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Non-steady-state modelling of faecal coliform removal in deep tertiary lagoons

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Abstract

In Noirmoutier, a French island off the Atlantic coast, secondary effluents flow into a series of four lagoons, 1.4–2.8 m deep, and are reused for agricultural irrigation. The excess water is disposed of to the sea. The aim of this study was to provide a model capable of predicting the microbiological quality of the water pumped for irrigation or discharged to the sea. Meteorological variables, flow rates, physical–chemical characteristics and faecal coliform (FC) contents were monitored for a year and a half. The hydraulic pattern of each lagoon was assumed to be that of completely mixed reactor because of the calculated dispersion numbers and the wind mixing effect. Coliform decay was assumed to follow first order kinetics in each lagoon. Die-off coefficients were calculated in each lagoon using a non-steady-state model. The main bacterial removal mechanism was shown to be solar irradiation. Empirical equations were established to calculate die-off coefficients as a function of received solar energy and temperature. FC die-off rates were higher in the first lagoon and then decreased successively in those following. FC numbers in the different lagoons were predicted with reasonable accuracy in spite of high variation in inlet water quality. The model will facilitate the prediction of water quality under various climatic conditions and different water reuse scenarios and will help to optimise reclamation and storage facilities. © 2002 Published by Elsevier Science Ltd.

Keywords: Tertiary lagoon; Faecal coliform; Die-off kinetics; Modelling; Water reuse

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1. Introduction

Wastewater reuse is becoming increasingly important in integrated water resources management because of the scarcity of water resources and the need for environmental protection. One of the critical factors involved in water reuse implementation is the provision of treated water in compliance with wastewater discharge and reuse standards. Tertiary lagoons have been widely used as the polishing treatment to guarantee the safety of public health and to protect the environment before wastewater discharge or reuse. Furthermore, tertiary lagoons can serve as storage reservoirs to meet peak, seasonal or long-term needs and to provide reliable irrigation supplies.

Low operation and maintenance costs coupled with effective pathogen removal have made stabilisation ponds widespread all over the world. However, the pathogen removal mechanisms and the system performance are not well established. The pathogen removal mechanisms involve a series of complex physical, chemical and biological interactions that occur naturally in aquatic systems. The most significant mechanisms causing decay involve (i) DNA damage caused by sunlight ultraviolet irradiation [1]; (ii) photo-oxidation caused by the formation of singlet oxygen, hydrogen peroxide and other superoxide and hydroxyle radicals due to humic substances adsorbing light and passing to oxygen [1]; (iii) predation and starvation due to lack of nutrients or carbon source [2,3] and (iv) algal toxins [4].

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Nomenclature

B	width of lagoon (m)
H	depth of lagoon (m)
L	length of lagoon (m)
S	surface of lagoon (m^2)
V	water volume of lagoon (m^3)
d	dispersion number
i	no. of lagoon, $i = 5, 6, 7, 8$
j	time (day)
I_0	solar intensity received on the surface of lagoon ($J/cm^2/day$)
I_m	depth-averaged solar intensity received in lagoon ($J/cm^2/day$)
I_x	solar intensity at depth x in lagoon ($J/cm^2/day$)
k	die-off coefficient (day^{-1})
k_T	die-off coefficient at temperature T (day^{-1})
k_{20}	die-off coefficient at temperature 20°C (day^{-1})
K	light extinction coefficient (m^{-1})
N_0	bacterial concentration in the influent (CFU/100 ml)
N	bacterial concentration in the effluent (CFU/100 ml)
Q	water flow rate of lagoon (m^3/day)
t	hydraulic retention time (day)
T	water temperature (°C)
υ	kinematic viscosity of the water (m^2/day)
θ	temperature coefficient

