 DOI: 10.22102/JAEHR.2019.153543.1107

ORIGINAL PAPER

Modelling of the loading rate in facultative wastewater stabilization ponds and the assessment of organic matter decline

Kazem Nadafi[1], Hassan Rasoulzadeh[2,✉], Bahman Akbarpour[1], Mehdi Hosseini[3], Arash Akbarzadeh[4], Somayeh Najafi Tobouz-Abad[5], Ali Teymurlouei[6]

1. Department of Environmental Health Engineering, School of Public Health, Tehran University of Medical Sciences, Tehran, Islamic Republic of Iran
2. Department of Environmental Health Engineering, School of Public Health and Safety, Shahid Beheshti University of Medical Sciences, Tehran, Islamic Republic of Iran
3. Department of Environmental Health Engineering, School of Health, Iran University of Medical Sciences, Tehran, Islamic Republic of Iran
4. Department of Biostatistics, School of Public Health, Tehran University of Medical Sciences, Tehran, Islamic Republic of Iran
5. Department of Civil Water Engineering, Faculty of Engineering, the Islamic Azad University, Science and Research Branch, Tehran, Islamic Republic of Iran
6. Department of Environmental Health Engineering, Health Center of Mamaghan, Azarshahr Health Care Network, Tabriz University of Medical Sciences, Tabriz, Islamic Republic of Iran

Date of submission: 24 Oct 2018, ***Date of acceptance:*** 19 Jan 2019

ABSTRACT

Wastewater stabilization ponds (WSPs) are natural, relatively simple, and cost-effective treatment processes that are used to stabilize the biodegradable compounds in wastewater. The present study aimed to propose a mathematical model for organic matter decline in facultative ponds (FPs). This analytical study yielded practical results, and the samples were collected from the ponds located in Yazd city, Iran. The reliability of the regression models (linear, quadratic, cubic, and exponential) was assessed and simulated by fitting the data. Initially, the data were fitted using linear and nonlinear curves. The comparative analysis of the results obtained from the models and Akaike information criterion (AIC) coefficient demonstrated that the linear model had the optimal correlations with surface loading ($L_{S,O}$) and minimum average monthly air temperature (Ta) with very high percentage accountability (R^2=0.939). The correlation-coefficients (R^2) for the second, third, and exponential models were estimated at 0.938, 0.939, and 0.938, respectively. Therefore, it could be concluded that there was a logical association between the $L_{S,O}$ and Ta, which suggests that these models are able to simulate the performance of the FPs. As such, the proposed models could be used to predict the reduction of organic materials in FPs, and the linear model was statistically selected as the optimal model for this purpose. In Iran and the neighboring countries where there are similar seasonal variations in temperature in most cities, the obtained models could be widely used for designing facultative ponds.

Keywords: Organic materials, Modelling, Air temperature, Surface loading, Facultative ponds

Introduction

Water pollution has become a grave environmental concern, recently attracting the attention of researchers across the globe.[1,2,3] Increased human activities, widespread urbanism, and development of numerous industries have led to the expansive production of wastewater, which is considered to be a primary concern in terms of water resource pollution and other ecological problems. Despite setting strict environmental regulations, there is an urgent need for proper wastewater treatment before discharge into the environment.[4] Urban wastewaters are mainly composed of municipal and industrial wastewater and agricultural runoff. Whether separately or in a combined manner, these

✉ *Hassan Rasoulzadeh*
Hrasoulzadeh@sbmu.ac.ir

Citation: Nadafi K, Rasoulzadeh H, Akbarpour B, Hosseini M, Akbarzadeh A, Najafi Tobouz-Abad S, et al. Modelling of the loading rate in facultative wastewater stabilization ponds and the assessment of organic matter decline. J Adv Environ Health Res 2019; 7(1): 53-60

wastewaters, are potentially capable of causing physical, chemical, and biological contamination.[5]

Wastewater treatment is essential to the prevention of environmental pollution and assuring public health protection. The discharge of treated wastewater is not considered a significant risk to environments and the inhabitants. Several studies have been focused on wastewater treatment using stabilization ponds in industrialized and developing countries. As biological treatment processes, stabilization ponds are used in numerous countries.[6] The treatment system has been designated for the municipal wastewater of the cities with small population sizes, and sedimentation and stabilization occur simultaneously. These ponds could significantly reduce the biochemical oxygen demand (BOD), suspended solids, viruses, and other pathogenic organisms.[7,8,9]

