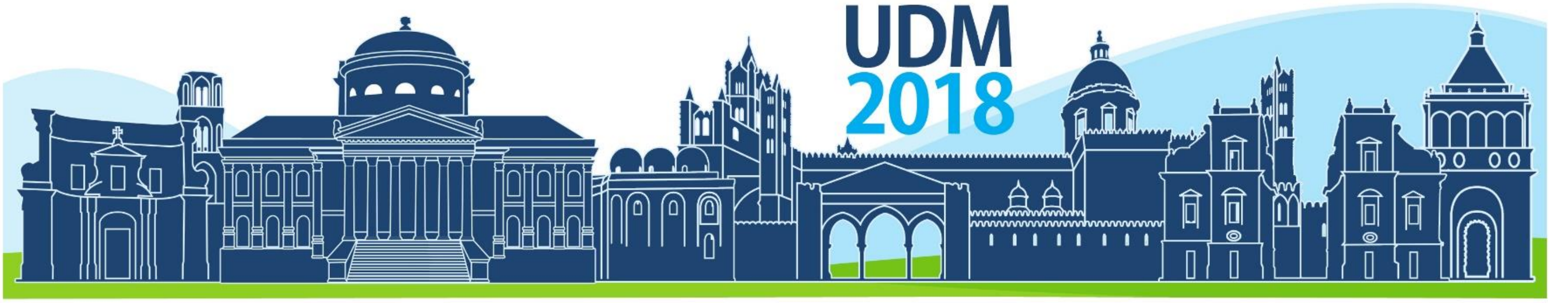
UDM 2018

PROCEEDINGS

11th International Conference on Urban Drainage Modelling (UDM)

Sep. 23–26, 2018

Palermo, Italy



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Wastewater modification processes in a stabilization reservoir: a new mathematical model

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Abstract: The paper presents a mathematical model for the simulation of the ecology of a wastewater stabilization reservoir (WSR). WSRs are hypertrophic aquatic systems devoted to water storage in warm countries where shortage conditions are often encountered. Several factors that affect the stabilization reservoir's effluent quality were taken into account: hydraulics and hydrology, solar radiation, reaeration, algae, zooplankton, organic matter, pathogens, and sediment-water interactions. The model quantifies the specific influence of each factor on effluent quality, and evaluating the correlation between the different factors. State variables included in the model were: algae, dissolved oxygen, organic matter, zooplankton and indicator bacteria. The model was applied to an Italian stabilization reservoir located in the south part of Sardinia: Simbirizzi lake. The model generated satisfactory results and can be employed as a useful tool for environmental water quality management of stabilization reservoirs.

Keywords: Water resources management, mathematical modelling, stabilization reservoir, wastewater treatment