Up to now, *E. coli* and faecal coliforms (FC) have been the most widely used microorganism indicators in investigating the inactivation mechanisms in the lagoons, as they can be rapidly and reliably identified and enumerated [5]. Coliform decay is usually considered to follow first order kinetics:

$$dN/dt = -kN, \quad (1)$$

where N is effluent bacterial concentrations; t is mean hydraulic retention time (day); k is die-off coefficient (day^{-1}). Thus, assuming ideal hydraulic flow patterns, the bacterial removal in an individual lagoon is expressed through frequently used formulae:

$$N = N_0 e^{-k \cdot t} \quad (2)$$

for plug-flow pattern and closed lagoon. Where N_0 is the influent coliform concentration.

$$N = N_0/(1 + k \cdot t) \quad (3)$$

for completely stirred tank reactor (CSTR) pattern. The CSTR hydraulic model is the most widely used in engineering design.

Many studies assumed that temperature was the most important factor determining pathogen decay [6–10]. The widely used expression of k as a function of temperature was given by Marais [11]

$$k_T = k_{20} \times \theta^{(T-20)}, \quad (4)$$

where θ is temperature coefficient; T is water temperature (°C); k_T and k_{20} are die-off coefficients at temperature T and 20°C (day^{-1}). It is recognised that these θ and k_{20} values reported in the literature scatter appreciably. This implies that the temperature would not be the sole factor influencing bacterial die-off coefficients, and other factors should be taken into consideration [12–14]. Moreover, it is difficult to obtain a universal kinetics law that can be applied to any lagoon due to different water quality, environmental conditions, geometric parameters and hydraulic regimes of lagoons. Some empirical formulae involving variables, such as solar radiation, BOD, pH, dissolved oxygen concentration and lagoon depth, were proposed in the literature [1,15,10,16].

Most bacterial removal models are based on the hypothesis that the inflow of the lagoon equals the outflow and the lagoon operation results in a steady-state regime. The effects of rainfall, evaporation and infiltration are neglected. The measured data in our research showed that the daily loss of water in the lagoons could account for 50% of the inflow in summer. Moreover, such models are not suitable for the tertiary lagoons used as reclaimed water reservoirs. The inflow rate and water quality are of high seasonal and daily variations. When stored water is pumped for agricultural irrigation in summer, the outflow of the lagoons can be several times higher than inflow; then lagoons are operated in a non-steady state [17,18]. Therefore, it is necessary to use non-steady-state models to investigate and predict the disinfection performances of lagoons used for reclaimed water storage.

In order to gain a better understanding of bacterial removal mechanisms, this study investigated the factors influencing FC disinfection in four deep lagoons in series in the Atlantic Ocean climate of Western Europe. Secondary effluents are stored in the lagoons in the rainy winter and pumped for agricultural irrigation from April to September. Microbiological and physical–chemical water quality in the entrance and exit of each lagoon were monitored bimonthly for a year and a half. Inlet and outlet flow rates and climatic parameters were also monitored.

Based on field monitoring data, FC die-off kinetics is established in different lagoons. A non-steady state perfectly mixed reactor model allows the prediction of the variation of coliform removal in the four lagoons

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under different climatic conditions and various water reuse requirements.

2. Materials and methods

2.1. Site description

The study was performed in a municipal wastewater treatment plant (55,000 p.e.) in Noirmoutier, a French island situated in the Atlantic Ocean. Wastewater agricultural irrigation has been implemented for 20 years in the island due to lack of fresh water. The combined effluents from aerated lagoons and secondary activated sludge systems flow into four tertiary lagoons in series (Lagoons 5–8 on Fig. 1) to remove pathogens and to store water for agricultural irrigation. Treated wastewater enters into the lagoons continuously. The inflow and outflow of Lagoon 5 are continuous over the whole year; thus a minimum removal efficiency is ensured. The following three lagoons are operated in a non-steady-state regime according to irrigation needs. During the irrigation period, when the water level in Lagoon 8 is too low to allow further abstraction, water is pumped directly from Lagoon 6 and Lagoon 7 is isolated. When agricultural water needs decrease in August, Lagoons 6–8 are refilled. After that the lagoons are operated continuously. The surplus effluent is discharged into the sea.

