for various organisms. Foxworthy & Kneeling (1969) and Gameson & Gould (1975) carried out light sensitivity experiments for the coliform group and, based on the concept of \( k_0 \), it can be concluded that a representative value is 0.320 cm² cal⁻¹.

No relationships between decay rates and salinity or temperature variations were presented. Although Chamberlin & Mitchell (1978) recognized that only a few field studies had been done until the end of the seventies, they speculated that the isolated action of other factors on decay rates of fecal indicator bacteria may also be important. As expected, in dark conditions a sudden decrease in bacterial decay was observed, and under these conditions factors such as temperature, salinity and predation have greater influence on the mortality of these bacteria.

Model proposed by Mancini (1978)

In order to measure the effect of other factors associated with solar radiation, Mancini (1978) developed a formulation that considers the combined effects of light, percentage of seawater, and temperature on the decay of coliform bacteria, based on data from laboratory and field experiments with both fresh and seawater systems. The bacterial die-off rate proposed by this author was given by:

\[
k = [0.8 + 0.006 \times (\% \text{seawater})] \times 1.07^{(T - 20)} + J \]  

(11)

In this equation salinity (\%seawater) is shown in relation to a standard salinity of 35 (i.e. 34 corresponds to 97.14% seawater), \( T \) is the temperature given in °C and \( J \) is the average solar radiation within the plume, given in cal cm⁻² h⁻¹, as established in Equation (8). This formulation was based on dark or light conditions. There are no explicit references to solar radiation levels. Temperature and \%seawater ranges were respectively 5–30 °C and 0–100%.

Model proposed by Šolić & Krstulović (1992)

The study presented by Šolić & Krstulović (1992) considers the interaction between environmental factors and FC decay. The FC decay rates in marine waters are presented as a result of the isolated action of temperature and the combined effects of solar radiation and temperature.

- Temperature (\( T \)): The isolated effect of the temperature was evaluated in field studies, showing that this parameter has a minor role in the survival of FC in the marine environment. However, the authors observed an exponential decrease of the initial concentration of FC with temperature increase. According to field experiments, these authors obtained the following relation between FC decay rate and temperature in °C:

\[
T_{90} = \exp(5.93 - 0.0837T)
\]  

(12)

- Solar radiation and temperature: Temperature exerts little influence on FC decay rates in the marine environment when it acts together with solar radiation. Furthermore, the associated action of these factors contributes synergistically to the FC die-off.

The determination of \( T_{90} \) (in hours) as a function of temperature (in °C), and solar radiation (in W m⁻²), is given by the following equation:

\[
T_{90} = \exp(3.985 - 0.00432R_S - 0.0187T)
\]  

(13)

The range of temperature and solar radiation used in determination of these equations were respectively 14.5–24.9 °C and 510–830 W m⁻².

Model proposed by Canteras et al. (1995)

These authors studied the influence of salinity, temperature and solar radiation on the decay of coliform bacteria through laboratory experiments and subsequent comparison with field measurements. The range of these parameters was 8.5–45, 18–42 °C and 0–960 W m⁻², respectively. Considering the decay rate (\( k \)) as a result of the simultaneous action of salinity, temperature and solar radiation, they developed the following equation:

\[
k = 2.533 \times 1.04^{(T - 20)} \times 1.012^S + 0.113J
\]  

(14)

where \( k \) is expressed in h⁻¹ (which can be converted from \( T_{90} \) applying Equation (3)), temperature (\( T \)) in °C, salinity (\( S \)), and the average solar radiation along the thickness of the plume (\( J \)) in W m⁻², as expressed in Equation (8). Under dark conditions decay rates showed a linear behavior in relation to temperature variations.
Model proposed by Sarikaya & Saatçi (1995)

Sarikaya & Saatçi (1995) carried out experiments in the laboratory with artificial and pollution-free seawater, under controlled environmental conditions. The range of temperature and solar radiation in the experiments was 20–40 °C and 2–50 cal cm⁻² h⁻¹, respectively.

The decay rate in h⁻¹ for intensities above 10 cal cm⁻¹ is given by:

\[ k_L = -0.3566 + 0.0789I \tag{15} \]

For radiation values below 10 cal cm⁻¹, the following relation applies:

\[ k_L = -0.06 + 0.065I \tag{16} \]

Some caveats apply to this model. The influence of salinity on coliform decay rates is not considered. Nevertheless, the authors assume that the lethal effects of salinity on sewage dilution are included in the saline water considered in the experiments.