1. INTRODUCTION

In recent decades, many areas experienced modifications to local rainfall characteristics, including the annual number of rainfall events, their average volume, and the frequency of intense rainfall events. Many authors have suggested an increasing trend in high intensity rainfall (De Michele et al., 1998; Pagliara et al., 1998; Brath et al., 1999; Kamaguchi et al., 1999). All these results have been ascribed to climate change which leads to a progressive increase of global temperatures and may progressively reduce water supply and increase water demand. In view of these conditions, alternative water resource management approaches can be of great benefit for coping with shortage conditions. More specifically, wastewater reuse for agricultural irrigation can be a good solution. Indeed, it is becoming a common and rapidly increasing practice in arid and semi-arid regions around the world, where treated wastewater serves as extra supplementary water source for the rural sector. New projects for reclamation and reuse of wastewater are frequently reported in countries across the globe. These consist of a variety of options including wastewater reuse systems, wastewater storage and treatment reservoirs, and stabilization reservoirs. These units allow for regulation between treated wastewater inflow, which occurs throughout the year, and withdrawal of irrigation effluent, which occurs during the dry summer months (Juanico and Shelef, 1994). Although these units were first used to accumulate treated effluent for irrigation purposes, thanks to their stabilization potentials, they are also used to treat raw wastewater (Mara and Pearson, 1992; Juanico and Shelef, 1994). Such reservoirs are similar to wastewater stabilization ponds. However, as these reservoirs are much deeper with much larger volumes, they are like small lakes. Therefore, limnological phenomena become more important in their dynamics (Friedler et al., 2003). Anaerobic stabilization ponds offer a cost-effective way to treat wastewater with high organic content, since they are mechanically simple, easy to operate by non-professionals and require less land than facultative and aerobic ponds (Arbeli et al., 2006). However, this simplicity belies the high complexity of their physical, chemical and microbial processes. As a consequence, the microbial process within lagoon systems is less understood than in biological reactors, while the effluent quality is less predictable (Grady et al.,1999). Mathematical models can provide a powerful tool to gain deeper insight into their ecology. In particular, comprehensive mathematical models, which simulate the main reservoir's primary physical, chemical, and biological processes that govern their water quality, can allow for more economical and sustainable reservoir management. The paper presents a semi-empirical mechanistic model derived by modification of previous models (Friedler et al., 2003; Mannina et al., 2008). The model takes into account various processes that influence effluent quality such as: hydraulics and hydrology, solar radiation, atmospheric reaeration, algae, zooplankton, organic matter, pathogen bacteria, and sediment/ water interactions. The model was calibrated to an Italian reservoir located in the south part of Sardinia. The model showed satisfactory results demonstrating the model's potential value as a tool for reservoir management.

2. MATERIALS AND METHODS

2.1 The mathematical model

The model is an ecological simulation model that describes the physico-chemical and biological water quality changes. It is a semi-empirical mechanistic model that takes into account the settling of particulate components and key chemical/biological processes. The model algorithms, which are partially derived from literature (Friedler et al., 2003; Mannina et al., 2008; Thébault and Salencon, 1993), consists of two connected sub-models: a thermal sub-model and a biological model. The former is superimposed as a forcing function and simulates the temperature of the hypolimnion and epilimnion by means of the following model equation:

$$T = T_m - a_t \cdot \cos\left[2\pi \times \frac{i + sfs + b_t}{365}\right] \quad (1)$$

where T is the temperature, T_m is the average annual temperature, i is the time in days, sfs is the lag-time between the first day of the year and the beginning of the simulation period, b_t is a coefficient and a_t is a coefficient which represents the waive amplitude.

By means of the derived temperatures of the hypolimnion and epilimnion, the model takes into account the possible formation of seasonal thermal stratification. Specifically, the water mass is divided into two spatially homogenous layers representing seasonal thermal stratification on the basis of the temperature profiles. In case of stratification, the surface layer or the epilimnion, is separated from the less turbulent bottom layer, the hypolimnion. Each layer is characterized by its volume, temperature, its depth and its solar radiation. Therefore, in the the water body is seasonally thermally stratified.

The biological sub-model simulates the reservoir's main biological processes. The model takes into account five model state variables for the water-column simulation (phytoplankton, dissolved oxygen, organic matter, zooplankton and indicator bacteria) and two model state variables for the sediments (organic matter and indicator bacteria). Model equations were set up taking into account the local conditions as in the case of evaporation where the Indelicato formula was applied (Indelicato et al., 1989). The biological sub-model was mainly based on the following hypothesis (Friedler et al., 2003; Mannina et al., 2008):

- the waterbody is divided in two zones: upper zone and sediment zone;
- the sediment zone is divided into 5 cm sediment layer height zones;
- the dynamic of each component is described by the mass conservation principle;
- molecular diffusion is negligible except for dissolved oxygen (DO).

The operational regime, physical structure of the reservoir, quality of the incoming effluent, precipitation, solar radiation, and thermal regime were treated as model forcing functions.

2.2 The case study

Simbirizzi lake is a water reservoir located about 8 km east of Cagliari (Sardinia, Italy). It has a maximum surface area of 3.2 km, and is the last link of the Flumendosa-Campidano system. Stretching from the Gennargentu (a mountainous system situated in the central part of Sardinia) to the island's southern coast, the above-mentioned system consists of several lakes, rivers, and man-made canals supplying drinking water to approximately one third of Sardinia's population.