2.2. Climatic characteristics

The climate is characterised as Atlantic coastal climate, dry in summer and rainy in winter. The average annual rainfall is 611 mm (Table 1). The evaporation rate is more than precipitation from April to September, corresponding to the period of irrigation (Table 2). The peak period of temperature and solar intensity is from May to August. The island is always windy but the wind force is stronger in winter.

2.3. Hydraulic characteristics of the lagoons

The hydraulic flow pattern of the lagoons is a critical factor in bacterial removal modelling, since it controls the retention time distribution. In the absence of tracer tests, its determination is somewhat difficult. It is influenced by climatic factors, such as atmospheric temperature, wind strength and direction, and the hydraulic and configuration parameters, such as liquid flow rate, lagoon shape and dimension, position and structure of inlet and outlet, etc.

Among these variables, the pond geometry seems to be one of the most important factors. Nameche and Vasel [19] reported that the hydraulic regimes of the lagoons with length/width ratio $\leqslant 8$ were similar to perfectly mixed reactors. The maximum error in lagoon efficiency estimation did not exceed 13%.

Disperse flow pattern is regarded as a pattern close to reality. The dispersion number d can be calculated from two empirical formulae [20,21].

- Agunwamba et al. [20]

$$d = 0.102\left[\frac{3(B+2H)t}{4LBH}\right]^{-0.410}\left(\frac{H}{L}\right) \times \left(\frac{H}{B}\right)^{-(0.981+1.385H/B)} \qquad (5)$$

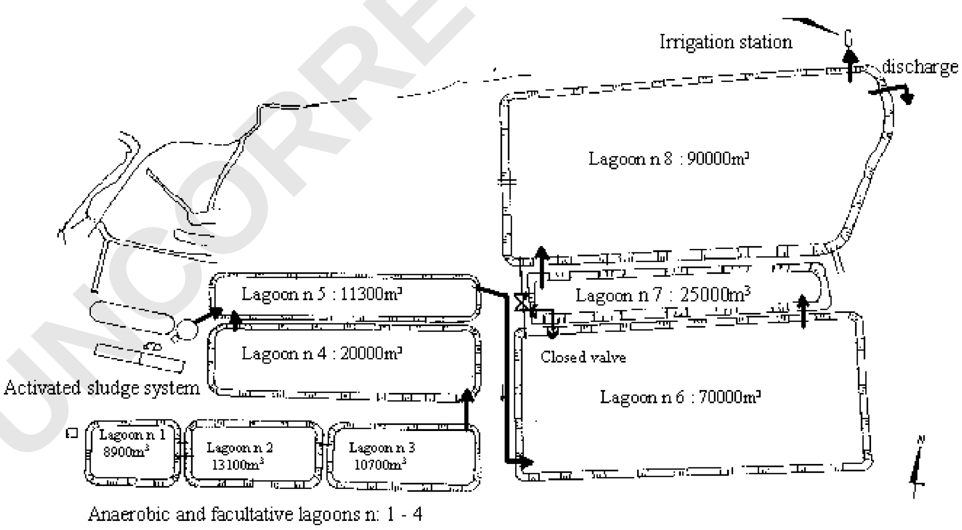

Fig. 1. Layout of La Salaisière wastewater treatment plant.

