Modelling of bacterial removal in wastewater storage reservoir for irrigation purposes: a case study in Sicily, Italy

S. Barbagallo*, F. Brissaud, G.L. Cirelli*, S. Consoli*, and P. Xu****

* Dipt. di Ingegneria Agraria, Univ. degli Studi di Catania, Via S. Sofia 100, 95123 Catania, Italy
(E-mail: *simona.consoli@unict.it*)

** Univ. Montpellier II, Case 57, 34095 Montpellier, France

Abstract In arid and semiarid regions the reclamation and reuse of municipal wastewater can play a strategic role in alleviating water resources shortages. Public awareness is growing about the need to recycle and reuse water for increasing supply availability. Many wastewater reuse projects have been put in operation in European and Mediterranean countries adopting extensive treatment systems such as aquifer recharge, lagooning, constructed wetlands, and storage reservoirs, mainly for landscape and agricultural irrigation. In agricultural reuse systems, there is an increasing interest in extensive technologies because of their high reliability, and easy and low cost operation and maintenance. Wastewater storage reservoirs have become the option selected in many countries because of the advantages they present in comparison with other treatment alternatives, namely the coupling of two purposes, stabilization and seasonal regulation. This paper describes an example of a wastewater storage system, built in Caltagirone (Sicily, Italy). The storage results in a tertiary treatment of a continuous inlet flow of activated sludge effluents. The prediction of the microbiological water quality has been evaluated by means of a non-steady-state first-order kinetic model. Single and multiple regressions were applied to determine the main variables that most significantly affected die-off coefficients. The proposed model has been calibrated using the results of a field monitoring carried out during a period from March to October 2000.

Keywords Effluent reuse; modelling bacteria removal; stabilisation reservoir; wastewater storage

Water Science and Technology: Water Supply **Vol 3 No 4 pp 169–175**

Introduction

Agricultural irrigation with recycled wastewater is becoming a common and rapidly increasing practice in arid and semi-arid regions. Reservoirs are an essential component of irrigation reuse schemes (Barbagallo *et al.*, 2001a and b). They serve two objectives: (a) storing water for a few days or several months, and (b) improving the stored water quality. Prediction of bacterial water quality is essential to provide an indication of health risks posed by faecal contamination (Wilkinson *et al.*, 1995) and to determine whether the reused water will reliably meet current health regulations. In the last few decades, much research has been carried out with the objective of predicting the bacterial removal resulting from the complex physical, chemical and biological interactions that occur naturally in aquatic systems (Xu *et al.*, 2002).

Common modelling of coliform removal in lagoons has long relied on three assumptions, which led to the well known Marais's Equation (1974): (a) coliform decay is a first-order kinetic process, (b) inlet and outlet flowrates are equal and constant, and (c) lagoons can be considered as perfectly mixed reactors. The first hypothesis provides a fair approximation of observed coliform decay; it should be valid for deep lagoons and reservoirs as well; die-off coefficients incorporate the effects of temperature and solar irradiation (Sarikaya *et al.*, 1987). The second assumption does not take infiltration, rainfall and evaporation into account; furthermore, it is not valid for reservoirs which are operated as seasonal storage. Therefore, and as demonstrated by Juanicó and Shelef (1994), it is necessary to use non-steady-state models. Perfectly mixed models can fit the needs of physico-chemical performance prediction but they are not always appropriate for coliform removal; mixing is never immediate and is strongly dependent on climatic conditions (Brissaud *et al.*, 2000 and 2003). This third assumption is likely to provide poor representations of the hydrodynamic behaviour of reservoirs, which is strongly affected by thermal stratification.

FC removal was monitored in a 5 m deep storage reservoir located in Eastern Sicily, together with climate parameters. The aim of this paper was to assess whether a simple non-steady-state model, assuming coliform decay is a first-order kinetic process and the reservoir a perfectly mixed reactor, can provide proper representation and prediction of the bacterial quality of the stored water.

Material and methods

The earth unlined reservoir has a maximum capacity of about 25,000 m^3 and a maximum depth of about 5 m. It was fed with secondary treated wastewater discharged from the activated sludge treatment plant of Caltagirone (Eastern Sicily). Treated wastewater inflow was continuous throughout the monitoring period, from March 6 to October 30, 2000, while discharge was discontinuous, depending on irrigation demand (Figure 1). In early March, around 11,000 m^3 treated wastewater were in the reservoir, remaining from the previous year storage operation. The entire duration of the study can be divided into two stages: (a) fill up (March 6 to May 1): in this stage approximately 7,000 m^3 wastewater were accumulated, after evaporation and infiltration losses; inflow rate varied between 440 m^3 and 2,600 m^3/d; and (b) irrigation (May 2 to October 30): treated wastewater continued to enter into the reservoir, with an average daily input of 300 m^3 to 4,000 m^3; at the same time reservoir water was continuously discharged to irrigate citrus orchards at a daily outflow rate between 330 and 3,000 m^3/d.