In many developed countries, especially those with a tropical climate, wastewater stabilization ponds (WSPs) are still among the most viable alternative methods for wastewater treatment.[10] In terms of investment, operation, and maintenance, WSPs are remarkably more convenient and economical compared to conventional purification methods. Oxidation/stabilization ponds are easily operated without the need for skilled and trained operators. In addition, some environmental conditions, especially the environments with higher temperatures, are favorable for biological reactions.[11,12]

WSPs are not sensitive to organic and hydraulic shocks due to their high hydraulic retention time.[13] The WSP system is composed of a series of ponds with a continuous stream, which contains anaerobic, facultative, and maturation ponds. Anaerobic ponds are mainly designed to remove most of the suspended organic materials and partially decompose the dissolved organic matters, while facultative ponds are designated to remove the remaining organic materials using algae and heterotrophic bacteria. The final stage involves the removal of pathogens and nutrients, which occurs in maturation ponds.[14,15]

Ecological models have been extensively applied since 1970 for the simulation of environmental management.[16] Use of mathematical models for the design and operation of water and wastewater ponds and similar structures have been reported in the current literature.[4,17,18,19] In a study, Olukanni *et al.* concluded that reactor design has a significant impact on the performance of WSPs.[20] Furthermore, Ghassemi *et al.* assessed the effects of the performance of WSPs and aerated lagoons on the removal of indicator microorganisms, and the results showed that variations in sunlight intensity, pH, and concentration of dissolved oxygen are among the foremost influential factors in bacterial reduction by WSPs. It is also notable that the dissolved oxygen in aeration ponds and sun intensity play a more pivotal role in bacterial decline compared to the other factors.[21]

In Iran, especially in Yazd city, using WSPs for wastewater treatment could be effective in terms of the costs and favorable climatic conditions in most of the regions. It is noteworthy that few studies have been focused on the principles of the design and performance of WSPs, and most of the new designs are based on the assumptions provided in other countries, which are not consistent with the conditions and features of Iran and the similar regions in most of the cases.[22,23]

The present study aimed to determine the appropriate functional associations between the response (surface loading) and the related input variable (minimum average monthly air temperature), develop empirical model equations that are essential to the design and construction of ponds, and assess organic matter decline in facultative ponds based on the results of modelling.

Materials and Methods

Features of the Studied Area

This analytical study yielded practical results and was conducted at a wastewater treatment located in the north of Yazd city, which is in the vicinity of the main road of Yazd Airport. The WSPs in Yazd are located at the approximate geographical latitude and longitude of 34.08° and 49.07°, respectively. The schematic view of the WSPs in Yazd is depicted in Figure 1.

The height of the ponds is 1,720 meters above the sea level. The system of the WSPs in Yazd is composed of three modules, the equipment of which is parallel to each other. The first module was utilized in 1993 and 2006 for the populations of 25,000 and 80,000, respectively. The module consists of three anaerobic ponds, followed by three facultative ponds and three secondary facultative ponds.

The output of the anaerobic ponds enters the primary and secondary facultative ponds. The effluent of the first unit of the treatment plant is reused for the irrigation of agricultural crops (Figure 2).[24] Agriculture is considered to be responsible for more than 80% of the total water consumption.[25]

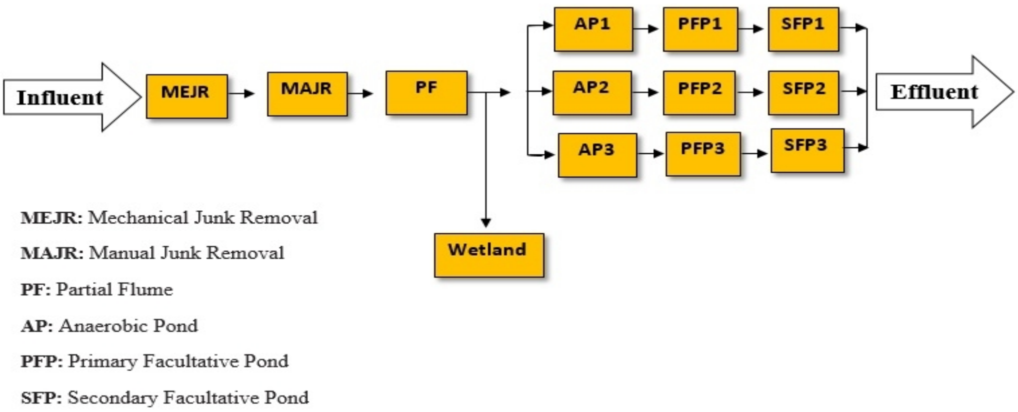

Fig. 1. Schematic flow diagram of WSPs in Yazd, Iran[24,26]

