Linking sanitation and wastewater treatment: from evaluation on the basis of effluent pollutant concentrations to evaluation on the basis of pollutant removal efficiencies

Yoshiaki Tsuzuki

ABSTRACT

The evaluation of centralised wastewater treatment plants (WWTPs) in planning and management is sometimes based solely on effluent pollutant concentrations or pollutant loads. For sanitation purposes, the effluent pollutant concentrations/loads of WWTPs are important; of course, but from the point of view of wastewater treatment, the pollutant removal performance should also be evaluated. Focussing on low- and middle-income countries, especially those in tropical regions, published kinetics studies on biological WWTPs (such as oxidation ditches and aerated lagoons) are summarised in this paper. In most studies, effluent pollutant concentrations/loads are described as first-order linear functions of influent pollutant concentrations/loads. Therefore, pollutant removal efficiencies can be expressed as first-order linear functions of the reciprocal of influent pollutant concentrations/loads with negative coefficients. This implies that pollutant removal efficiencies increase with influent pollutant concentration/load increases. Based on pollutant removal efficiency functions, biological or ecological WWTPs when operating with small influent pollutant concentrations/loads should change their management to increase influent pollutant concentrations/loads in order to increase pollutant removal efficiencies. It may, however, be possible for technological development in wastewater treatment to overcome this problem.

Key words | ecological wastewater treatment, influent and effluent pollutant concentration, influent and effluent pollutant load, removal efficiency (removal ratio)

INTRODUCTION

Halving the percentage of people living without safe drinking water and appropriate sanitation by 2015 is a target of the Millennium Development Goals (MDGs). Huge investments have been made in the water and sanitation sectors since the Water Supply and Sanitation Decade (1981–90). It is predicted that the water supply target will be met by 2015; however, the sanitation target is viewed as very difficult to achieve. The main purposes of the sanitation goal are infectious disease prevention, hygiene, and providing health and lifestyle improvements. On the other hand, wastewater treatment, particularly in developed countries, targets pollutant discharge reduction.

Centralised wastewater treatment plants (WWTPs) have been developed in middle-income countries, and transitions from sanitation to wastewater treatment are anticipated. The evaluation of WWTPs is sometimes based only on effluent pollutant concentrations in comparison with effluent pollutant criteria, even in cases in which the inflowing pollutant concentrations are low (e.g. Japan International Cooperation Agency (JICA) Thailand Office 2010). Small or negative pollutant removal efficiencies have also been reported (Environment & Laboratory Co. Ltd 2008; Tsuzuki et al. 2013b). Muhammad et al. (2006) recommended increasing the river and surface drain water volume flowing into wastewater collection pipelines, thereby increasing the influent biological oxygen demand (BOD) of WWTPs in Bangkok, Thailand, when inflowing pollutant concentrations and loads are small. Giri et al. (2006) discussed the low organic concentrations in influent sewage in Thailand, and suggested that this was due to the non-usage of...
Methods

Kinetics studies of biological WWTPs were summarised based on the available literature targeting a relationship between influent pollutant concentrations and pollutant removal efficiencies that is comparable across all cases (Table 1). The WWTP sizes range from laboratory to full scale. The types of WWTPs examined include: stabilization reservoir, activated sludge, oxidation ponds, rotating biological contactor (RBC), waste stabilization pond (WSP, normal, hybrid and complete), continuous stirred tank reactor (CSTR), stabilisation lagoon, wastewater stabilization reservoir, and aerated lagoon. Pollutant parameters considered were the number of faecal coliform (F. coli) and total coliform (T. coli), fermentable and readily biodegradable organic substrates, nitrate plus nitrite nitrogen, chemical oxygen demand (COD), BOD, human intestinal nematode eggs (HIN-eggs), nitrogen, algae, dissolved oxygen (DO), organic matter, indicator bacteria, zooplankton, Escherichia coli (E. coli) and suspended solid (SS).

Based on the summary, the relationships between influent pollutant concentrations and pollutant removal efficiencies were calculated in order to find a comparable relationship between influent and effluent pollutant concentrations or loads across the spectrum of WWTP types.