Water samples were collected at intervals of 7 to 14 days at three sampling locations: (a) two at the point of maximum depth, approximately at the same distance from the inlet and outlet, respectively at 0.2 m below the water surface and 0.5 m above the bottom of the reservoir; and (b) one near the reservoir embankment (about 10 m from the inlet) at a depth varying between 0.6 and 1.5 m (always corresponding to half of the water depth at the time of sampling).

Samples were analysed according to *Standard Methods* (APHA, 1999) for the following parameters: SS (180°C), BOD_5, COD, total phosphorus, nitrogen (Kjeldahl, ammonia, nitrates and nitrites), TC, FC, *E. coli*, fecal streptococci, *Salmonella* spp. and helminth eggs. The following parameters were measured *in situ* using portable equipment: temperature, electrical conductivity (EC), pH and DO.

Assuming that coliform decay is a first-order kinetic process and the reservoir a perfectly mixed reactor, FC contents should verify the non-steady-state bacterial mass-balance expressed by Eq. (1),

$$\frac{\Delta(VN_t)}{\Delta t} \approx V \cdot \frac{\Delta N_t}{\Delta t} = I_t \cdot N_0 - O_t \cdot N_t - K_T \cdot N_t \cdot V \qquad (1)$$

where,
Δt: the time step between two following samplings;
V: the water volume in the reservoir (m^3);
I_t and O_t: the inflow and outflow rates (m^3/d) respectively, during a time step;
N_0 and N_t: the FC concentrations (CFU/100 ml), respectively at the inlet and in the reservoir at the time t;

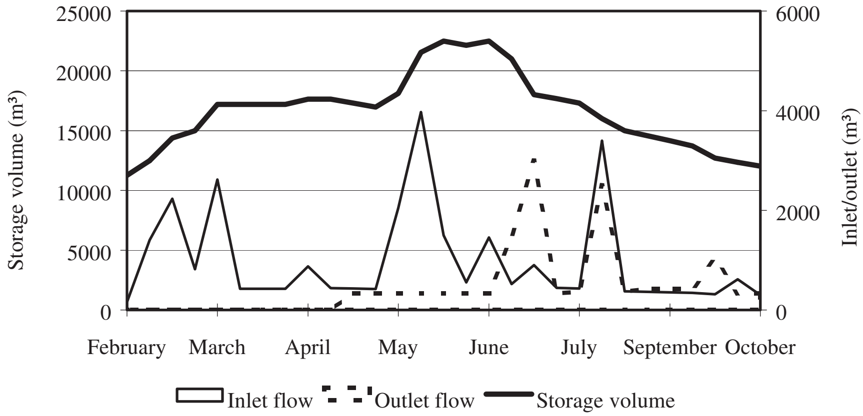

Figure 1 Stored water volume and inlet and outlet flow rates

$\Delta N_t = N_t – N_{t-\Delta t}$; and
K_T: the FC die-off coefficient.
V, I_t and O_t are measured values. N_t is the average of FC concentrations measured at the three sampling locations. Eq. (1) was used to calculate die-off coefficients from observed data.

As the bacterial decay is known to greatly vary with climatic conditions, it was attempted to relate die-off coefficients calculated from Eq. (1) to recorded water temperature, T (°C), and the depth averaged solar intensity, I (J/cm^2·d), using regression techniques. The received solar intensity was evaluated by the following expression:

$$I = I_0 \cdot (1 - e^{-KH}) / KH \qquad (2)$$

where,

I_o: the solar intensity received at the surface of the reservoir (J/cm^2·d),
K: the light extinction coefficient (m^{-1}), calculated from an empirical formula K = 0.69·SS+25 (Xu *et al.*, 2002),
SS: the suspended solid concentration (mg/L), and
H: the water depth (m) which varied between 2.5 m and 4.5 m.