Fig. 2. Application of pond effluents in irrigation of agricultural crops in Yazd, Iran

Sampling

Samples were collected within a calendar year, with weekly grab sampling from the inflow and outflow effluent of the facultative ponds. Moreover, another sample was obtained from the inside of the facultative pool. In total, approximately 37 samples (three liters per week) were collected from the influent, and 37 samples (three liters per week) were collected from the effluent and tested. The samples were immediately placed in an ice box and transferred to the laboratory.

After transferring the samples to the laboratory, BOD_5 and chemical oxygen demand (COD) tests were carried out immediately. In addition, pH was measured in-situ using a pH meter (model: Kent EIL7020) to evaluate the effects of other parameters, and the basic data on the principles of the wastewater treatment plant in Yazd city and meteorological organization were used.[27]

The grab samples from various points of the inlet, outlet, and inside of the facultative ponds were collected, so that a composite sample of the outlet, a composite sample of the inlet, and a composite sample of the inside of the facultative pond could be achieved in every sampling. We attempted to use fixed points for sampling for the evaluation of the change process of various parameters. In order to improve the accuracy of the data, all the experiments were conducted in triplicate, and the mean value was adopted. It is noteworthy that all the stages of the sampling, maintenance, and transfer of the samples were based on the standard recommendations for water and wastewater examination.[28] Moreover, curve estimation and regression analysis were used for the observations in the linear and nonlinear models. Data analysis was performed using the R software version 3.0.3.

Climate

Yazd has a relatively cold and dry climate with the maximum temperature of 38 ºC in summer and minimum of -10 ºC in winter. The average temperature in the coldest month of the year is -7.48 ºC, and 300 millimeters of average rainfall and average annual relative humidity of 50% have been recorded.[24]

Curve Fitting

Curve fitting is a powerful technique for exploring the correlations between one or more predictive variables and a dependent variable. The final goal of curve fitting is access to optimum fitting in terms of the available data. Based on the findings of the current research and previous studies in this regard, linear and nonlinear models were used (Table 1).[29,30,31]

Table 1. Equations of linear and nonlinear curve fitting models

Type of Model	Formula	Equation
Linear Regression Model	$y=\beta_0+\beta_1 x+\varepsilon$	1
Polynomial Regression Model	$y=\beta_0+\beta_1 x+\beta_2 x^2+\ldots+\beta_k x^k+\varepsilon$	2
Exponential Regression Model	$Y=\gamma_0 \exp(\gamma_1 X)+\varepsilon$	3

We used linear models, including linear regression model (Equation 1) with one predictive variable and polynomial regression model (Equation 2) with squared and higher-order terms of the predictive variable. In both models, β_i denoted the regression coefficient, and ε represented random error. In order to find a good estimator for the regression parameters, we employed the least squares method. Furthermore, the exponential regression model (Equation 3) with a single predictive variable (Equation 3) was used as a nonlinear model. In this nonlinear regression model, the γ parameter was the regression coefficient, γ_0 and γ_1 denoted the regression parameters, and ε represented the random error.

Akaike Information Criterion (AIC)

After introducing a model with a high predictive power to ensure the achievement of the final model, the Akaike information criterion (AIC) coefficient was used to compare these models with nonlinear models. It is noteworthy that the AIC coefficient simultaneously considers the model fitness and complexity, eventually suggesting a value to select the optimal model

Results and Discussion

Figure 3 shows the surface load input to the wastewater treatment plant (kg BOD_5/ha day) on different days. The average surface load that was introduced into the plant during the year was equal to 286.95±10.69.

