Relationship between first-order decay coefficients in ponds, for plug flow, CSTR and dispersed flow regimes

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Abstract Adequate consideration of the hydraulic regime of a pond is essential in the analysis of BOD and coliform removal, and considerable divergence exists in the literature when reporting removal coefficients. This paper aims at integrating the existing approaches, by quantifying the relationship between the first-order removal coefficients \( K \) from the three main hydraulic regimes (CSTR, plug flow and dispersed flow) adopted in the design and performance evaluation of ponds. Based on theoretical considerations and statistical regression analyses, the relationship between the \( K \) values is investigated, quantified and modelled. Two tables are presented and two equations are proposed, which allow conversion of \( K \) values obtained for dispersed flow to (a) \( K \) for CSTR and (b) \( K \) for plug flow, based on the hydraulic detention time \( t \) and the dispersion number \( d \). These coefficients, when applied in the CSTR or plug-flow equations, will give approximately the same prediction of the effluent concentration as that obtained when using the dispersed-flow model with its proper coefficient. With this approach designers can apply, and researchers can report, \( K \) values for the two idealised flow patterns (CSTR and plug flow).

Keywords Waste stabilisation ponds; decay coefficient; first-order kinetics; dispersed flow; CSTR; plug flow

Introduction
In the design and performance evaluation of waste stabilisation ponds, adequate consideration of the appropriate hydraulic regime is essential. The effluent concentration of a particular pollutant is a function of the hydraulic regime of the pond and of the reaction kinetics representing the pollutant decay. Reaction kinetics of the two most important parameters (BOD and coliforms) is usually assumed to be first order. Regarding the hydraulic regime, the two idealised and extreme models of CSTR (continuous stirred tank, or completely mixed) and plug flow are frequently assumed. The dispersed flow model is more generic and able to represent all types of reactors but, in spite of its better representation of reality, is less frequently used by designers. Additionally, when evaluating the performance of an existing pond and subsequently calculating the decay coefficient \( K \), the two idealised regimes (CSTR and plug flow) are frequently assumed, often independently of the geometric configuration of the pond.

Table 1 presents the formulae for the estimation of the effluent concentration of a first-order decay pollutant, as a function of the hydraulic regime assumed for the pond. For an existing pond, the coefficient \( K \) can be calculated by rearranging Equations 1 and 2, and making \( K \) explicit, provided the influent concentration \( C_0 \), the effluent concentration \( C \) and the detention time \( t \) are known or have been determined (also the dispersion number \( d \), for dispersed flow models). These equations are also presented in Table 1.

For a given removal efficiency, the estimation of \( K \) based on the detention time and on the influent and effluent concentrations leads to the following two divergent situations: (a) adoption of the CSTR model leads to \( K \) values which are greater than those found for dispersed flow; (b) adoption of the plug-flow model leads to \( K \) values which are lower than those found for dispersed flow. The following example will help to clarify the point.
An existing pond has the following average values of performance indicators: (a) influent coliform concentration: \( C_0 = 1 \times 10^7 \) FC/100 ml; (b) effluent coliform concentration: \( C = 2.13 \times 10^5 \) FC/100 ml; (c) detention time: \( t = 30 \) days; (d) Dispersion Number: \( d = 0.5 \).

Use of Equations 4 and 5 will lead to the \( K \) coefficients for plug flow and CSTR, respectively. An iterative process of trial-and-error will lead to the \( K \) coefficient for dispersed flow.

The following \( K \) values are obtained: (a) plug flow: \( K = 0.13 \) d\(^{-1}\); (b) CSTR: \( K = 1.53 \) d\(^{-1}\); (c) dispersed flow: \( K = 0.30 \) d\(^{-1}\). As can be seen, different \( K \) values are obtained for the same pond, depending on the hydraulic regime assumed.