Results

A wide variety of equations are used in the existing literature to describe pollutant removal efficiencies (Table 2). For activated sludge processes, focused studies have been conducted to develop a group of IWA Activated Sludge Models (e.g. Gujer et al. 1995). Many parameters have been developed to describe materials in liquid and solid phases in the activated sludge processes. For example, hydrolysis process rates are described by equations (see Table 2).

For other biological wastewater treatment methods or ecological WWTPs, including stabilisation ponds, aerated lagoons, and oxidation ditches, experiments describing effluent pollutant concentrations/loads and pollutant removal efficiencies have been conducted using parameters such as hydraulic retention time, temperature, influent pollutant concentrations or loads (Table 2) (e.g. Pinto et al. 1996; Banerjee 1997; von Sperling 1999; Banda et al. 2005; Jupsin & Vasel 2007). For example, \( \lambda_{\text{rem}} \) (removed COD) functions were presented in Pinto et al. (1996). Effluent COD load (\( \lambda_{\text{el}} \)) can be expressed as the difference between
applied COD load ($\lambda_{appl}$) and removed COD ($\lambda_{rem}$). This leads to an expression such as this for an anaerobic pond:

$$\lambda_{ef} = \lambda_{appl} - \lambda_{rem} = 0.195\lambda_{appl} + 10.15$$  \hspace{1cm} (1)

For ecological WWTPs, equations describing effluent pollutant concentrations/loads were often first-order linear functions of influent concentrations/loads: inflow COD in an oxidation pond (Pinto et al. 1996), inflow nitrogen in stabilisation lagoons (Middlebrooks et al. 1999), inflow BOD, COD and F. coli in tropical and subtropical stabilisation ponds with continuous stirred tank reactors (CSTR) (von Sperling 1999), inflow BOD and E. coli in waste stabilisation pond systems with anaerobic, facultative and...

<table>
<thead>
<tr>
<th>Author</th>
<th>Journal/Conference</th>
<th>Major reference</th>
<th>Type of WWTP</th>
<th>Pollutant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pinto et al. (1996)</td>
<td>Water Science and Technology</td>
<td>Wehner &amp; Wilhelm (1996)</td>
<td>Rotating biological contactor (RBC)</td>
<td>Hydraulics study to determine function and the value of a parameter (d)</td>
</tr>
</tbody>
</table>
### Table 2: Miscellaneous equations in the literature on the relationships between influent and effluent pollutant concentrations/loads or pollutant removal efficiencies and influent pollutant concentrations/loads