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Table 1
Monthly climatic characteristics in Noirmoutier

	Precip. (mm)	Evap. (mm)	*P*–*E* (mm)	Temperature (°C)			Wind speed (m/s)			Solar intensity (J/cm^{-2}/day)
				Min	Max	Mean	Min	Max	Mean	
Jan.	91	14.1	76.9	6.0	10.6	8.3	6.0	24.0	13.1	411
Feb.	57	23.6	33.4	8.1	12.2	10.1	6.0	34.0	15.0	658
Mar.	61	53.7	7.3	6.3	12.2	9.3	7.0	17.0	10.9	1268
Apr.	5	83.2	−78.2	8.4	15.5	11.9	6.0	18.0	10.6	1556
May	26	114.2	−88.2	11.7	20.1	15.9	6.0	23.0	13.0	2214
Jun.	69	140.6	−71.6	13.8	21.7	17.7	6.0	19.0	10.8	2413
Jul.	84	152.8	−68.8	17.5	26.4	21.9	7.0	14.0	9.8	2284
Aug.	23	129.5	−106.5	17.5	26.7	22.1	6.0	18.0	10.5	2095
Sep.	52	83.7	−31.7	13.5	19.7	16.6	6.0	17.0	10.9	1369
Oct.	134	44.4	89.6	13.5	19.9	16.7	5.0	29.0	12.4	1013
Nov.	137	18.7	118.3	7.4	13.4	10.4	7.0	29.0	14.6	526
Dec.	109	12.7	96.3	4.2	8.3	6.3	6.0	20.0	11.8	293

Table 2
Monthly influent and irrigation water volumes (m^3)

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Influent	108,900	92,142	88,870	88,073	94,418	71,723	136,248	161,095	68,378	55,731	75,756	84,908
Irrigation				35,080	44,320	135,240	32,059	14,770	8877			

- and Yanez [21]

$$d = \frac{(L/B)}{-0.261 + 0.254(L/B) + 1.014(L/B)^2}, \qquad (6)$$

where L, B and H are length, width and depth of the lagoon (m); t is hydraulic retention time HRT (day); υ is kinematic viscosity of the water (m^2/day), $\upsilon = 0.325\,T^{-0.45}$, according to the empirical formula of Sperling [22]. Yanez's formula comprises only pond geometry as variable while Agunwamba's formula estimates the dispersion number more precisely with HRT and temperature. The calculated dispersion numbers of the four lagoons indicate that the water is well mixed in the lagoons, particularly in Lagoons 6 and 8 (Table 3). However, these formulae do not allow for the impact of wind. In Noirmoutier, the average annual wind speed is as high as 12.3 m/s, which leads to a very good mixing effect in the lagoons. Thus in this study, the hydraulic pattern is assumed to be CSTR in each lagoon, because of the geometric dimension of the lagoons (Table 3) and the effect of relatively strong winds over the whole year.

The HRT of each lagoon is calculated from the water volume and inflow rate. The shortest retention time occurs in summer due to agricultural irrigation (Fig. 2). A large amount of stored water is pumped out in June and July and then the rate gradually decreases (Table 2). With the increased volume of pumped water, water volume in the Lagoon 8 cannot meet the water needs in late June and water is withdrawn from Lagoon 6 directly. During this period, no water enters Lagoons 7 and 8 and the shortest total HRT reaches 21 days. With the decreased water needs in August, the lagoons are filled gradually and retention times increase.

2.4. Water quality in the lagoons

The physical–chemical characteristics of the lagoons' influent and final effluent are summarised in Table 4. Water quality of the influent is worse from mid-June to November than in other periods of the year because of the population increase due to summer tourism. Suspended solids (SS), organic concentrations, and FC numbers are high in summer. Organic matter and nitrogen contents are degraded in tertiary lagoons. The average degradation efficiencies of BOD and NH_4^+ are about 51% and 74%, respectively. In the effluent of Lagoon 8, SS concentration is higher than in secondary effluent due to algal growth, while pH and DO rise slightly.