In principle, there should be only one coefficient, representing the decay of the constituent, according to its kinetics. However, the inadequacy in representing in a perfect manner the hydraulic pattern in the reactor leads to the deviations that occur in practice. The reason for the differences observed in the example above is that, since CSTR reactors are the least efficient for first-order removal kinetics, the lower efficiency is compensated by a higher \( K \) value. Conversely, since plug-flow reactors are the most efficient reactors, the \( K \) value is reduced to produce the same effluent quality. Depending on the length-to-breath \( (L/B) \) ratio of the pond (dispersion characteristics), the deviation can be very large, inducing considerable errors in the estimation. Naturally, \( K \) coefficients for dispersed flow are assumed to best represent reality and the true reaction kinetics. However, the confidence in \( K \) values for dispersed flow relies very much on the confidence on the assumed or determined values of the dispersion number \( d \).

These divergences have been the subject of considerable confusion in the literature, when expressing \( K \) values. Reported values show considerable variations (von Sperling, 1999b), a large part of which can be attributed to inadequate consideration of the hydraulic regime of the pond.

The aim of the present work is to investigate the relationship among the \( K \) values obtained according to the three main hydraulic regimens. In this respect, it presents advances with regards to von Sperling (1999a), due to the inclusion of the plug-flow regime, other analyses and examples of application.

### Table 1

<table>
<thead>
<tr>
<th>Hydraulic regime</th>
<th>Formula for the effluent concentration</th>
<th>Formula for the decay coefficient (( K ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plug flow</td>
<td>( C = C_0 \cdot e^{-Kt} ) (1)</td>
<td>( K = \frac{-\ln(C/C_0)}{t} ) (4)</td>
</tr>
<tr>
<td>CSTR</td>
<td>( C = \frac{C_0}{1+Kt} ) (2)</td>
<td>( K = \frac{(C_0/C) - 1}{t} ) (5)</td>
</tr>
<tr>
<td>Dispersed flow</td>
<td>( C = C_0 \cdot e^{\frac{4ae^{1/2d}}{(1+a)^2e^{a^{1/2d}} - (1-a)^2e^{a^{1/2d}}}} ) (3)</td>
<td>( K ) value not explicit</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Equation number</th>
<th>Equation number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>(trial- and- error or error function minimisation)</td>
</tr>
</tbody>
</table>

\( C_0 = \) influent concentration (org/100 ml)

\( C = \) effluent concentration (org/100 ml)

\( K = \) first-order decay coefficient (d\(^{-1}\))

\( t = \) hydraulic detention time (d)

\( d = \) dispersion number = \( D/U \cdot L = D. t L^2 \) (dimensionless)

\( D = \) coefficient of longitudinal dispersion (m\(^2\)/d)

\( U = \) average flow velocity in the reactor (m/d)

\( L = \) length of the longitudinal distance in the reactor (m)
Based on theoretical considerations and on statistical regression analyses, the relationship among the $K$ values is investigated, quantified and modelled. Two equations are proposed, which allow conversion of $K$ values obtained for dispersed flow to (a) $K$ for CSTR and (b) $K$ for plug flow, based on the hydraulic detention time $t$ and the Dispersion Number $d$. These coefficients, when applied in the CSTR or plug-flow equations, will give approximately the same prediction of the effluent concentration as that obtained when using the dispersed-flow model with its proper coefficient. With this approach, designers can apply and researchers can report $K$ values for the two idealised flow patterns (CSTR and plug flow).

**Relationship between $K$ for idealized regimens (CSTR and plug flow) and $K$ for dispersed flow**

The present section investigates and quantifies the relationship between $K$ for the idealised flow patterns, CSTR ($K_{\text{CSTR}}$) and plug flow ($K_{\text{plug}}$), and $K$ for the general pattern, dispersed flow ($K_{\text{disp}}$).

The following explanation demonstrates the methodology applied for the CSTR regime. A similar methodology, using the appropriate equations, was also used for the plug-flow regime. Using Equation 2 for CSTR and Equations 3 and 4 for dispersed flow, it was calculated, for different values of the dimensionless product $K_{\text{disp}} \cdot t$ and dispersion number $d$, the corresponding $K_{\text{CSTR}}$, which yields the same efficiency of removal (first-order kinetics). The dispersion numbers $d$ ranged from extremely high values (100,000, representing completely mixed conditions) to extremely low values (0.001, representing plug-flow conditions).