<table>
<thead>
<tr>
<th>Reference and type of WWTP</th>
<th>Pollutant</th>
<th>Kinetics or empirical relationship between influent pollutant concentration and pollutant removal efficiency</th>
<th>Explanation of research and parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liran et al. (1994), Stabilization reservoir</td>
<td>Faecal coliform, Total coliform</td>
<td>Coliform removal percentage was experimentally investigated in a full-scale stabilisation reservoir: (1) coliform removal percentage was one to two orders of magnitude when the reactor was operated as a flow reactor, (2) coliform removal percentage could reach more than five orders of magnitude when operated as a batch reactor, (3) coliform removal was high in the epilimnion and low in the hypolimnion, and (4) effect of vertical mixing of the water column was an important factor</td>
<td>Removal of faecal and total coliforms was investigated experimentally</td>
</tr>
<tr>
<td>Gujer et al. (1995), IWA Activated Sludge Model No. 2</td>
<td>Fermentable, readily biodegradable organic substrates, Nitrate plus nitrite nitrogen</td>
<td>Hydrolysis processes: Aerobic hydrolysis: ( K_b \times \frac{S_{O2}}{K_{O2} + S_{O2}} \times \frac{X_S}{X_H + X_S/X_H} \times X_H ) Anoxic hydrolysis: ( K_b \times \eta_{NO3} \times \frac{K_{O2}}{K_{O2} + S_{O2}} \times \frac{S_{NO3}}{S_{NO3} + S_{NO3}} \times \frac{X_S}{X_H + X_S/X_H} \times X_H ) Anaerobic hydrolysis: ( K_b \times \eta_{Fe} \times \frac{K_{O2}}{K_{O2} + S_{O2}} \times \frac{S_{NO3}}{S_{NO3} + S_{NO3}} \times \frac{X_S}{X_H + X_S/X_H} \times X_H )</td>
<td>( K_{b}: ) Hydrolysis rate constant (T(^{-1})) ( K_{O2}: ) Saturation/inhibition coefficient for oxygen, ( S_{O2} ) (( M_{O2} ) L(^{-3})) ( K_{NO3}: ) Saturation coefficient for particulate COD, ( X_S ) (( M_{COD} ) L(^{-3})) ( X_H: ) Heterotrophic organisms (( M_{COD} ) L(^{-3})) ( S_{Fe}: ) Fermentable, readily biodegradable organic substrates (( M_{COD} ) L(^{-3})) ( S_{NO3}: ) Nitrate plus nitrite nitrogen (( M_N ) L(^{-3})) ( \eta_{NO3}: ) Reduction factor for denitrification (( )–() ( \eta_{Fe}: ) Maximum rate for fermentation (( M_{COD} M_{COD} ) T(^{-1}))</td>
</tr>
<tr>
<td>Pinto et al. (1996), Oxidation pond (Stabilization pond system consisting of two series of anaerobic and facultative ponds running in parallel)</td>
<td>COD, Sludge digestion</td>
<td>COD removal percentage was investigated with: – Hydraulic retention time, and – Temperature ( S = S_0/(1 + x_{T-20}) ) ( K_T = K_0 (1/x_{T-20}) ) (&lt;\text{Anaerobic pond}&gt;) ( \lambda_{rem} = 0.805 \lambda_{appl} - 10.15 ) (( R^2 = 0.87 )) Retention time did not show correlation Temperature increase over 20°C increased the sludge digestion activity accompanied by a higher gas generation, solids resuspension and COD increase in the effluent (&lt;\text{Facultative pond}&gt;) ( \lambda_{rem} = 0.698 \lambda_{appl} - 79.575 ) (( R^2 = 0.76 )) ( \lambda_{rem} = 0.834 \lambda_{appl} - 34.168 ) (( R^2 = 0.92 )): Filtered effluent ( K_{Hilt,20}c = 0.0055 \lambda_{appl} - 0.03 ) (( R^2 = 0.73 )) ( K_w ) was not constant as a function for temperature but correlated with COD load</td>
<td></td>
</tr>
</tbody>
</table>