In the absence of light, the equation below shows the variation of the decay rate as a result of temperature only:

\[ \log T_{90} = 2.37 - 0.0283T \tag{17} \]

Model proposed by Guillaud et al. (1997)

Guillaud et al. (1997) established the relationship between the average solar radiation (\(I\), in \(\mu E \, m^{-2} \, h^{-1}\)) and the coliform decay rate (hours) in French coastal waters:

\[ T_{90} = 53683I^{-0.666} \tag{18} \]

These authors did not present the experimental ranges of temperature and salinity. Thus, it is supposed that the decay model is better adapted to thermohaline environments, similar to those in the French waters.

Experimental solar radiation levels varied from \(2 \times 10^5\) to \(6 \times 10^6\) \(\mu E \, m^{-2} \, h^{-1}\). Computed decay rates for low turbidity and high levels of solar radiation show \(T_{90}\) values of less than 2 h. Under the same levels of radiation, but in waters with high turbidity, \(T_{90}\) values exceeded 10 h.

Model proposed by Yang et al. (2000)

Yang et al. (2000) evaluated \(E. \, coli\) decay as a function of sewage dilution in marine waters, solar radiation, salinity (Table 1) and predation (this is the first model that includes this parameter).

Under the influence of predatory microorganisms, coliform decay rates were found to be three to five times higher than those found in systems where these microorganisms were absent. Furthermore, due to the complexity of bacterial survivorship under predation, the decay values found in environments subject to predators were found to be more variable, and consequently modeling in these conditions is less accurate. The proportional increases in decay with salinity and solar radiation occur in both the presence and the absence of predatory microorganisms according to the following equations.

Considering the effects of predatory microorganisms, \(E. \, coli\) decay is given by:

\[ k_p = -2.8787 \times 10^{-2} + 3.4919 \times 10^{-7} L + 1.4365 \times 10^{-3} S \tag{19} \]

Without the presence of predators, \(E. \, coli\) decay follows the relationship:

\[ k_p = 6.5537 \times 10^{-3} + 1.5299 \times 10^{-7} L + 1.5566 \times 10^{-4} S - 1.8111 \times 10^{-4} + 1.6312 \times 10^{-12} L^2 + 3.6222 \times 10^{-9} LR \tag{20} \]

where the decay rate \(k\) is expressed in min⁻¹; \(L\) corresponds to light intensity in lux; \(S\) is salinity and \(R\) is the dilution of sewage in marine water. The corresponding correlation coefficients \(r^2\) of Equations (19) and (20), considering the activity or absence of predators, are respectively 0.8959 and 0.5045.

The effects of solar radiation, salinity and dilution can be better understood in systems without the existence of predatory microorganisms. The random effect of the predatory microorganisms, causing more variations in the decay rates, can be attributed to the fact that they are also affected by environmental factors such as salinity and light intensity. Based on the aforementioned facts, it can be concluded that, under all the uncertainties related to

![Table 1](https://waponline.com/wst/article-pdf/68/3/622/440158/622.pdf)

**Table 1** Range of variation of the parameters employed in experiments carried out by Yang et al. (2000)

<table>
<thead>
<tr>
<th>Factors</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light intensity (Lux)</td>
<td>0–20,270–50,000–79,730–100,000</td>
</tr>
<tr>
<td>Salinity</td>
<td>0, 8, 20, 32 and 40</td>
</tr>
<tr>
<td>Dilution</td>
<td>1, 20, 50, 80 and 100</td>
</tr>
</tbody>
</table>

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the presence of predators, and assuming a more conservative position, the use of models that do not take into consideration the action of predatory microorganisms is recommended.

PROCEDURES FOR COMPARISON OF DECAY MODELS

Even though there are distinctions between the coliform group of bacteria (total coliform, FC and E. coli), this does not invalidate the comparison between the presented models, because according to Marais (1974) and Cabelli (1978) the decay rates of all these microorganisms are quite similar. In addition, the physical parameters that control decay overlap the genetic differences between species of bacteria and the types of effluent (Noble et al. 2004).

