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The comparison of different mathematical methods to determine the BOD parameters, a new developed method and impacts of these parameters variations on the design of WWTPs

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A B S T R A C T

One of the most common tests for the determination of strength and organic content of wastewater is the biochemical oxygen demand (BOD). This test is widely applied to define organic water pollution and to control the performance of wastewater treatment plants. Generally, BOD is standardized by the measurement of oxygen consumption in 5 days (BOD_5). But, determination of the ultimate biochemical oxygen demand (BOD_u), which is taken 28 days and the reaction rate constant (k) are necessary to understand the organic strength of the wastewater. In this study, the different mathematical methods in order to determine the BOD parameters (BOD_u, k) and two different BOD test method (respirometer and dilution method) are investigated comparatively. Also, a new method based on cubic spline method to estimate ultimate BOD values is developed. Moreover, the impacts of BOD parameters on the design of an activated sludge and aerated lagoon systems are analyzed by using a written user-friend program, which is developed for designing WWTPs by the mean of C++ programming language.

Analytical results show that there is a satisfactory linear relationship between respirometric and dilution BOD values. Also, the mathematical methods, including new developed method generally provide consistent results with high correlation coefficients. On the other hand, it is found that LOG differences method for respirometric test and the new developed method for dilution test do not give good correlation coefficients. Moreover, activated sludge and aerated lagoons systems' sizes show significant changing depending on the variations of the BOD parameters. Consequently, BOD parameters show significant changes depending on the different test and mathematical methods. Therefore, the changing of these parameters impact a lot of situation such as ultimate BOD estimation, the wastewater treatment plants design, the dimensions of the plants and cost of the plants.

1. Introduction

The most widely used parameter of organic pollution applied to both wastewater and surface water is the 5-day BOD (BOD_5). This determination involves the measurement of the dissolved oxygen used by microorganism in the biological oxidation of organic matter. The reason is that BOD test results are now used to determine the approximate quantity of oxygen

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that will be required to biologically stabilize the organic matter present, to determine the size of wastewater facilities, to measure the efficiency some treatment processes and to determine compliance with wastewater discharge permits.

Biochemical oxidation theoretically takes an infinitive time to go to completion because the rate of oxidation is assumed to be proportional to the amount of organic matter remaining. Usually, only 5-day period used for BOD test, but determination of the ultimate biochemical oxygen demand (L) and the reaction rate constant (k) are necessary to understand the organic strength of the wastewater. More than 5 days period is necessary to obtain these parameters experimentally. Moreover, within a 20-day period, the oxidation of the carbonaceous organic matter is about 95–99% complete, while in the 5-day period used for the BOD test, oxidation is from 60% to 70% complete (Fig. 1). These parameters are also extensively used for the treatment plant optimization studies. Thus, many investigators have worked on developing and refining methods and formulas for the deoxygenation (k_1), reaeration (k_2) parameters and the ultimate BOD (L).

Among the deterministic models proposed to describe mathematically the laboratory BOD progression in time, first-order kinetics is the most widely accepted. The model was originally proposed by Phelps [1,2]. One of the problems associated with models is parameter estimation. For deterministic, first-order BOD kinetics the parameters are the ultimate BOD (L) and the first-order rate coefficient (k). Since reliable values of these parameters are necessary for adequate use of the model, particular efforts have therefore been directed to the parameter estimation problem.

There are several ways of determining k_1 and uBOD from the results of series of BOD measurements including the least-squares method, the log differences method, the slope method, the graphical method, the method of moments, and the series method. Reed Theriault least-squares method published in 1927 give the most consistent results, but it is time consuming and tedious. Computation using a digital computer was developed by Gannon and Downs [3,4].

In 1936, a simplified procedure, the so-called log-difference method of estimating the constant of the first-stage BOD curve, was presented by Fair [5]. The method is also mathematically sound, but it is also difficult to solve [5].

Thomas [6] followed Fair et al. [7,8] and developed the ‘slope’ method, which, for many years, was the most used procedure for calculating the constants of the BOD curve. Later, Thomas [9] presented a graphic method for BOD curve constants. In the same year, Moore et al. [10] developed the ‘moment method’ that was simple, reliable, and accurate to analyze BOD data; this soon became the most used technique for computing the BOD constants [6–10].

Researchers found that k_1 varied considerably for different sources of wastewaters and questioned the accepted postulate that the 5-day BOD is proportional to strength of the sewage. Oxford and Ingram [11] discussed the monomolecular equation as being inaccurate and unscientific in its relation to BOD. They proposed that the BOD curve could be expressed as a logarithmic function [11].

Tsivoglou [12] proposed a ‘daily difference’ method of BOD data solved by a semi graphical solution. A ‘rapid ratio’ method can be solved using curves developed by Sheehy [13]. O’Connor [14] modified the least-squares method using BOD_5 [12–14].

Berkun [15] investigated the suitability of the first- and second-order models using BOD data obtained from extensive experiments using a respirometer and conventional dilution technique [15].

Leduc et al. [16] proposed a stochastic model for first-order BOD kinetics, assuming random inputs [16].