(continued)
## Table 2 | continued

<table>
<thead>
<tr>
<th>Reference and type of WWTP</th>
<th>Pollutant</th>
<th>Kinetics or empirical relationship between influent pollutant concentration and pollutant removal efficiency</th>
<th>Explanation of research and parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Banerjee (1997),</td>
<td>Chloride concentration</td>
<td>$C/C_0 = 4a \exp \left(1/(2d)\right)/\left[(1 + a)^2 \exp \left(a/2d\right) - (1 - a)^2 \exp \left(-a/2d\right)\right]$</td>
<td>$t$: the mean liquid retention time, and $K$: a first-order reaction rate constant per unit time</td>
</tr>
<tr>
<td>Rotating biological</td>
<td>was monitored experimentally</td>
<td>$a = (1 + 4Ktd)^{1/2}$</td>
<td>-------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>contact (RBC) process</td>
<td>using sodium chloride (NaCl) as tracer</td>
<td></td>
<td>-------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Middlebrooks et al. (1999),</td>
<td>Nitrogen</td>
<td>$VdC/dt = Q(C_0 - C_0) - kA(NH_3)$</td>
<td>$Q$: Influent flow rate (m$^3$/d)</td>
</tr>
<tr>
<td>Stabilization lagoons</td>
<td></td>
<td>$Kb = [NH_4^+] [OH^-]/[NH_3]$</td>
<td>$C_0$: Influent concentration of (NH$_4^+$ + NH$_3$) (mg-N/L)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$[H^+] = Kw/[OH^-]$</td>
<td>$C_e$: Effluent concentration of (NH$_4^+$ + NH$_3$) (mg-N/L)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$C = NH_4^+ + NH_3$</td>
<td>$V$: Volume of the pond (m$^3$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$C_e/C_0 = 1/(1 + Ak [1/(1 + 10^{pKw - pKb - pH}))]/Q$</td>
<td>$k$: Mass transfer coefficient (m/d)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ammonia loss rate constant of ammonia stripping (Stratton 1968, 1969)</td>
<td>$A$: Surface area of the pond (m$^2$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ammonia loss rate constant $\propto e^{1.57(pH - 8.5)}$</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Ammonia loss rate constant $\propto e^{0.13(T - 20)}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nitrogen removal in facultative lagoon, plug flow model (Reed 1984, 1985; Reed et al. 1995)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$N_t = N_0 \times e^{-K_t [7.560 [pH - 6.60]}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$pH = 7.3e^{0.0005 ALK}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$T = T_a + QT_i / 0.5A + Q$</td>
<td>US EPA (1983), Reed (1984)</td>
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<tr>
<td></td>
<td></td>
<td>Nitrogen removal in facultative lagoons – Complete Mix Model (Middlebrooks 1985)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$N_t = 1 + t \times (0.000576T - 0.00028) \times e^{(1.080 - 0.0423)(pH - 6.60)}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$T = 0.5AT_a + QT_i / 0.5A + Q$</td>
<td>Mancini &amp; Barnhart (1976)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BOD, Faecal coliforms (F. coli), Human intestinal nematode eggs (HIN-eggs)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>BOD$<em>{anaerobic}$: 170 g m$^{-3}$, BOD$</em>{anaerobic}$: 170 g m$^{-3}$,</td>
<td>Subscription</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(F. coli)$_{faecal}$: $5 \times 10^7$ per 100 ml,</td>
<td>Inflow</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(F. coli)$_{ffacilitative}$: $2.3 \times 10^5$ per 100 ml</td>
<td>Anaerobic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(F. coli)$<em>{u-Irrigation}$: $1 \times 10^5$ per 100 ml and (HIN-eggs)$</em>{u-Irrigation}$ was</td>
<td>Facultative</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1500 per litre, (HIN-eggs)$_{anaerobic}$ was 150 per litre,</td>
<td>u-Irrigation: unrestricted irrigation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(HIN-eggs)$_{ffacilitative}$: 1 per litre</td>
<td></td>
</tr>
</tbody>
</table>
von Sperling (1999), Tropical and subtropical waste stabilization ponds: Continuous stirred tank reactor (CSTR)

BOD, COD, Faecal coliforms (N)

Plug flow: \( N = N_0 \times \exp (-K_b t) \)

CSTR (1 cell): \( N = N_0/(1 + K_b t) \)

CSTR (equal cells in series): \( N = N_0/(1 + K_b t)^n \)

Dispersion flow: \( N = N_0 \times 4a \exp (1/2d)/(1 + a)^2 \exp [a/2d] \)

\( a = (1 + 4K_b d)^{1/2} \)

\( K_b \) (CSTR): 0.2 – 43.6 (d⁻¹)

\( K_b \) (plug flow): 0.73 – 1.1 (d⁻¹)

\( K_b \) (dispersed flow): 0.26 – 2.42 (d⁻¹)

Friedler et al. (2005), Wastewater stabilization reservoirs

Algae, DO, Organic matter, Indicator bacteria, Zooplankton

Organic matter

\( D_{OG} = D_{OG(20)} \times \theta_{OG} \times \left( \frac{C_{OG}}{K_{OG} + C_{OG}} \right) \times F_{D(O2)} \)

\( F_{D(O2)} = \begin{cases} 
1 + [ \cos (a(\Pi/2))]^2 & \text{CO}_2 \geq 0 \text{ (mg/l)} \\
2 & \text{CO}_2 = 0 \text{ (mg/l)} \text{ (more than 24h)}
\end{cases} \)