As FC is commonly used in water reuse and discharge guidelines, it is used as the microbiological indicator for water quality modelling. FC contents in the influent of Lagoon 5 are around 10^4–10^6 CFU/100 ml. The peak

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Table 3
Features of La Salaisière tertiary lagoons

Lagoons	Volume (m^3)	Ratio L/B	Depth (m)	Surface (m^2)	HRT (day)			Infiltration (mm/day)	Dispersion number	
					Min	Max	Mean		d_{Yanez}	$d_{Agunwamba}$
5	11,300	5.8	1.4	8071	3	20	9	12.73	0.16	0.21–0.38
6	70,000	1.9	2.2	31,818	16	135	54	1.84	0.49	0.31–0.62
7	25,000	6.5	2.8	8929	0	50	18	3.06	0.15	0.17–0.34
8	90,000	1.7	2.3	39,130	0	180	63	1.84	0.55	0.30–0.64
Total	196,300			87,949	21	385	144			

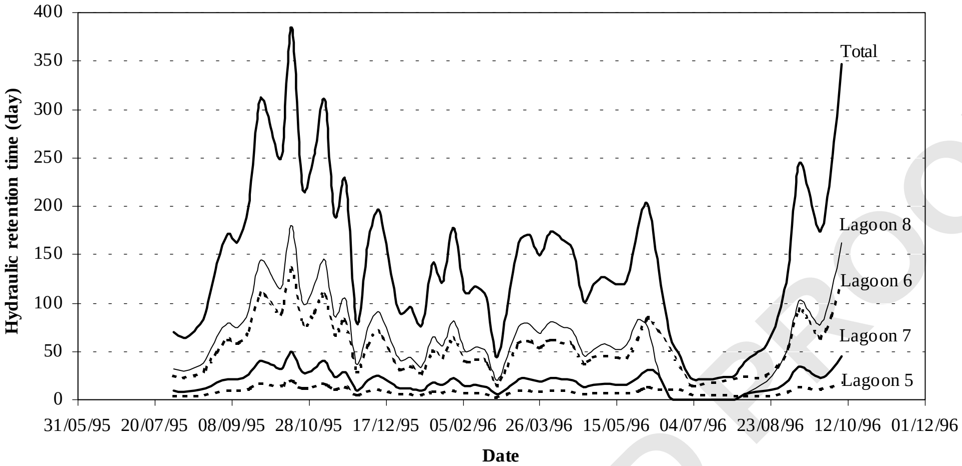

Fig. 2. Hydraulic retention time in La Salaisière tertiary lagoons.

concentration occurs in summer (Fig. 3). The mean FC reduction is about 0.8 log in Lagoon 5, and 1.8 log in Lagoon 6, while FC reduction decreases to 0.2 log in Lagoon 7 and is negligible in Lagoon 8.

The seasonal variation of FC reduction with cumulated mean hydraulic retention time in the four lagoons is described in Fig. 4. At the same season, die-off rates differ from one lagoon to another. And at all the seasons, after FC numbers have been reduced by 2 orders of magnitude, the die-off rate decreases significantly. This suggests that FC die-off kinetics should be studied separately in the four lagoons. It is feasible to suppose that coliform reduction follows first order kinetics in each single lagoon.

2.5. Modelling FC removal

The model is based on bacterial mass balance (Fig. 5). It is expressed as

$$V_i\frac{\Delta N(i,j)}{\Delta t} = Q_{(i-1,j)}N_{(i-1,j)} - Q_{(i,j)}N_{(i,j)} - k_iN_{(i,j)}V_i, \quad (7)$$

where i is the ith lagoon, from 5 to 8; V_i is water volume in the Lagoon i (m^3); $\Delta N_{(i,j)} = N_{(i,j)} - N_{(i,j-1)}$; Δt is the time step, $\Delta t = 1$ day; $N_{(i-1,j)}$ and $N_{(i,j)}$ are FC concentrations at the inlet and in Lagoon i respectively in the day j (CFU/100 ml); $Q_{(i-1,j)}$ and $Q_{(i,j)}$ are the inflow and outflow rates of Lagoon i (m^3/day); k_i is the die-off coefficient of Lagoon i.

Flow rates and lagoon water volumes are calculated through water balances, at each time step, from inlet flow rate in Lagoon 5, rainfall, evaporation, infiltration and irrigation withdrawal.