The reservoir has a maximum storage capacity of 28.8 Mm^3 and it represents the last tank of the main transportation line of the water resources of the Flumendosa's system. Simbirizzi's lake has been designed, during the winter period, as a regulation reservoir for the treated wastewater flow from the Is Arenas treatment plant,, and to guarantee a mixing with the waters from Flumendosa's lake and Fluminimannu's catchment. Simbirizzi'lake is characterized by a persistent eutrophic state with a tendency to hypereutrophy. In order to limit the phosphorus inflow to Simbirizzi's lake from the wastewater treatment plant, the latter has been upgraded to include phosphorus removal. From 2002 to 2003, an extensive field data gathering campaign has been carried out for collecting both quantity and quality data for the lake. Specifically, monitored parameters were sampled and analyzed according to standard procedures recommended by APHA (1999), and included: chemical-physical parameters: BOD5, COD, total suspended solids, chlorophyll *a*, total phosphorus, NH_4-N, NO_2-N, NO_3-N, Ca^{++}, Mg^{++}, K^+, Na^+, chlorides, sulphates, fluorides, boron; microbiological parameters: total coliforms, faecal coliforms (FC), faecal streptococci, E. coli, Salmonella and Helminth eggs (*Ascaris lumbricoides*, Taenia). Temperature, specific conductance, pH and dissolved oxygen were measured on site, using portable equipment.

3. RESULTS AND DISCUSSION

The model was applied for a continuous period of two years from 2002 through 2003.. The calibrated parameters have been limited to the most sensitive ones as well as field data availability with the different values of the parameters with respect to the mean values given only for the calibrated parameters. The model parameters were evaluated on a combination of measured data, literature data and model calibration using a uniform random search and by minimizing an object function calculated as the root square of the error variance.

In Figure 1 the results in terms of temperature and water budget are reported. As can be observed (Figure1a), the reservoir exhibited thermal stratification during the highest and lowest temperatures. Such a fact influenced the biological processes and therefore the overall receiving water quality. The reservoir was characterized by continuous periods of non-zero inflows and outflows. Specifically, during a first period (namely until March 2003) the water budget was positive thus accumulating water. Conversely, after March 2003 the cumulative volume was negative thus indicating an emptying of water.