The correlation between K_T and the climate data was validated by introducing K_T values calculated from climate data into the bacterial mass balance (Eq. (1)) so as to calculate FC content in the reservoir. Calculated values were compared with the observed FC concentrations. Then, a more simple model was tested, assuming that the hydrodynamic regime is the succession of steady states with different mean residence times (MRT); K_T values were those derived from climate data. The expression of N_t is given by Eq. (3).

$$N_t = \frac{N_o}{1 + K_T \cdot MRT} \qquad (3)$$

MRT was calculated according to Juanicó formula (Juanicó, 1999):

$$MRT_t = \frac{[(MRT_{t-1} + 1) \cdot V_{t-1}] + (0.5 \cdot I_t)}{(V_{t-1} + I_t)} \qquad (4)$$

Results

Along the monitoring period, FC contents measured at the surface, bottom and near the embankment varied in the same manner, with a few exceptions (Figure 2). Differences

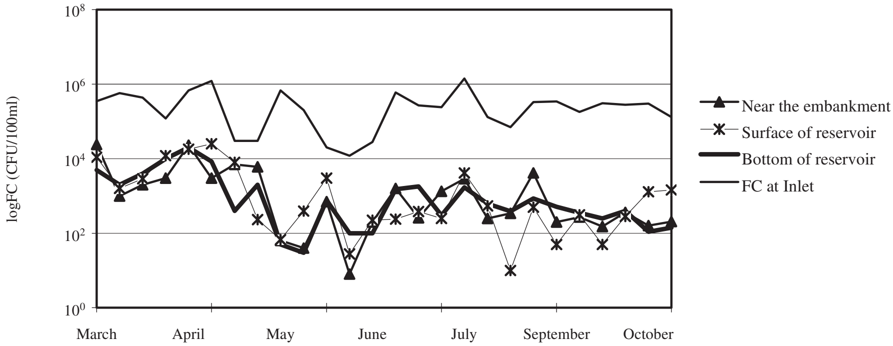

Figure 2 FC concentrations measured near the embankment, at surface, bottom and inlet of the reservoir

between concomitant values were relatively low; thus FC content of the stored water can be represented by the mean of the 3 measured values. This is not to say that the reservoir always behaved as a nearly perfectly mixed reactor. Differences between bottom and surface contents were noticeable and, surprisingly, sometimes positive and sometimes negative. The same observation was made for the differences between FC contents measured near the embankment and at the surface or the bottom. This means that the hydrodynamic behaviour of the reservoir was affected by changes in the operation procedure (inflow and outflow) and the climate (wind, temperature and solar radiation). Behaviour changes were illustrated by differences in temperature, EC, DO and pH profiles (Figure 3). However, owing to the relatively long observation time step, the evidence of links between FC content and operation and climatic conditions was not feasible.

Experimental results confirmed that treated wastewater storage with continuous inflow represents a valuable treatment option for FC removal. Inlet water had a FC concentration of about 10^5 – 10^6 CFU/100 ml. FC reduction ranged between 94.70% to 99.99%. The average removal was 2.3 Ulog. FC content seldom exceeded 10^3 CFU/100 ml during the irrigation period. The removal was low in early Spring, during the first feeding period

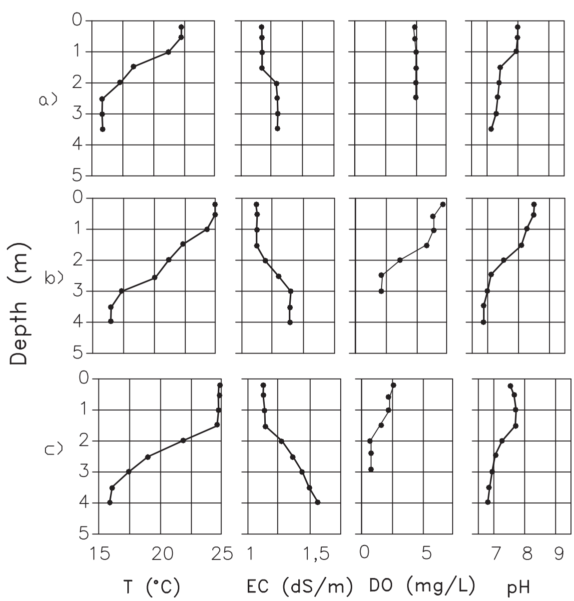

Figure 3 Temperature, EC, DO and pH vertical profiles on May 2, May 30 and June 13 2000

and greater during the end of the irrigation stage (September), due to the bettering of climatic conditions (Figure 4).