\( a = \text{MAX} \left( \frac{C_{O2} \cdots C_{O2}}{C_{O2}} \right) \)

Indicator bacteria

\( M_{PT} = (M_{PT(20)} \theta_{PTM} \times \alpha_{PTM}) \times F_{PT(O2)} \)

\( F_{PT(O2)} = \begin{cases} 
1 & \text{CO}_2 \geq 0 \text{ (mg/l)} \\
0.67 & \text{CO}_2 = 0 \text{ (mg/l)} \text{ (more than 24h)}
\end{cases} \)

\( N \): F. coli concentration (org/100 ml)

\( N_0 \): Inflow F. coli concentration (org/100 ml)

\( K_b \): Coliform die-off coefficient (d⁻¹)

\( t \): Hydraulic retention time (d)

\( n \): Number of ponds in series (-)

\( d \): (=D/UL = Dt/L²) (-)

\( D \): Coefficient of longitudinal dispersion (m²/d)

\( U \): Average flow velocity in the reactor (m/d)

\( L \): Pond length (m)

\( D_{OG} \): Organic matter degradation rate

\( D_{OG(20)} \): Maximum organic matter degradation rate at 20°C

\( \theta_{OG} \): Temperature coefficient for organic matter degradation

\( C_{OG} \): Organic matter concentration

\( K_{OG} \): Half saturation coefficient for organic matter degradation in relation to organic matter

\( F_{D(O2)} \): Oxygen factor for organic matter degradation

\( a \): Coefficient

\( C_{O2} \): Dissolved oxygen concentration

\( C_{O2} \): Dissolved oxygen concentration below which oxygen starts to limit aerobic organic matter degradation

\( M_{PT} \): Indicator bacteria mortality rate

\( M_{PT(20)} \): Indicator bacteria mortality rate at 20°C

\( \theta_{PTM} \): Temperature coefficient for indicator bacteria die-off

\( a \): Factor for light effect on indicator bacteria mortality

(continued)
<table>
<thead>
<tr>
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<th>Kinetics or empirical relationship between influent pollutant concentration and pollutant removal efficiency</th>
<th>Explanation of research and parameters</th>
</tr>
</thead>
</table>
| **Banda et al. (2005), Complete waste stabilization ponds (WSP) systems (anaerobic, facultative and maturation ponds)** | BOD, *E. coli* | BOD <Modern Design >: Facultative ponds (Mara 1987) $L_n(t) = L_n/[1 + 0.1(1.05)^{T-20} \theta_f]$ | $I$: Solar radiation intensity  
$F_{PT(O2)}$: Oxygen factor for indicator bacteria mortality |
|                          |          | *E. coli* <Modern Design >: Anaerobic pond (Mara 2004) $N_e = N_i/(1 + k_{B(T)}\theta_f)$ | $L$: BOD (mg/l) and pond length (m)  
$N$: *E. coli* (cell/ml)  
$T$: Temperature (°C)  
$\theta$: Mean hydraulic retention time (day)  
$k_{B(T)}$: First-order rate constant for *E. coli* removal (d⁻¹)  
$\delta$: Dispersion number (°) |
|                          |          | $k_{B(T)} = 2(1.07)^{T-20}$ Facultative and maturation ponds (von Sperling 1999, 2005) $N_e = N_i \left[\frac{4a}{1 + a}\right] \exp\left[(1 - a)/2\delta\right]$ | |
|                          |          | $a = (1 + 4k_{B(T)}\theta_f/\theta_a)^{1/2}$ $\delta = (L_{in}/L_{out})^{1/2}$ $k_{B(T)} = 0.92 (D_{in}/B_{in})^{0.88} (B_{in})^{0.33}$ (1.07)$^{T-20}$ | |
|                          |          | $E. coli$ < Classical design > (Marais 1974, Mara 1997) $N_e = N_i/(1 + k_{B(T)}\theta_f)$ (1 + $k_{B(T)}\theta_{m1(\text{min})}$) (1 + $k_{B(T)}\theta_{m2}$)$^n$ | |
|                          |          | $k_{B(T)} = 2.6(1.19)^{T-20}$ |  
| **Jupsin & Vasel (2007), Aerated lagoons** | SS, BOD | $X = \frac{1}{X_0} = \frac{1 + \theta/t_{50}}{1 + \theta/t_{50}}$  
$L_n(X_{\text{max}} - X) = L_n(X_{\text{max}} - X_0) - K_S * t$ |  
|                          |          | $X_{in}$: Inlet SS concentration  
$X$: Outlet SS concentration  
$\theta$: Hydraulic residence time  
$t_{50}$: Time (experimental) to get 50% efficiency  
$X_{\text{max}}$: Maximum value that corresponds to a given pond  
$K_S$: Experimental resuspension parameter |
maturation ponds (Banda et al. 2005), and inflow SS and BOD in aerated lagoons (Jupsin & Vasel 2007) (Table 2). Jupsin & Vasel (2007) also described the importance of sediment activity and settling on pollutant removal efficiencies. In the first-order reactions of influent pollutant concentrations/loads, other parameters such as temperature and reactor morphology were also included. Middlebrooks et al. (1999) was the only study to clearly provide equations describing pollutant removal rates as well as effluent pollutant concentrations/loads with first-order linear functions of influent pollutant loading rates (Table 3). A further factor influencing pollutant removal efficiencies is wastewater collection systems, i.e. combined sewers as opposed to separate sewers. This factor is not considered in this paper although collection systems significantly affect influent pollutant concentrations and loads.