The results, presented in Table 2, show the ratio between $K$ for CSTR and $K$ for dispersed flow ($K_{\text{CSTR}} / K_{\text{disp}}$). The interpretation of the table is as follows. The same pond analysed in the previous section, with $d = 0.5$, detention time $t = 30$ days and $K_{\text{disp}} = 0.3 \text{ d}^{-1}$ has the dimensionless product $K_{\text{disp}} \cdot t = 0.3 \cdot 30 = 9.0$. For $d = 0.5$ and $K_{\text{disp}} \cdot t = 9$, the table shows that the $K_{\text{CSTR}}$ is equal to 5.144 times $K_{\text{disp}}$. In other words, $K_{\text{CSTR}} = 5.144 \cdot 0.3 = 1.54 \text{ d}^{-1}$. This value is, apart from rounding values, the same obtained in the previous section (1.53 $\text{d}^{-1}$), indicating the applicability of the table. The estimation of the BOD or coliform removal efficiency using the dispersed-flow model (Equations 3 and 4, with $K_{b}$ for dispersed flow) and the CSTR model (Equation 2 with $K_{b}$ for CSTR) will lead to the same results.

Table 3 shows the corresponding values for the plug-flow model. In the same example, it is seen from Table 3 that, for $d = 0.5$ and $K_{\text{disp}} \cdot t = 9$, $K_{\text{plug}}$ is 0.430 times $K_{\text{disp}}$. Therefore, $K_{\text{plug}} = 0.430 \cdot 0.3 = 0.13 \text{ d}^{-1}$ which is exactly the same value determined in the previous section.

Figure 1 illustrates the data from Tables 2 and 3. It can be clearly seen that, for the CSTR regime, the smaller the dispersion number $d$, the greater the departure between $K_{\text{CSTR}}$ and $K_{\text{disp}}$. Conversely, for the plug-flow regime, the greater the dispersion number $d$, the greater is the departure between $K_{\text{plug}}$ and $K_{\text{disp}}$. The departure also increases with the detention time $t$. Another point to be observed is that the relative departures can be much larger for the CSTR regime than for the plug flow regime, indicating that an even greater caution needs to be exercised when applying the CSTR model.

The lowering of the dispersion number $d$ occurs with the increase in the $L/B$ ratio. In other words, a baffled pond is likely to have a low value of $d$. Under these circumstances, utilization of the CSTR model will be completely unsuitable, due to the large difference between $K_{\text{CSTR}}$ and $K_{\text{disp}}$, the latter being naturally expected to be a better predictor of the actual behaviour in the pond. In a baffled pond, use of the CSTR model for design purposes, adopting “typical” values of $K_{\text{CSTR}}$ from the literature will lead to an underestimation of the
Table 2. Ratio between the \( K \) coefficients obtained for the CSTR model and the dispersed-flow model, for different values of the dispersion number \( d \) and the product \( K_{\text{disp}} \).