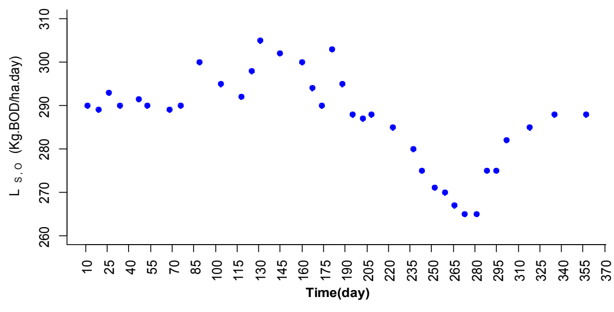

Fig. 3. Diagram of surface loading entry during year

In the present study, four models were evaluated, including linear, quadratic, cubic, and exponential models (Table 2). Figure 4 is a graph depicting the linear and nonlinear models. Before fitting the model, the assumptions of the constant variance, uncorrelated variance, and normality of the errors were evaluated, and the mentioned conditions were established in different models. However, none of the observations were detected as an outlier.

Table 2. Equations of estimated curves based on observations

Model	Model equation
Linear	$L_{s.o}=254.58+1.023Ta$
Quadratic	$L_{s.o}=252.4+1.4Ta-0.004Ta^2$
Cubic	$L_{s.o} = 259.04 + 0.39T + 0.04Ta^2 - 0.001Ta^3$
Exponential	$L_{s.o}=256\times e^{0.004Ta}$

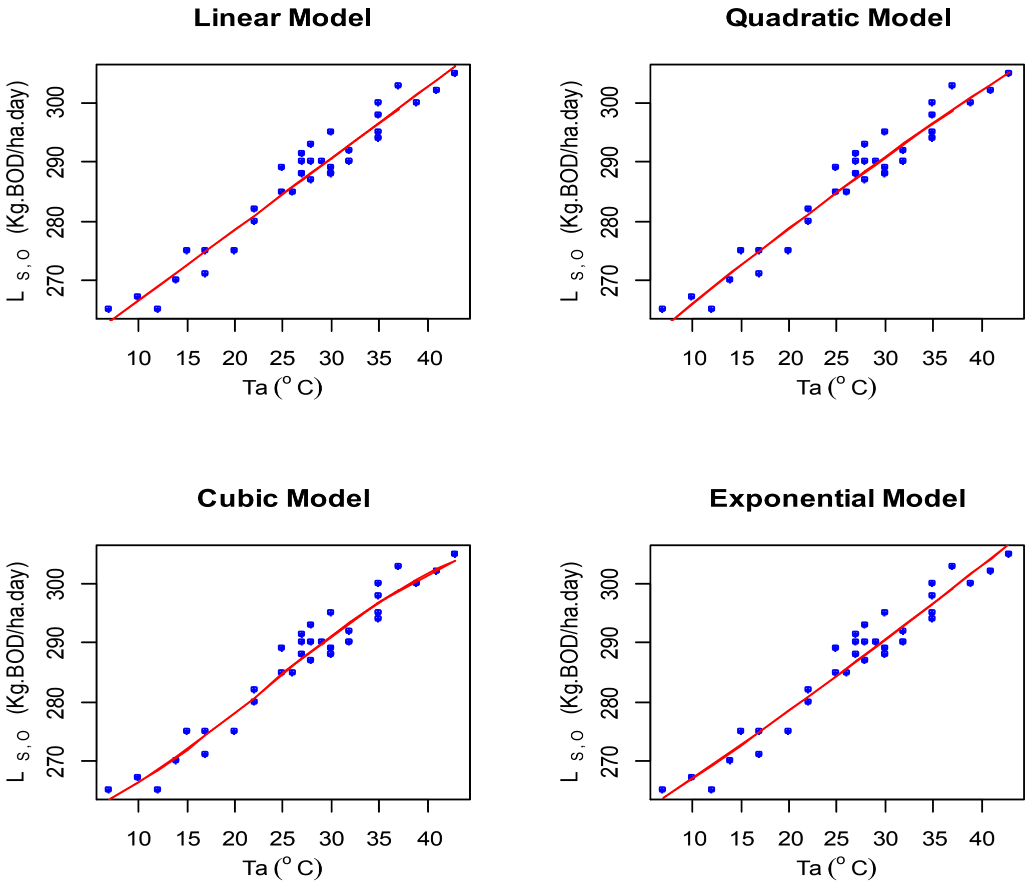

Fig. 4. Linear and nonlinear models

Table 3 shows R^2, which is a coefficient of determination for each of the models. According to the information in this table, the linear model had 93.9% accountability of the observations, and the coefficient of the regression line was equal to 1.02. In addition, the quadratic model could explain 93.8% of the observations, while the second-order coefficient regression was not considered significant.