When looking at low- and middle-income countries in tropical regions, water temperature can be treated as a constant throughout the year. If temperature is constant, the effluent pollutant concentrations/loads can be expressed as first-order linear functions of influent pollutant concentrations/loads (Equation (2)) based on the results found in the literature (Tables 2 and 3).

$$C_{ef} = a \times C_{in} + b$$  \hspace{1cm} (2)

where $C_{ef}$ is effluent pollutant concentration/load (g m$^{-3}$ or g d$^{-1}$); $C_{in}$ is influent pollutant concentration/load (g m$^{-3}$ or g day$^{-1}$); $a$ is a coefficient (unitless); and $b$ is a coefficient (g m$^{-3}$ or g d$^{-1}$).

When first-order linear equations are adopted, removal efficiencies are expressed as functions of the reciprocal of influent pollutant concentrations/loads (Equation (3)). Because of the negative coefficient, $-b$, pollutant removal efficiency is large when the influent pollutant concentration/load is large.

$$\text{Removal Efficiency (\%)} = \left(1 - \frac{C_{ef}}{C_{in}}\right) \times 100$$

$$= \left(1 - a \frac{b}{C_{in}}\right) \times 100$$  \hspace{1cm} (3)

<table>
<thead>
<tr>
<th>Nitrogen removal equation</th>
<th>Correlation coefficient</th>
<th>HRT (days)</th>
<th>Comparison with max retention time (%Dif)</th>
<th>System</th>
</tr>
</thead>
<tbody>
<tr>
<td>TKN removal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\ln \frac{C_{ef}}{C_{0}} = 0.0129 \times (\text{HRT})$</td>
<td>0.911</td>
<td>125</td>
<td>5.3</td>
<td>Ponds 1, 2 and 3, Mean monthly</td>
</tr>
<tr>
<td>TKN removal rate $= 0.809 \times (\text{TKN loading rate})$</td>
<td>0.983</td>
<td>132</td>
<td>0.0</td>
<td>Total system. Mean monthly</td>
</tr>
<tr>
<td>TKN removal rate $= 0.0946 \times (\text{BOD}_5$ loading rate)</td>
<td>0.967</td>
<td>113</td>
<td>14.4</td>
<td>Total system, Mean monthly</td>
</tr>
<tr>
<td>TKN fraction removed $= 0.0062 \times (\text{HRT})$</td>
<td>0.959</td>
<td>129</td>
<td>2.3</td>
<td>Ponds 1, 2 and 3, Mean monthly</td>
</tr>
<tr>
<td>Ammonia-N removal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\ln \frac{C_{ef}}{C_{0}} = 0.0205 \times (\text{HRT})$</td>
<td>0.798</td>
<td>79</td>
<td>40.2</td>
<td>All data, Mean monthly data</td>
</tr>
<tr>
<td>NH$_3$-N removal rate $= 0.869 \times (\text{NH}_3$-N loading rate)</td>
<td>0.968</td>
<td>92</td>
<td>30.3</td>
<td>Total system, Mean monthly</td>
</tr>
<tr>
<td>NH$_3$-N removal rate $= 0.0606 \times (\text{BOD}_5$ loading rate)</td>
<td>0.932</td>
<td>132</td>
<td>0.0</td>
<td>Total system, Mean monthly</td>
</tr>
<tr>
<td>NH$_3$-N fraction removed $= 0.0066 \times (\text{HRT})$</td>
<td>0.936</td>
<td>121</td>
<td>8.3</td>
<td>Ponds 1, 2 and 3</td>
</tr>
</tbody>
</table>

Table 3 | Equations for TKN removal and ammonia N removal in Middlebrooks et al. (1999)
DISCUSSION