<table>
<thead>
<tr>
<th>( K_{\text{disp}} )</th>
<th>( d=100,000 )</th>
<th>( d=4 )</th>
<th>( d=1 )</th>
<th>( d=0.5 )</th>
<th>( d=0.2 )</th>
<th>( d=0.1 )</th>
<th>( d=0.02 )</th>
<th>( d=0.001 )</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
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<td>1.000</td>
</tr>
<tr>
<td>1</td>
<td>1.000</td>
<td>1.040</td>
<td>1.140</td>
<td>1.230</td>
<td>1.400</td>
<td>1.520</td>
<td>1.670</td>
<td>1.715</td>
</tr>
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<td>2</td>
<td>1.000</td>
<td>1.075</td>
<td>1.290</td>
<td>1.515</td>
<td>1.950</td>
<td>2.320</td>
<td>2.940</td>
<td>3.180</td>
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<tr>
<td>3</td>
<td>1.000</td>
<td>1.120</td>
<td>1.457</td>
<td>1.853</td>
<td>2.677</td>
<td>3.550</td>
<td>5.380</td>
<td>6.300</td>
</tr>
<tr>
<td>4</td>
<td>1.000</td>
<td>1.163</td>
<td>1.635</td>
<td>2.213</td>
<td>3.658</td>
<td>5.393</td>
<td>10.150</td>
<td>13.175</td>
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<tr>
<td>5</td>
<td>1.000</td>
<td>1.210</td>
<td>1.832</td>
<td>2.646</td>
<td>4.950</td>
<td>8.180</td>
<td>19.440</td>
<td>28.800</td>
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<td>6</td>
<td>1.000</td>
<td>1.255</td>
<td>2.043</td>
<td>3.150</td>
<td>6.617</td>
<td>12.283</td>
<td>37.620</td>
<td>64.667</td>
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<tr>
<td>7</td>
<td>1.000</td>
<td>1.300</td>
<td>2.271</td>
<td>3.729</td>
<td>8.814</td>
<td>18.214</td>
<td>73.000</td>
<td>149.000</td>
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<tr>
<td>8</td>
<td>1.000</td>
<td>1.346</td>
<td>2.525</td>
<td>4.388</td>
<td>11.600</td>
<td>26.813</td>
<td>141.000</td>
<td>350.000</td>
</tr>
<tr>
<td>9</td>
<td>1.000</td>
<td>1.394</td>
<td>2.789</td>
<td>5.144</td>
<td>15.156</td>
<td>39.111</td>
<td>272.780</td>
<td>831.111</td>
</tr>
<tr>
<td>10</td>
<td>1.000</td>
<td>1.444</td>
<td>3.080</td>
<td>6.010</td>
<td>19.660</td>
<td>56.500</td>
<td>524.000</td>
<td>1995.000</td>
</tr>
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</table>

Table 3. Ratio between the \( K \) coefficients obtained for the plug-flow model and the dispersed-flow model, for different values of the dispersion number \( d \) and the product \( K_{\text{disp}} \).

<table>
<thead>
<tr>
<th>( K_{\text{disp}} )</th>
<th>( d=100,000 )</th>
<th>( d=4 )</th>
<th>( d=1 )</th>
<th>( d=0.5 )</th>
<th>( d=0.2 )</th>
<th>( d=0.1 )</th>
<th>( d=0.02 )</th>
<th>( d=0.001 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>1</td>
<td>0.695</td>
<td>0.715</td>
<td>0.762</td>
<td>0.805</td>
<td>0.878</td>
<td>0.926</td>
<td>0.984</td>
<td>1.000</td>
</tr>
<tr>
<td>2</td>
<td>0.551</td>
<td>0.578</td>
<td>0.640</td>
<td>0.699</td>
<td>0.797</td>
<td>0.868</td>
<td>0.967</td>
<td>1.000</td>
</tr>
<tr>
<td>3</td>
<td>0.463</td>
<td>0.493</td>
<td>0.562</td>
<td>0.626</td>
<td>0.736</td>
<td>0.820</td>
<td>0.950</td>
<td>1.000</td>
</tr>
<tr>
<td>4</td>
<td>0.404</td>
<td>0.435</td>
<td>0.506</td>
<td>0.574</td>
<td>0.689</td>
<td>0.782</td>
<td>0.935</td>
<td>0.999</td>
</tr>
<tr>
<td>5</td>
<td>0.359</td>
<td>0.392</td>
<td>0.465</td>
<td>0.532</td>
<td>0.652</td>
<td>0.749</td>
<td>0.920</td>
<td>0.998</td>
</tr>
<tr>
<td>6</td>
<td>0.325</td>
<td>0.358</td>
<td>0.432</td>
<td>0.500</td>
<td>0.620</td>
<td>0.721</td>
<td>0.907</td>
<td>0.997</td>
</tr>
<tr>
<td>7</td>
<td>0.298</td>
<td>0.331</td>
<td>0.405</td>
<td>0.473</td>
<td>0.593</td>
<td>0.696</td>
<td>0.894</td>
<td>0.996</td>
</tr>
<tr>
<td>8</td>
<td>0.276</td>
<td>0.309</td>
<td>0.383</td>
<td>0.450</td>
<td>0.569</td>
<td>0.674</td>
<td>0.882</td>
<td>0.995</td>
</tr>
<tr>
<td>9</td>
<td>0.257</td>
<td>0.291</td>
<td>0.364</td>
<td>0.430</td>
<td>0.549</td>
<td>0.654</td>
<td>0.870</td>
<td>0.994</td>
</tr>
<tr>
<td>10</td>
<td>0.241</td>
<td>0.274</td>
<td>0.347</td>
<td>0.413</td>
<td>0.530</td>
<td>0.636</td>
<td>0.859</td>
<td>0.993</td>
</tr>
</tbody>
</table>