In the cubic model, the justifiability of the observations was equal to 93.9%, and the regression coefficients were not considered significant. On the other hand, the exponential model could explain 93.8% of the variations in the observations. The regression coefficient was considered significant with the estimated value of 0.004, which represented a logical correlation between the $L_{S,O}$ and Ta, showing that with these models, the performance of the facultative ponds could be simulated. The proposed models could also be used to predict the reduction or elimination of organic materials in facultative ponds.

Despite the justifiability of the variations in the observations in order to determine the R^2 coefficient, the linear model was introduced with a high predictive power. However, the AIC coefficient was used for further consideration and model comparison. Considering the lack of significance in the coefficient of the cubic model, comparison of the fitness of the significant models was investigated. The result of the AIC coefficient indicated that the linear regression model had the lowest value, and it was recognized as the optimal model (Table 4).

Table 3. Regression coefficients of fitted models

Model	Model equation
Linear	$L_{s.o}$=254.58+1.023Ta
Quadratic	$L_{s.o}$=252.4+1.4Ta-0.004Ta^2
Cubic	$L_{s.o}$=259.04+0.39Ta+0.04Ta^2-0.001Ta^3
Exponential	$L_{s.o}$=256×e$^{0.004Ta}$

Table 4. Selection of optimal model

Model	df	AIC†
Linear	3	176.17
Quadratic	4	177.45
Exponential	3	177.32

Similar results have been obtained with the linear model by Mara[32] and Arthur *et al.*[33] However, the slope of the line equation obtained in the mentioned studies was larger, and the difference could be attributed to the extensiveness of the latitude of the studied regions. The slope in both of the equations was estimated at 20 with the intercept of -120 and -60, respectively. The current research was conducted at a relatively low Latitude (in a city), and due to the uniformity of the target community, the intercept of the obtained equation was high. In Iran and the neighboring countries, where seasonal variations in the air temperature, culture, and customs are similar in most cities, the resulting models could be widely applied in the design of facultative ponds.

In a study in this regard, Arceivala concluded that there is an indirect correlation between $L_{S,O}$ and local conditions, particularly sunlight and temperature, which vary with latitude. Furthermore, the authors proposed a linear model between the allowed $L_{S,O}$ and latitude of the location, where $L_{S,O}$ was considered to be the dependent variable, and the latitude of the location was considered to be the independent variable, with the slope of the line equation estimated at -6.25, and the intercept determined to be 375.[34]

The results of the study by McGarry and Pescod, which was focused on the stabilization pond design criteria in tropical Asia, indicated that in the facultative ponds within the range of normal load operation, the hydraulic retention time, input BOD_5 concentration, and depth of the pond had insignificant effects on the removal of BOD_5. Therefore, it was concluded that there was a significant correlation between the maximum applied $L_{S,O}$ and the minimum average air temperature based on the exponential model.[35] Similarly, the study performed by Gloyna entitled "Facultative Waste Stabilization Pond Design" indicated that long residence time in facultative ponds necessitated the consideration of the ultimate BOD. Additionally, the author proposed an equation in conjunction with facultative pond design, which involved the parameters of pond volume, wastewater flow, final wastewater BOD, temperature, and algae inhibitory coefficient.[36]

In the present study, the evaluation of the models suggested that the surface load increased with the elevation of the monthly minimum average air temperature. These changes directly affected the influential factors in designing pool area and their retention time, so that as a result of increased $L_{S,O}$, the designed flow would also increase, thereby increasing the pool area and volume. In the designing of facultative ponds, lower depth and larger area should be considered in order to achieve the acceptable efficiency. These findings are consistent with the results obtained by Sperling *et al.* in Brazil, which indicated that in shallow ponds, the coliform die-off coefficient (K_b) was high. This was the main reason for the efficient removal of the coliforms present in the ponds with lower depths.[37]

Transformation of nitrogen in primary facultative ponds is mainly performed using the denitrification method since with the decomposition of organic matters by microorganisms, autotrophic bacteria would have lower growth due to the unfavorable conditions for the nitrification process (e.g., alkaline pH and high organic matter). Instead, the bacteria provide the opportunity for the growth of denitrifier and heterotrophic bacteria.[38] This has been confirmed in a study performed by Senzia *et al.* in Tanzania based on the slightly higher load in facultative ponds.[39]

Considering the models proposed in the present study, it could be noted that the removal efficiency of organic matters changes with the variations in temperature in ponds, which could be attributed to the temperature sensitivity of heterotrophic bacteria, as well as the conditions of primary facultative ponds (neutral and alkaline oriented pH, suitable temperature, and high BOD). As a result, these bacteria have higher activity compared to other bacteria.