Effluent pollutant concentrations/loads can be described as first-order linear functions of influent pollutant concentrations/loads incorporating other parameters, such as temperature and reactor morphology derived from the existing literature. The number of parameters for ecological WWTPs is limited compared with the complex set of parameters and equations needed for activated sludge models (e.g. Gujer et al. 1995). The existing literature on ecological WWTP kinetics would improve more by introducing activated sludge model methods.

Equation (2) is a common formula in the existing literature. However, the performance of ecological WWTPs are evaluated mainly on the basis of how well effluent pollutant concentrations compare with local criteria (e.g. JICA; Middlebrooks 1999). Therefore, possible studies (e.g. Banerjee et al. 1999; von Sperling 1999; Banda et al. 2005) while Pinto et al. (1996) developed equations which had positive and management.

The y-axis intercept of Equation (2), ‘b’, is zero in many studies (e.g. Banerjee 1997; Middlebrooks et al. 1999; von Sperling 1999; Banda et al. 2005) while Pinto et al. (1996) developed equations which had positive ‘b’ values (Equation (1)). Therefore, possible ‘b’ values in Equation (2) are most likely positive or zero. For each experimental dataset from several stabilisation lagoons, Middlebrooks et al. (1999) calculated first-order linear equations with y-axis intercept values of zero (Table 2). For the annual average data of the four WWTPs in Middlebrooks et al. (1999), the relationship between influent concentration and removal ratio of nitrogen resulted in a positive value of ‘b’ (Figure 1). These results support the conclusion described above, and the relationship shown in Figure 1 is consistent with Equation (3). The meaning of a positive ‘b’ value depends on pollutant parameters. For example, with ecological WWTPs, organic carbon can be produced by phytoplankton production using nutrients under certain conditions.

The following discussion is based on Equations (2) and (3) under conditions with a zero or positive value of ‘b’. Figure 2 shows the relationship between influent pollutant concentrations/loads, \( C_{in} \), and effluent pollutant concentrations/loads, \( C_{ef} \), when ‘a’ equals 0.2. \( C_{ef} \) increases when \( C_{in} \) increases for all the ‘b’ values, from zero to 100. In the shaded triangle area, \( C_{ef} \) is larger than \( C_{in} \) and pollutant removal efficiency has a negative value. Such situations are sometimes found in ecological WWTPs.

Figure 3 shows the relationship between an influent pollutant concentration or load and pollutant removal efficiency when ‘a’ equals (a) 0.2, (b) 0.1 and (c) 0.05, limited to the area of positive removal efficiency. The value of ‘a’ corresponds to the maximum removal efficiency: (a) 80%, (b) 90% and (c) 95%, which is shown as the horizontal line when ‘b’ equals zero. The values of ‘b’ correspond to the y-axis intercept of effluent pollutant concentrations/loads (Figure 2) and the curvature of the relationship between \( C_{in} \) and pollutant removal efficiencies (Figure 3). The curve is smooth when ‘b’ is large, and vice versa.