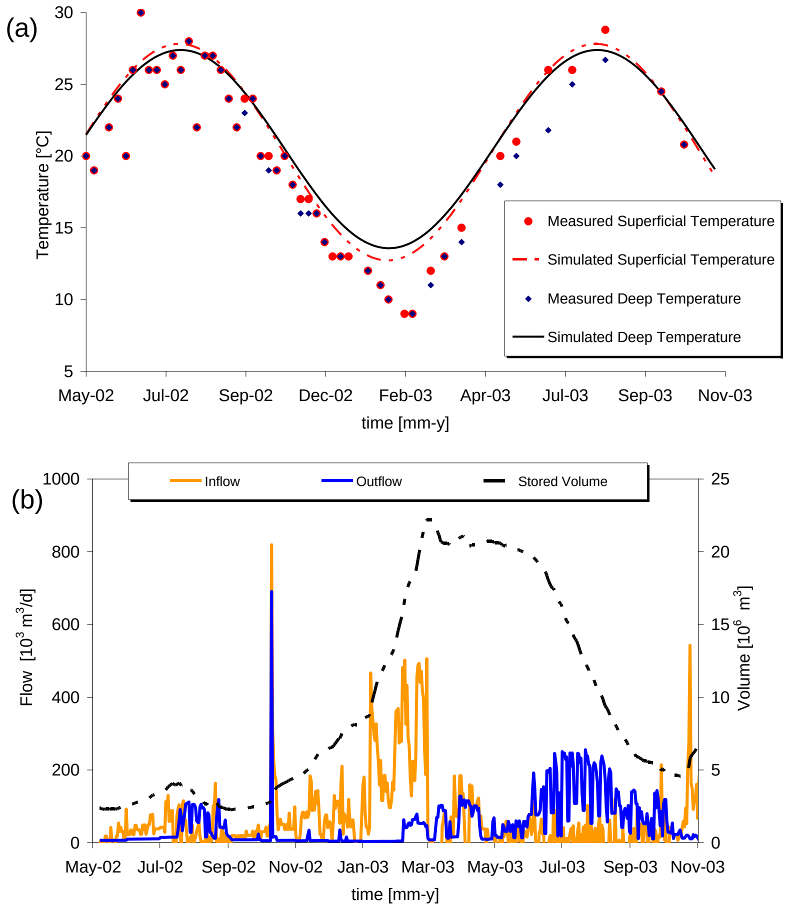

Figure 1. Temperature profiles (a); water budget balance (b).

It is important to stress that biological models do not allow the exact superimposition of simulated and measured data as for the case of physical process models (Thébault and Salencon, 1993). Indeed, measurements provide an instantaneous image of an ecosystem which is subjected to major space-time fluctuations, whereas the model simulates only the evolution of the mean variables. Bearing in mind such considerations, discrepancies between measured and simulated data have to be expected.