Conclusion

According to the results, there was a logical correlation between the $L_{S,\ O}$ and Ta, which indicated that the proposed models could simulate the performance of facultative ponds. Therefore, the proposed models could be used to predict the reduction or elimination of organic materials in facultative ponds. The linear model was statistically selected as the optimal model for this purpose. In the proposed models, the increased minimum average monthly air temperature caused the $L_{S,\ O}$ to follow the same trend, and these changes directly affected the retention time and factors involved in pool area design. The obtained models could be widely used in the design of facultative ponds in Iran and the neighboring countries, where there are similar seasonal variations in the temperature and climate.

Acknowledgements

Hereby, we extend our gratitude to the Student Research Committee of Shahid Beheshti University of Medical Sciences in Tehran (Iran), Tehran University of Medical Sciences, and Water and Wastewater Organization of Tehran and Yazd for assisting us in this research project.

References

1. Massoudinejad M, Rasoulzadeh H, Ghaderpoori M. Magnetic chitosan nanocomposite: Fabrication, properties, and optimization for adsorptive removal of crystal violet from aqueous solutions. Carbohydr polym 2019; 206: 844-853.
2. Alimohammadi M, Saeedi Z, Akbarpour B, Rasoulzadeh H, Yetilmezsoy K, Al-Ghouti MA, et al. Adsorptive removal of arsenic and mercury from aqueous solutions by eucalyptus leaves. Water Air Soil Pollut 2017; 228(11): 429.
3. Yaghmaeian K, Jaafarzadeh N, Nabizadeh R, Rasoulzadeh H, Akbarpour B. Evaluating the performance of modified adsorbent of zero valent iron nanoparticles–Chitosan composite for arsenate removal from aqueous solutions. Iran J Health Environ 2016; 8(4): 535-548.
4. Ho LT, Van Echelpoel W, Goethals PL. Design of waste stabilization pond systems: A review. Water Res 2017; 123: 236-248.
5. Gloyna EF. World Health Organization. Waste stabilization ponds: WHO, Geneva; 1971.
6. El deep Ghazy MM, El sensoy WM , Abdel-Aatty AM, Kamel M. Performance evaluation of a waste stabilization pond in a rural area in Egypt. Am J Environ Sci 2008; 4(4): 316-325.
7. Brooks AS, Rozenwald MN, Geohring LD, Lion LW, Steenhuis TS. Phosphorus removal by wollastonite: A constructed wetland substrate. Ecol Eng 2000; 15(1): 121-132.
8. Shah M, Hashmi HN, Ali A, Ghumman AR. Performance assessment of aquatic macrophytes for treatment of municipal wastewater. J Environ Health Sci Eng 2014; 12(1): 106.
9. Verbyla ME, Mihelcic JR. A review of virus removal in wastewater treatment pond systems. Water Res 2015; 71: 107-124.
10. Mayo AW. Modeling coliform mortality in waste stabilization ponds. J Environ Eng 1995; 121(2): 140-152.
11. Fritz JJ, Middleton AC, Meredith DD. Dynamic process modeling of wastewater stabilization ponds. J Water Pollut Control Fed 1979; 51 (11): 2724-2743.
12. Butler E, Hung Y-T, Al Ahmad MS, Yeh RY-L, Liu RL-H, Fu Y-P. Oxidation pond for municipal wastewater treatment. Appl Water Sci 2017; 7(1): 31-51.
13. Mayo AW. Effect of pond depth on bacterial mortality rate. J Environ Eng 1989; 115(5): 964-977.
14. Olukanni DO, Ducoste JJ. Optimization of waste stabilization pond design for developing nations