Equation (3) shows that if pollutant concentrations/loads should be large for ecological WWTPs to have large pollutant removal efficiencies. When examining WWTP performance in terms of water pollutant chemical and bacterial indicators, not only pollutant discharge but also the pollutant removal efficiency should be evaluated, especially when wastewater treatment is pursued beyond sanitation. Evaluations employing bacterial removal efficiencies as well as effluent bacterial concentrations/loads,
which are important from the viewpoint of sanitation or infectious disease prevention, will lead to environmental water quality improvement. This is because bacterial indicators, e.g. *E. coli* and F. coli concentrations, are more directly related to infectious diseases and sanitation. The removal efficiencies of these bacterial indicators may be related to influent organic carbon concentrations as well as influent bacterial concentrations. Effluent bacterial concentrations or loads can be practically controlled not only by the primary biological and ecological processes in WWTPs but also by disinfection. In addition to such WWTP functions, chemical and bacterial pollutant discharge from households and pollutant loads in water bodies can also be decreased by soft interventions in households and natural purification processes in rivers (Tsuzuki *et al.* 2010a, b).

In this paper, the WWTP performance was evaluated in terms of pollutant removal efficiencies and influent pollutant concentrations. The literature evaluated focussed on a broad range of processes, with different operative conditions, different influent characterisations, and different working scales, and none of these parameters are explained here in detail, e.g. hydraulic retention time, chemical and biological reaction rates, morphologies of reaction tanks, length, width and depth, etc. However, a common feature of ecological WWTPs has been extracted from the existing literature, the relationship between influent pollutant concentrations/loads and pollutant removal efficiencies. For planning, management, and operation of ecological WWTPs, other socioeconomic conditions should also be considered, such as monetary and non-monetary benefit–cost ratios of wastewater treatment systems (Tsuzuki & Koottatep 2010; Tsuzuki 2011), and comprehensive analyses should be performed using economical, environmental, technical and socio-cultural indicators in the field of wastewater management (Balkema *et al.* 2002).

The results and discussion in this paper do not necessarily argue only for the importance of increasing influent pollutant concentrations/loads in ecological WWTPs. Such modification in actual WWTPs should only be considered in combination with several other factors including socioeconomic conditions. Moreover, technological development in wastewater treatment may overcome the problem of small influent pollutant concentrations/loads in the future.

**CONCLUSIONS**

The relationships between influent and effluent pollutant concentrations/loads were summarised based on the existing literature. When examining ecological WWTPs, most studies showed first-order linear relationships between influent and effluent pollutant concentrations/loads. When first-order linear relationships are used, pollutant removal ratios can be expressed as first-order linear equations of the reciprocal of influent pollutant concentration/load with negative coefficients. When the influent pollutant concentration/load of an ecological WWTP is small and pollutant removal efficiency is small, influent pollutant concentrations/loads should be increased in order to increase efficiency, especially when evaluating the pollutant removal performance of the WWTP.

The results and discussion in this paper show the importance of pollutant removal efficiencies and influent pollutant
concentrations/loads in addition to effluent pollutant concentrations for evaluation purposes. Influent pollutant concentration/load increases should be considered in some WWTPs especially for those in middle-income countries with small influent pollutant concentrations/loads.

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REFERENCES

Idelovitch, E. 1978 Wastewater reuse by biological-chemical treatment and groundwater recharge. Journal of the Water Pollution Control Federation 50, 2723–2740.
Middlebrooks, E. J. 1985 Nitrogen Removal Model Developed for inclusion in U.S. Environmental Protection Agency.
Reed, S. C. 1984 Nitrogen Removal in Wastewater Stabilization Ponds. USA CRREL Report 84-13, Hanover, NH.


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