3. Results and discussions

3.1. Variation of k coefficients in the tertiary lagoons

Die-off coefficients are calculated according to Eq. (7). Other variables have been obtained from the field monitoring data, including FC numbers in the entrance and exit of each lagoon, flow rates of inflow, outflow, rainfall, evaporation and withdrawal. Infiltration rate is assessed based on water balance. The coefficients vary significantly with the season and in different lagoons as shown in Fig. 6.

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Table 4
Physical–chemical characteristics of secondary effluent and final effluent from Lagoon 8

	COD (mg/l)		BOD_5 (mg/l)		SS (mg/l)		NH^{4+} (mg N/l)		Temperature (°C)		pH		DO (mg/l)	
	Infl	Effl	Infl	Effl	Infl	Effl	Infl	Effl	Infl	Effl	Infl	Effl	Infl	Effl
Min	67	41	2	2	2	5	19.9	0.5	4.4	3.6	6.51	6.66	1.2	3.9
Max	112	104	46	21	58	139	51.1	18.2	23.2	24.6	8.22	9.01	17.4	14.2
Mean	88	62	2	6	25	38	37.0	9.5	17.2	13.8	7.60	7.90	6.7	7.7

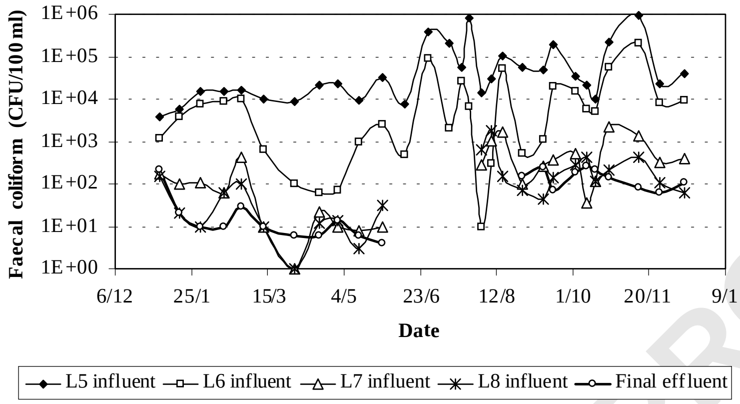

Fig. 3. FC contents in La Salaisière lagoons.

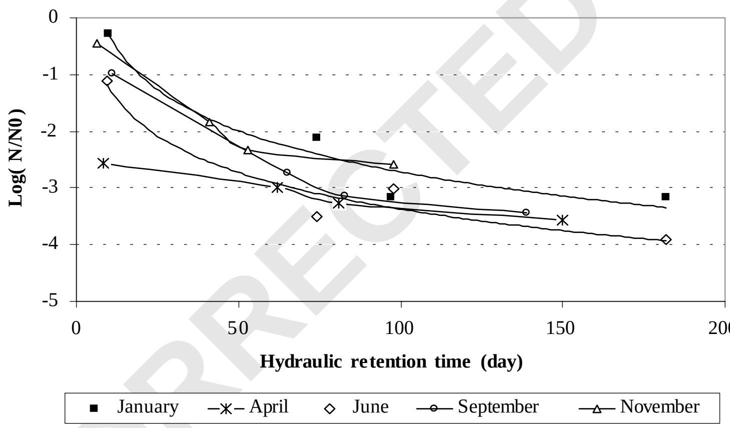

Fig. 4. Variation of FC reduction with hydraulic retention time at different sampling period.