Figure 1. Relationship between coefficients \( K \) for CSTR and plug flow with the coefficient \( K \) for dispersed flow, as a function of the dispersion number \( d \) and the hydraulic detention time \( t \).
removal efficiency in the pond. On the other hand, for an existing baffled pond, the calculation of the coefficient $K$ using the CSTR model will lead to an overestimation of the $K$ coefficient, in order to compensate for the inherent lower efficiency associated with the CSTR model.

**Regression analysis between $K_{\text{CSTR}}$, $K_{\text{plug}}$ and $K_{\text{disp}}$**

In order to extend the applicability of Tables 2 and 3, a regression analysis was done, having as dependent variable the ratio between the $K$ value for the idealised regime (CSTR or plug flow) and the $K$ value for the general regime (dispersed flow). The dependent variables were then $K_{\text{CSTR}} / K_{\text{disp}}$ and $K_{\text{plug}} / K_{\text{disp}}$. The independent variables were the dimensionless product $K_{\text{disp}.t}$ and the dispersion number $d$. Two regression analyses were done, each one having different applicability ranges. The equations of best fit obtained were:

*Wider applicability range (d from 0.1 to 4.0; $K_{\text{disp}.t}$ from 0 to 10; n = 55 values from Tables 2 and 3):*

For CSTR ($R^2 = 0.994$):

$$
\frac{K_{\text{CSTR}}}{K_{\text{disp}}} = 1.0 + \left[ 0.0020 \ (K_{\text{disp}.t})^{3.0137} \ d^{1.4145} \right]
$$

(6)

For plug flow ($R^2 = 0.956$):

$$
\frac{K_{\text{plug}}}{K_{\text{disp}}} = 1.0 - \left[ 0.2414 \ (K_{\text{disp}.t})^{0.4157} \ d^{0.1880} \right]
$$

(7)

*Narrower applicability range (d from 0.1 to 1.0; $K_{\text{disp}.t}$ from 0 to 5; n = 24 values from Tables 2 and 3):*

For CSTR ($R^2 = 0.994$):

$$
\frac{K_{\text{CSTR}}}{K_{\text{disp}}} = 1.0 + \left[ 0.0540 \ (K_{\text{disp}.t})^{3.8166} \ d^{0.8426} \right]
$$

(8)

For plug flow ($R^2 = 0.987$):

$$
\frac{K_{\text{plug}}}{K_{\text{disp}}} = 1.0 - \left[ 0.2425 \ (K_{\text{disp}.t})^{0.5351} \ d^{0.3415} \right]
$$

(9)

All fits were very good, as indicated by the high $R^2$ values obtained. The reason for having equations for two applicability ranges is that the wider-range equation is not very accurate for lower values of $d$ or $K_{\text{disp}.t}$, therefore making the narrower-range equations more suitable under these circumstances. Equations (6) and (8) are slightly different from those presented by von Sperling (1999a, 1999b), because a different range of data has been used in this study, and also because the equations were forced to have on the right-hand side the value of 1.0. From the equations, it is seen that $K_{\text{CSTR}} / K_{\text{disp}}$ will always be greater than 1.0, whereas $K_{\text{plug}} / K_{\text{disp}}$ will always be less than 1.0. Figure 2 presents the plots “observed predicted” for the wider-range regressions, showing the goodness of the fit, but also indicating the regions where the deviation from the observed values are larger.