The die-off coefficient, K_T, which was calculated using the Eq. (1), showed great variations during the observation period (Figure 5). K_T values ranged between 0.04 and 40 d^{-1}, with a mean value of 2.6 d^{-1}. K_T was low in March and April, with values less than 1 d^{-1} and higher in late Spring, Summer and early Fall, with a mean value higher than 5 d^{-1}. Peak values could be associated with chance variations in inlet FC contents.

The seasonal evolution of the die-off coefficient can be partly explained by the climate conditions. Temperature and solar radiation were lower in early Spring than during the rest of the monitoring period (Figure 6).

Therefore, relating the die-off coefficient to climate variables could be envisaged. Results from multiple regressions have highlighted a good correlation ($R^2 = 0.91$) between die-off coefficients, received solar intensity I and temperature T. However, due to the mathematical procedure, low K_T values are likely not to have been modelled as accurately as high values. The regression equation for die-off coefficient estimation was the following:

$$K_T = 0.676 \cdot (0.915^{(T-20)} \cdot e^{0.17 \cdot I}) \quad (5)$$

Values derived from Eq. (5) are 35 times higher than those determined by Xu *et al.* (2002) for a 1.4 m deep lagoon receiving secondary treated effluent of Noirmoutier, France. This important gap cannot be explained by the influence of the water depth on

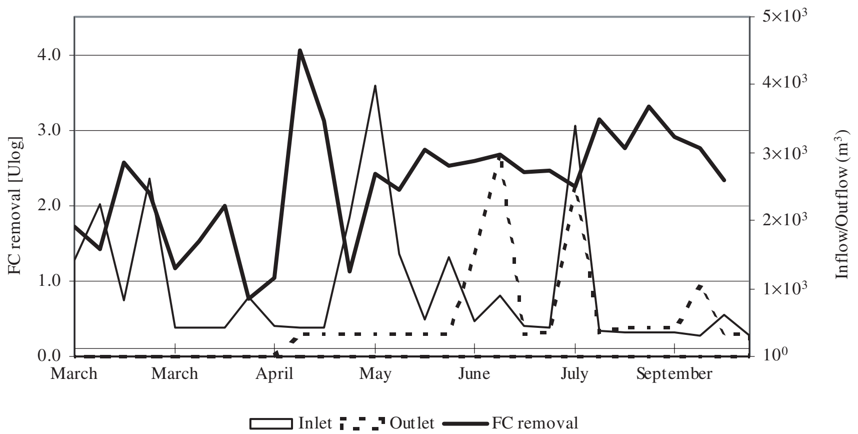

Figure 4 Inflow and outflow rates and FC removal (calculated with the usual expression log FC inlet – log FC reservoir)

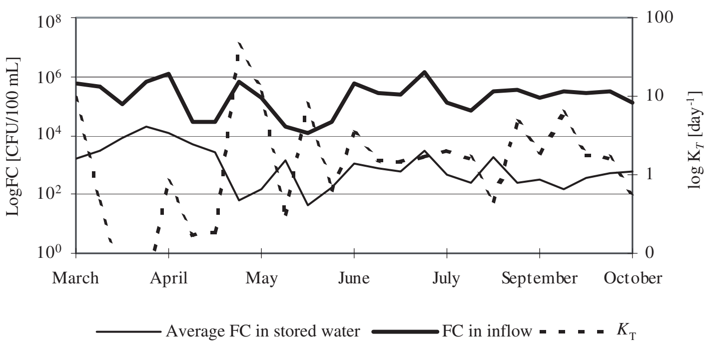

Figure 5 Variation of FC and die-off coefficient (K_T) in the reservoir

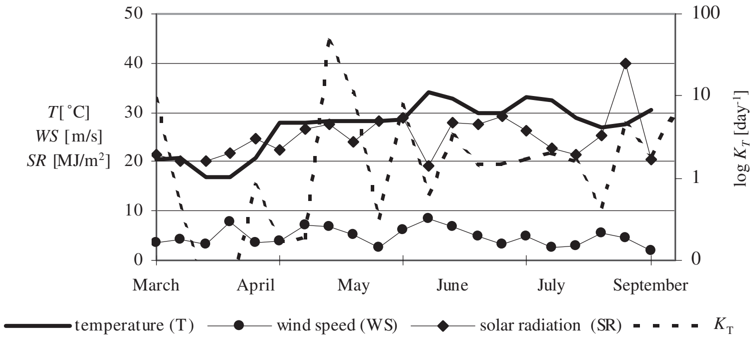

Figure 6 Climatic data and K_T calculated from the bacterial balance (Eq. (1))