In order to proceed with the comparisons of the models, identical environmental conditions were applied in the equations, so that the results could be plotted in graphs. As the values were applied to the bacterial decay model proposed by Yang et al. (2000), some inconsistencies were observed in the decay rates. Under low levels of solar radiation, negative values were obtained, and an excessively high bacterial die-off rate was observed, under small volumetric mixing ratios of seawater and wastewater. Although the authors could not explain this behavior, the short duration of each experiment (only 2 h) may have affected the results, because no adaptation time for the inoculated bacteria was allowed.

The models of Gameson & Gould (1975), Mancini (1978), Šolić & Krstulović (1992) and Sarikaya & Saatçî (1995) evaluated coliform decay under dark conditions. Table 2 indicates the parameters and the environmental patterns used in the comparison of the bacterial decay models. Salinity and temperature values were considered as, respectively, 35 and 25 °C, and the solar radiation was calculated by the methodology proposed by Martin et al. (1999).

The analyses of the results were based on the methodology proposed by Tukey (1977), which considers the interquartile range (dI) represented by the difference between the third (Q3) and the first (Q1) quartiles. The Tukey’s fence is the range between (Q1–1.5 dI) and (Q3 + 1.5 dI). The values outside the fence were considered outliers and were therefore removed from the analyses. Furthermore, the comparisons of means were tested with Student’s T-test, and a correlation matrix was calculated.

<table>
<thead>
<tr>
<th>Environmental Patterns</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar radiation: Summer, clear sky</td>
<td>Plume surface thickness 5 m</td>
</tr>
<tr>
<td>Solar radiation: Summer sky 100% cloudy</td>
<td>Secchi depth 5 m</td>
</tr>
<tr>
<td>Absence of solar radiation (night)</td>
<td>Coefficient of proportionality ( k_l = 0.32 \text{ cm}^2 \text{ cal}^{-1} (E. coli) )</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSION

Comparison of models considering the influence of solar radiation

Figure 2 shows hourly values of the \( T_{90} \) parameter in summer with clear skies (Figure 2(a)) or fully cloudy conditions (Figure 2(b)). For each model these values were calculated considering identical conditions of salinity, temperature and solar radiation.

![Figure 2](https://iwaponline.com/wst/article-pdf/68/3/622/440158/622.pdf)
Based on Tukey’s fence, as shown in Figure 1, in both cloudy and clear sky conditions, $T_{90}$ values calculated by the Šolić & Krstulović (1992) model are higher than the upper limit given by $(Q_3 + 1.5 d_i)$. Thus, these values are considered outliers and will be excluded from subsequent analysis.

In Figure 3(a) and (b) calculations were carried out without the model of Šolić & Krstulović (1992). In this new condition it can be verified that $T_{90}$ values calculated by Bellair et al. (1977) and Chamberlin & Mitchell (1978) are now considered outliers. The former model presents values higher than the upper Tukey’s fence limit $(Q_3 + 1.5 d_i)$ under clear sky conditions, and the second one has values under the lower limit $(Q_1 – 1.5 d_i)$ under cloudy sky conditions.

The model proposed by Chamberlin & Mitchell (1978) should be used with some caution due to its dependency on the coefficient of proportionality $k_l$ (cm² cal⁻¹), which measures the sensitivity of a specific organism to solar radiation. This coefficient was obtained from several laboratory and field experiments, and presents a wide range of values for the same microorganism.

According to Figures 2 and 3, it may be noticed that the model proposed by Chamberlin & Mitchell (1978) has underestimated $T_{90}$, while the equations of Bellair et al. (1977) provide slightly higher values. Because of this result, and also because they were considered outliers by the Tukey’s fence procedure, they will be excluded from the following analysis.

The remaining models of Mancini (1978), Canteras et al. (1995), Sarikaya & Saatçi (1995) and Guillaud et al. (1997) presented results within the limits of Tukey’s fence, as shown in Figure 4(a) and (b). Based on this analysis, it can be concluded that there is a good agreement between the $T_{90}$ values calculated with these models. With these remaining models a comparison of means, using the statistical Student’s T-test, allowed the identification of differences between these various results (Table 3). The test was applied to the means of all data combined (cloudy and clear sky), showing that, although the four models remain within the limits of the Tukey’s fence, results associated with the model by Canteras et al. (1995) are dissimilar. To be dissimilar from the other models it does not mean that the models are not valid, but it means that the conditions under which they were applied were distinct.