using computational fluid dynamics. Ecol Eng 2011; 37(11): 1878-1888.
15. Gruchlik Y, Linge K, Joll C. Removal of organic micropollutants in waste stabilisation ponds: A review. J Environ Manage 2018; 206: 202-214.
16. Jørgensen SE, Bendoricchio G. Fundamentals of ecological modelling: Applications in Environmental Management and Research Elsevier; Volume 21 ,4th Edition, 2011.
17. Hense I, Burchard H. Modelling cyanobacteria in shallow coastal seas. Ecol Modell 2010; 221(2): 238-244.
18. Salacinska K, El Serafy G, Los F, Blauw A. Sensitivity analysis of the two dimensional application of the Generic Ecological Model (GEM) to algal bloom prediction in the North Sea. Ecol Modell 2010; 221(2): 178-190.
19. Craggs RJ, Zwart A, Nagels JW, Davies-Colley RJ. Modelling sunlight disinfection in a high rate pond. Ecol Modell 2004; 22(2): 113-122.
20. Olukanni DO. Evaluation of the influence of reactor design on the treatment performance of an optimized pilot-scale waste stabilization pond. Int J Eng Technol 2013; 3(2): 189-198.
21. Ghassemi SA, Danesh S. Waste stabilization ponds and aerated lagoons performance in removal of wastewater indicator microorganisms. Water wastewater 2013;24(2):53-61.
22. Tchobanoglous G, Burton FL, Stensel HD. Wastewater engineering, treatment and reuse. McGraw-Hill. 1991, 1th Edition, New York.
23. Reed SC, Crites RW, Middlebrooks EJ. Natural systems for waste management and treatment: 1998; McGraw-Hill, Inc.
24. Farzadkia M, Ehrampoush MH, Sadeghi S, Kermani M, Ghaneian MT, Ghelmani V, et al. Performance evaluation of wastewater stabilization ponds in Yazd-Iran. Environ Health Eng Manage J 2014; 1(1): 7-12.
25. Naddafi K, Hassanvand M, Dehghanifard E, Razi DF, Mostofi S, Kasaee N, et al. Performance evaluation of wastewater stabilization ponds in Arak-Iran. Iran J Environ Health Sci Eng 2009; 6(1): 41-46.
26. Ebrahimi A, Ehrampoosh MH, Shahsavani E, Hosseini E, Hashemi H, Talebi P, et al. Survey on removal efficiency of linear alkylbenzene sulfonate in Yazd stabilization pond. International Journal of Environmental Health Engineering 2015; 4(1): 10.
27. Specialized meteorological statistics, Statistics of Yazd's Meteorological station, Yazd. 2010, Iran Meteorological Organization.
28. APHA. Standard methods for the examination of water and wastewater, 21sted. Washington, DC, New York: American Public Health Association; 2005.
29. Wilks DS. Statistical methods in the atmospheric sciences: Academic press; 3rd Edition, Volume 100, 2011.
30. Draper NR, Smith H. Applied regression analysis: John Wiley & Sons; 2014.
31. Kutner MH, Nachtsheim CJ, Neter J, Li W. Applied linear statistical models. McGraw-Hill Fifth edition, 2005, Irwin Boston.
32. Mara DD. Design manual for sewage lagoons in the tropics. Unpublished preprint, (PF 06 E MAR), 1978 1975.
33. Arthur J P. Notes in the design and operation of waste stabilization ponds in warm climates of developing countries: The World Bank; 1983.
34. Arceivala SJ. Simple waste treatment methods: Aerated lagoons, oxidation ditches, stabilization ponds in Warm and temperate Climates. METU Engineering Faculty Publication. 44: Middle East Technical University; 1973.
35. Mcgarry M, Pescod M. Stabilization pond design criteria for tropical Asia. 1970.
36. Gloyna EF. Facultative waste stabilization pond design. Ponds as a Wastewater Treatment Alternative; 1976, Water Resources Symposium.
37. Von Sperling M. Performance evaluation and mathematical modelling of coliform die-off in tropical and subtropical waste stabilization ponds. Water Res 1999; 33(6): 1435-1448.
38. Tchobanoglous G, Burton FL. Wastewater engineering treatment, disposal and reuse: 1991, McGraw-Hill, Inc.
39. Senzia M, Mayo A, Mbwette T, Katima J, Jørgensen S. Modelling nitrogen transformation and removal in primary facultative ponds. Ecol Modell 2002; 154(3): 207-215.