The calculated k values indicate that bacterial removal is faster and more important in Lagoon 5, and that die-off coefficients then decrease gradually in the following lagoons. The first two tertiary lagoons remove a large part of the FC with a mean reduction of 2.4 log units. The variation of the die-off coefficients is particularly significant in Lagoon 5, from 0.08 day^{-1} in winter to 58 day^{-1} in summer. It may be associated with climatic conditions and the variation of water quality. It is found that k_5 values are very high in April and May, and fairly low in June and July. In April and May, the solar intensity is quite high and water quality of the secondary effluent is the best in the year. Moreover, water has been stored in the lagoons for a long time. While in June and July, raw water quality is lower and water flow rises due to the large number of tourists. This increases the hydraulic and organic loads of the activated sludge and aerated lagoon systems. As a result, suspended solids concentration in the secondary effluent is very high and the water colour in Lagoon 5 is brown. This suggests that suspended solids concentra-

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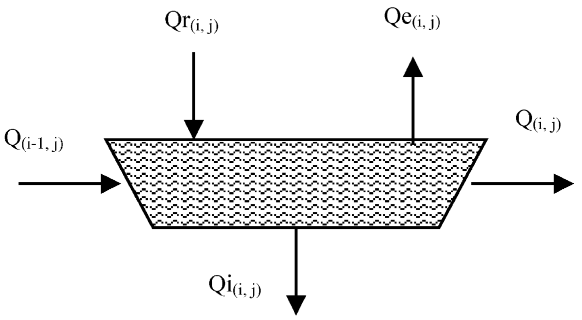

Fig. 5. Schematic diagram of water flows in Lagoon *i*.

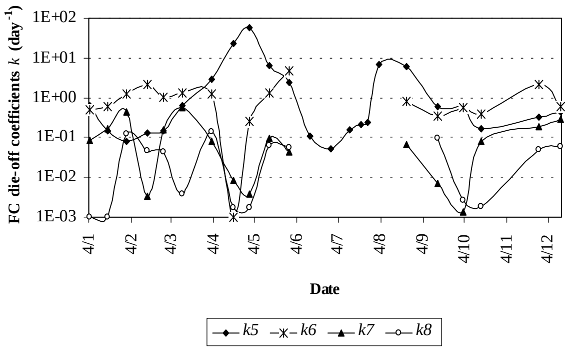

Fig. 6. Seasonal variation of FC die-off coefficients in Lagoons–8.

tion or a light absorbance coefficient should be included in the prediction of kinetic constants.

The coefficient k_6 varies in the range of 0.25–5.0 day^{-1}. But k_7 and k_8 are fairly constant and range from 0 to 0.50 and 0 to 0.14 day^{-1}, respectively.

3.2. *Predicting k coefficients*

Because die-off coefficients vary greatly with season, especially in Lagoon 5, the prediction of k coefficients should take into account climatic and water quality factors.

The sunlight intensity received in the basins varies with depth according to Beer's law:

$$I_x = I_0 e^{-Kx}, \quad (8)$$

where I_x is the solar intensity (J/cm^2/day) at depth x (m); I_0 is the solar intensity received on the surface of lagoon (J/cm^{-2}/day); K is light extinction coefficient (m^{-1}), calculated from an empirical formula: $K = 0.69 \times \text{SS} + 24.09$; and SS: suspended solids concentration (mg/l). I_x can be integrated over the entire depth H (m) to yield I_m the depth-averaged solar intensity received in the lagoon (J/cm^2/day):

$$I_m = I_0(1 - e^{-KH})/KH. \quad (9)$$

Multiple regression shows that k_5 coefficient depends more on solar intensity received in the lagoon than temperature. Temperature can explain only 31% of the variation of the calculated k_5 values, while solar intensity (I_m) can explain 78% of the variation (Table 5). The predictive accuracy increases to 87% when these two parameters are taken into account together (Eq. (10)). Other water quality variables, such as BOD, pH, DO, contribute very little to k_5 prediction. This suggests that solar radiation disinfection is the prevailing decay mechanism in the first tertiary lagoon. The values of k_6 can be obtained also with the combination of both I_m and temperature (Eq. (13)), and a relatively good prediction is gained.