Under clear sky conditions a very good agreement was observed between Mancini (1978), Canteras et al. (1995), Sarikaya & Saatçi (1995), and Guillaud et al. (1997) models ($r = 1.00$, $n = 13$). Under cloudy sky conditions, the formulation of Mancini (1978) is well correlated with Sarikaya &...
Saatçi (1995) ($r = 0.98$, $n = 13$), whereas the equations of the Mancini (1978) model produced, under both weather conditions, slightly higher $T_{90}$ values (as shown in Table 3). The Guillaud et al. (1997) and Sarikaya & Saatçi (1995) models presented similar tendencies under clear and cloudy sky conditions respectively ($r = 0.99$, $n = 26$).

Despite the good correlation between the models of Mancini (1978), Sarikaya & Saatçi (1995) and Guillaud et al. (1997) some points have to be highlighted:

- The equation proposed by Guillaud et al. (1997) does not take into consideration the variations of salinity and temperature. Even though temperature and salinity variations are less relevant under daylight conditions, these parameters play a major role in bacterial decay during the dark hours. Thus, this equation cannot predict bacterial decay under fully natural conditions.
- The formulation of Sarikaya & Saatçi (1995) neglects salinity variations, limiting their model to a restrictive salinity range used in the experiment.
- The models of Mancini (1978) and Canteras et al. (1995) consider the influence of the combined effects of solar radiation, temperature and salinity on bacterial decay. However, the $T_{90}$ values obtained by Mancini’s formulations were slightly higher than the values obtained by Canteras et al. (1995). Therefore, the former model can lead to a more conservative evaluation of the coliform plume in the marine environment.

Evaluation of models in the absence of solar radiation

Table 4 presents $T_{90}$ variations under dark conditions. Among the authors previously mentioned, only Mancini (1978), Šolić & Krstulović (1992) and Sarikaya & Saatçi (1995) developed formulations which evaluate bacterial decay in the dark. Additionally, Gameson & Gould (1975) determined that the decay of coliform bacteria in seawater (salinity = 35) in the absence of solar radiation as a function of temperature is given by the equation: $T_{90} = 2.292 - 0.02957T$.

Based on these results presented in Table 4 and on some aspects observed in the experimental conditions, the following considerations can be made:

- The model proposed by Šolić & Krstulović (1992), which considers bacterial decay as a function of temperature, was obtained by only a few data samples and is not fully reliable.
- Bacterial decay as a function of temperature as presented by Sarikaya & Saatçi (1995) follows the same principles proposed by Gameson & Gould (1975). Besides, it was developed with only a few data samples, and also establishes correlations of little significance ($r^2 = 0.69$).
- The values presented by Mancini (1978), despite being underestimated when compared with the others, were obtained from a large, consistent database resulting from experiments carried out in the field and in the laboratory. The values presented by this author are also consistent with in situ measurements performed by Bellair et al. (1977).

CONCLUSIONS

The evaluation of the decay of fecal indicator bacteria in the marine environment is a complex task due to the large number of variables and uncertainties involved in the process. Furthermore, the concentration of these microorganisms in wastewater can vary by orders of magnitude, and the variations in the initial (in sewage) concentration of microorganisms released to the marine environment can compromise the quality of the evaluations. However, bacterial decay models are essential for estimating the die-off rates of fecal indicator microorganisms, a paramount parameter for the management of populated maritime and riparian coasts.
As for the analyses of the models presented in this study, the results generated by the models of Mancini (1978), Sarikaya & Saatçi (1995) and Guillaud et al. (1997) were considered to produce the best estimates of bacterial decay rates. The other evaluated models should not be considered wrong, but it is possible that they have more restricted conditions of application. Actually, it is advisable that the choice of one or another model should be preceded by an evaluation of the application range and whether the parameters included in the model are significant for the system under study. Therefore, for instance, during winter in temperate environments a model of bacterial decay must consider night-time processes, while in tropical environments very little variation in temperature between sewage and seawater is observed, so temperature would be a less important parameter.

The proposal of this work was to evaluate different bacterial decay models as a tool for modeling coliform plumes from ocean outfalls. Based on this analysis the model of Mancini (1978) is recommended, as it assesses the bacterial decay in the absence of light, considering the combined action of temperature and salinity. In addition this model produces consistent results compared with measured data presented by Canteras et al. (1995), Fujioka et al. (1981), and Alkan et al. (1993).

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