Figure 3 plots the contours of the $K_{\text{CSTR}} / K_{\text{disp}}$ and $K_{\text{plug}} / K_{\text{disp}}$ values obtained from the wider-range regression analyses (Equations 6 and 7), for different values of $K_{\text{disp}.t}$ and $d$. The influence of $K_{\text{disp}.t}$ and $d$ on the relative departure from the value of 1.0 can be clearly seen.
Equations 6 and 7 can be further developed, taking the denominator of the left-hand side
to the right-hand side:

Wider applicability range ($d$ from 0.1 to 4.0; $K_{disp}$, $t$ from 0 to 10):

$$K_{CSTR} = K_{disp} + \left[ 0.0020 \ K_{disp}^{0.0137} \ t^{3.0137} \ d^{-1.4145} \right]$$

(10)

$$K_{plug} = K_{disp} - \left[ 0.2414 \ K_{disp}^{1.4157} \ d^{-0.1880} \right]$$

(11)

Narrower applicability range ($d$ from 0.1 to 1.0; $K_{disp}$, $t$ from 0 to 5)

$$K_{CSTR} = K_{disp} + \left[ 0.0540 \ K_{disp}^{2.8166} \ t^{1.8166} \ d^{-0.8426} \right]$$

(12)

$$K_{plug} = K_{disp} - \left[ 0.2425 \ K_{disp}^{1.5351} \ d^{0.5351} \ d^{0.3415} \right]$$

(13)

Equations 10 to 13 allow the direct estimation of $K_{CSTR}$ and $K_{plug}$ based on the prior
determination of $K_{disp}$ and the prior knowledge of $t$ and $d$.

Applying equations 10 and 11 (wider-range regression, because $K_{disp} \ t = 9 > 5$) to the
example presented in the first and second sections of this paper leads to the following
results: $K_{CSTR} = 1.50$ d$^{-1}$ and $K_{plug} = 0.14$ d$^{-1}$. These values are very close to those obtained
in the previous section, when applying Equations 4 and 5 directly ($K_{CSTR} = 1.53$ d$^{-1}$ and
$K_{plug} = 0.13$ d$^{-1}$).

Figure 2 Observed predicted values for the regression analyses estimating $K_{CSTR}/K_{disp}$ and $K_{plug}/K_{disp}$
(wider-range regression, Equations 6 and 7)
Applicability of the relationships

Utilisation of Equations 8 and 9, as well as Tables 2 and 3, requires the prior knowledge of the dispersion number \( d \), which is, however, not frequently known in most studies concerning waste stabilisation ponds. For an existing pond, the dispersion number can be obtained from tracer studies. For ponds being designed and also for existing ponds, \( d \) can be estimated using empirical formulae available in the literature, based on geometrical characteristics of the pond (Polprasert and Bhattarai, 1985; Agunwamba et al., 1992; Yanez, 1993; von Sperling, 1999b). If \( d \) is known, it can be directly utilised in Equations 8 and 9 or Tables 2 and 3, so allowing the estimation of the \( K \) value for any of the idealised hydraulic regimes.

The applicability of the proposed approach increases even further if the dispersed-flow model is used, since the \( K \) values are independent of the geometrical configuration of the ponds. For design purposes, if \( K_{\text{disp}} \) can be estimated using empirical equations (such as that proposed by von Sperling, 1999b for coliform removal), then the proposed approach can be directly used for any of the hydraulic regimes.

Conclusions

The present paper investigates and quantifies the relationship between first-order removal coefficients \( K \) for BOD or coliforms in ponds, derived under the CSTR, plug flow and dispersed-flow regimes. For a given removal efficiency, the calculated coefficients are
different, due to the difference in the structure of the CSTR, plug flow and dispersed flow formulae.

Based on theoretical considerations, the correspondence of the hydraulic regime for different values of the dimensionless product $K.t$ is established. The paper presents two tables and four equations for the estimation of $K$ for the CSTR and plug flow models, based on $K$ for dispersed flow, the hydraulic detention time $t$ and the dispersion number $d$. These calculated coefficients, when applied in the CSTR and plug-flow equations, will give approximately the same prediction of the effluent concentration as that obtained when using the dispersed-flow model with its proper coefficient.

Considering the substantial amount of divergence in the literature regarding kinetic coefficients, and also due to the great importance played by the geometry of the pond, it is very important that any modelling study of BOD or coliform decay should explicitly present a set of basic information, which is not always included in the technical literature. The minimum information required is: flow regime assumed in the calculations, physical data of the pond (length, width, depth), liquid temperature and flowrate.

References