As to the stable values of k_7 and k_8, it would be feasible to utilise mean die-off coefficients, 0.13 and 0.05 day^{-1} respectively, to estimate the bacterial contents in Lagoons 7 and 8. Thus, the calculated die-off coefficients can be reintroduced into Eq. (7) to estimate FC concentration in each lagoon. The values for k_5 and k_6 are calculated from Eqs. (10) and (13), and k_7 and k_8 are mean values. The comparison of the predicted and observed FC concentrations is shown in Fig. 7. The peak FC content in the final effluent which occurs in July is the result of water reuse. As mentioned previously, irrigation water is pumped directly from Lagoon 6 if the water level in Lagoon 8 is too low to be drawn. Thus, the water quality of the final effluent is lower due to short retention time. Nevertheless, reclaimed water quality can still meet WHO waste water unrestricted irrigation guidelines—1000 FC/100 ml.

Table 5
Regression equations for die-off coefficients estimation

Equation	R^2	Equation number
$k_5 = 0.019 \times 0.915^{(T-20)} e^{0.170 I_m}$	0.871	(10)
$k_5 = 0.063 \times e^{0.121 I_m}$	0.783	(11)
$k_5 = 0.099 \times e^{0.172 T}$	0.314	(12)
$k_5 = 0.065 \times 0.915^{(T-20)} e^{0.191 I_m}$	0.783	(13)

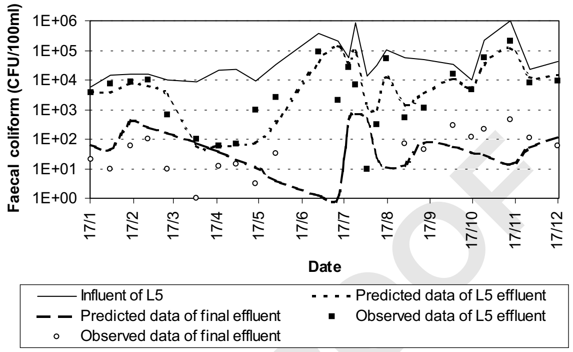

Fig. 7. Comparison of the predicted and observed FC concentration in the effluents of Lagoons 5 and 8.

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The predicted results fit the observed data fairly well. However, this calibration is performed with the same data for the calculation of die-off coefficients. The model would be checked with the data collected from other years.

4. Conclusions

The study of coliform reduction kinetics in tertiary lagoons is of great importance in the designing of lagoon systems and the prediction of the effluent water quality. A bacterial mass balance model was developed to investigate FC decay and predict FC removal in tertiary lagoons. This non-steady-state model allows for the variation of water quality, inlet flow rate, rainfall, evaporation, infiltration and agricultural water withdrawals. It is assumed that the hydraulic regime of the lagoons is CSTR and FC decay follows first order kinetics in each lagoon. Based on field monitoring data, FC reduction kinetics in the four tertiary lagoons was studied.

Some primary conclusions can be drawn:

1. FC die-off coefficients differ from one lagoon to another and vary with the season. Die-off rates are higher in the first lagoon and then decrease successively in those following.
2. Multiple regression reveals that the main factors influencing FC reduction are the depth-averaged solar intensity I_m and temperature. However, the contribution of I_m to FC reduction is more important in the first tertiary lagoon than in those following. Solar radiation disinfection is the prevailing mechanism responsible for FC die-off.
3. Effluent microbiological qualities in the different lagoons could be predicted with reasonable accuracy, from inlet flow rate, irrigation withdrawal, volume and depth of lagoons, climatic conditions (rainfall, evaporation, solar intensity and temperature) and the water quality only described by the concentration of suspended solids. However, the empirical equations developed to calculate FC die-off coefficients are still limited to Noirmoutier case study. Better understanding of the impact of water quality on bacterial removal may help to explain the differences in the die-off kinetics of successive lagoons and the empirical equations used for their calculation. It may help also to work out expression of die-off kinetics which can be extended to other facilities.

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