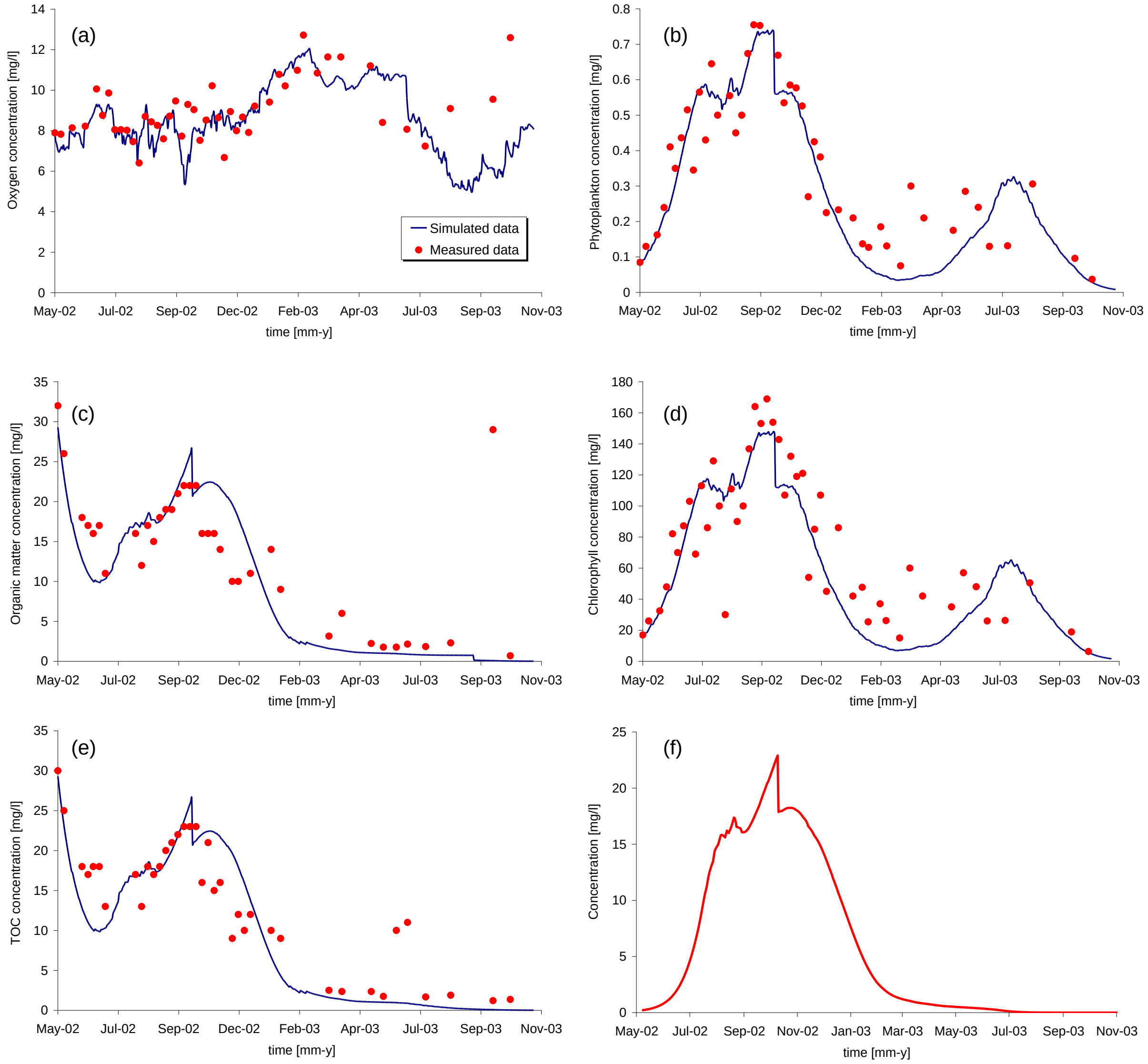

Figure 2. Model results in terms of: oxygen concentration (a); phytoplankton(b); organic matter (c); chlorophyll (d); TOC (e) and zooplankton (f).

Figure 2 shows model results for the five model outputs; namely: organic matter, oxygen concentration, phytoplankton, chlorophyll and total organic carbon (TOC). At first glance, there is a globally good agreement between measured and modelled data. The model is able to satisfactory simulate the system reproducing the main physical/chemical and biological processes.

The results indicate that the reservoir was affected by two periods of algal bloom: a first period where the algal bloom was much more intensive, August-September 2002 and another smaller bloom during the period July 2003. The higher intensity of the first period was caused by the simultaneously occurrences of several phenomena: inflow of wastewater in the reservoir, thermal stratification, and solar radiation intensity. All these phenomena caused an increase of the photosynthesis rate leading to the high algal bloom (Figure2b -d).

The gradual reduction during the winter periods could be due to the activity of the bacteria that reducing the organic matter, reduce the oxygen concentration leading to a worse environment for the algal**.**

Based on Figure 2, the following observations can be drawn:

- During the initial simulated periods, the inflow of wastewater and the lower water column heights in the reservoir caused the establishment of a high organic matter concentration.
- During the winter and spring periods, when the reservoir was completely mixed, the organic matter was uniform in the reservoir.
- During the thermally stratified period, the reservoir consisted of two different water masses: an upper and a lower one. The first one was characterized by high oxygen concentrations. Conversely, the lowest one was characterized by a higher sediment oxygendemand (SOD) thus resulting in anaerobic and anoxic conditions. Because the thermocline isolated the hypolimnion, during the period June-August, the oxygen concentration is reduced. On the other hand, as soon as the reservoir was completely mixed, a over-saturation of oxygen took place.
- During the last period of the reservoir simulation, the outflow volumes were higher than the inflow volume and the reservoir started to be emptied (Figure 1b). Such a fact led to a reduction of the reservoir's depth and allowed complete mixing. This latter condition coupled with the limited inflow caused a reduction of the organic matter and phytoplankton bacteria. As a matter of the fact, the oxygen concentration of the latter simulated period showed a decreasing trend reaching the minimum values of the overall simulated period.

CONCLUSIONS

A mathematical model for the simulation of the behaviour of a stabilization reservoir was presented. The model was applied to a reservoir that stores wastewater located in the South part of Sardinia (Italy). The reservoir was fed by a continuous inflow and was characterized by two periods: a first period during which the cumulative volume was positive thus indicating an accumulation of water and a second period characterized by a decreasing trend of the cumulative volume. The model showed good agreement with the measured data thus indicating its efficacy. The model can be applied for a stabilization reservoir performance assessment enabling a comparison between different management strategies. Specifically, the model can be employed for predicting water quality. Therefore, the model allows the assessment different management scenarios in order to optimize the economic management costs maintaining healthy reservoir ecological status.

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