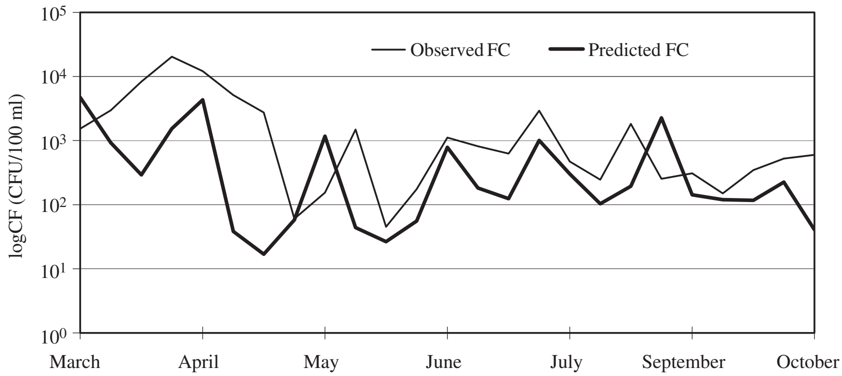

Figure 7 FC concentration observed and predicted through a bacterial balance (Eq. (1))

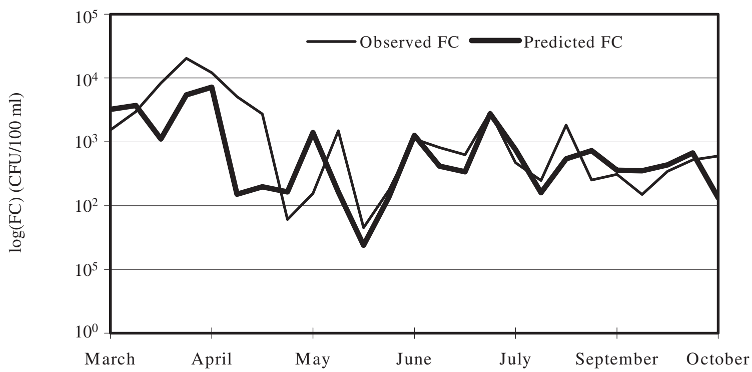

Figure 8 Comparison of the predicted and observed FC concentration in the effluent of the reservoir using the Eq. (5)

received solar radiation. It suggests essential differences in the removal mechanisms. As the lagoon is only 1.4 m deep and the wind always blowing, water in the Noirmoutier lagoon is permanently stirred. The Caltagirone reservoir is deeper, often stratified; thus, settling can greatly influence bacterial removal in Caltagirone and not in Noirmoutier.

FC content was calculated from the reservoir operation and the climate data, using Eq. (5) for K_T evaluation and the bacterial balance Eq. (1). Comparison with the observed values showed that the trend of FC content along the monitoring period was fairly well modelled, but not without an overestimation of FC removal (Figure 7). The most important differences were noticed in early Spring, when the prediction of K_T from the climate data was likely to have been affected by a drawback of the mathematical procedure.

The Eq. (3) was used to determine the FC decay, instead of bacterial balance (Eq. (1)); MRT was calculated from Eq. (4) and the die-off coefficient according to Eq. (5). The comparison of the predicted and observed FC concentration in the reservoir is shown in Figure 8. Both FC concentrations predicted using Eqs (1) and (5) fit fairly well the observed data.

Conclusions

The development of models to assess microorganism die-off is an important issue to design and to establish operation rules of wastewater reservoirs. The prediction of bacterial die-off of the continuous-flow reservoir located in Caltagirone was performed using a simple non-steady-state bacterial balance and considering a first-order kinetic bacterial die-off. Several linear and non-linear multiple regressions were fitted and tested by combining die-off coefficients values with the main climate variables, design and operational characteristics of the reservoir. Regression analysis reveals that FC reduction is mainly influenced by received solar intensity (I). Calculated K_T values are higher in comparison with those derived from Xu *et al*. (2002) applying the same model in a shallow reservoir in Noirmoutier (France). These values suggest essential differences in the removal mechanisms between shallow and deep reservoir. The K_T peaks observed are probably due to the large time step at which measures were made (in Noirmoutier a continuous monitoring of flow rates, climate data and water quality was performed). Further investigations on deep storage reservoirs, taking into account the need of a continuous monitoring, could improve the understanding of the FC decay dynamics and the modelling of bacterial die-off.

Acknowledgements

This research activity was co-supported by the University of Catania (Project 2002: Accumulo di acque reflue urbane e modelli di qualità).

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