However, many authors [17–20] have cautioned against the supposition that first order model adequately describes the BOD exertion behavior of all wastewaters [17–20]. Accordingly, a number of alternative models have been proposed based on half order kinetics by Adrian and Sanders [19] second-order by Young and Clark [21], Tebbutt and Berkun [22] and mixed

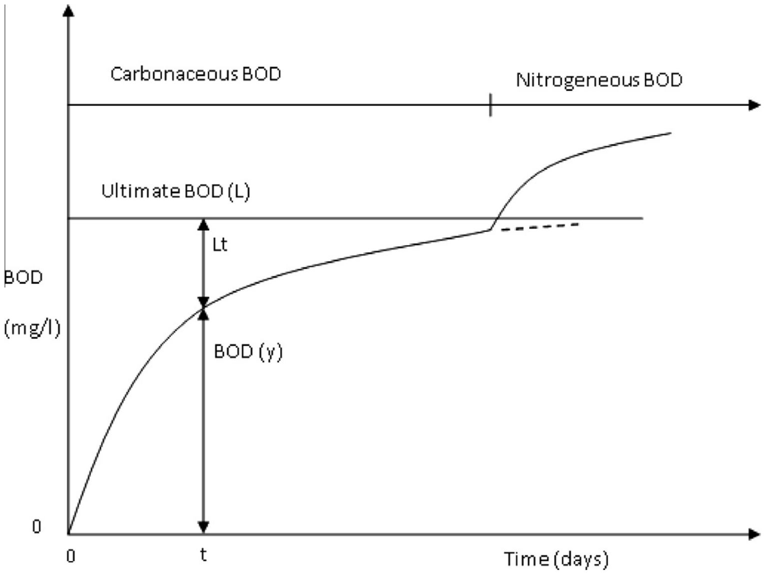

Fig. 1. BOD curve.

order by Hewitt et al. [18], Borsuk and Stow [20]. The half-order and second-order models have met with limited success, however the mixed-order model as applied by Borsuk and Stow [20] has provided an excellent fit to long-term data. Furthermore, Analytical solutions for DO sag equations have been developed incorporating a three halves order BOD reaction by Adrian, et al. [23], a second-order BOD reaction by Adrian and Sanders [24], and multi order BOD reactions by Adrian et al. [25] and Baird and Smith [26] provide a review of BOD literature, while Young and Cowan [27] provide guidance on application of respirometers to BOD measurements. Borsuk and Stow [20] developed a Bayesian parameter estimation method for BOD reactions and found that mixed-order reactions were likely, with the reaction order usually above one and sometimes above four. Roider et al. [28] extended the applicability of the second-order BOD decay model by incorporating loss of BOD by sedimentation before solving analytically the associated DO model. Roider and Adrian [29] studied comparative evaluation of three river water quality models and reported that the first-order BOD model most frequently fit the river data best, followed by the three-half order and the second-order BOD models. Berkun and Onal [30] studied the effects of inorganic chemicals on the DO deficit curve formation. The effect of toxic metals on modifying the first-order BOD reaction rate constants and the implications of these constants on DO prediction in rivers was examined by Berkun [31]. The effect of applied parameter estimation methods and existence of inorganic metals on the stream self-purification mechanism model parameters were investigated by Berkun and Aras [32].

In this paper, the different mathematical methods in order to determine the BOD parameters (uBOD, k) and two different BOD test method (respirometer and dilution method) are investigated comparatively. Also, a new method based on cubic spline method to estimate ultimate BOD values is developed. Moreover, the impacts of BOD parameters on the design of an activated sludge and aerated lagoon systems are analyzed by using a written user-friend program, which is developed for designing WWTPs by the mean of C++ programming language.

2. Material and methods

In this study, the BOD data was obtained from respirometric and dilution BOD values of raw domestic wastewater (Tables 1 and 2) [15]. First-order reaction parameters obtained from different mathematical methods are relatively used. Also, a new method based on cubic spline method to estimate ultimate BOD is developed by the mean of MATLAP [33]. An activated sludge system and an aerated lagoon are assumed as the wastewater treatment plant models. Therefore, a user-friend program is written in C++ programming language to WWTPs designs. Moreover, the program is written based on the BOD data, thus the impact of BOD values on the WWTPs units investigate comparatively.

The rate of BOD oxidation is modeled based on the assumption that the amount of organic material remaining at any time t is governed by a first order function, as given below (Eq. (1)).

$$y = L(1 - e^{-kt}), \tag{1}$$

where,

y = Biochemical oxygen demand
L = Ultimate biochemical oxygen demand
k = BOD reaction rate constant
t = Time.

The value of k is needed if the BOD_5 is to be used to obtain uBOD, the ultimate or 20-day BOD. The usual procedure followed when the values are unknown is to determine k_1 and uBOD from a series of BOD measurements.

2.1. A new extrapolation method based on cubic spline method (cubic spline extrapolation method)

The developed model is based on generating an interpolation curve with cubic splines and extract it reach up to required data range. A series of unique cubic polynomials are fitted between each of the data points, providing the obtained curve be continuous and appear smooth. These cubic splines can then be used to determine rates of change and cumulative change over an interval. In this method, a third-order polynomial are generated per data range as cubic spline method. The polynomial constants are obtained from first, second and third-order derivations, provided by the interpolation curve and the

Table 1
BOD values, obtained from respirometer.

Sample	y_1 mg/l	y_2 mg/l	y_3 mg/l	y_4 mg/l	y_5 mg/l
Respirometric 1	188	244	308	344	388
Respirometric 2	200	276	344	374	398
Respirometric 3	166	222	288	322	346
Respirometric 4	144	222	266	288	322
Respirometric 5	100	188	210	254	288

Table 2
BOD values, obtained from dilution technique.

Sample	y_1 mg/l	y_2 mg/l	y_3 mg/l	y_4 mg/l	y_5 mg/l
Dilution 1	143	342	398	439	455
Dilution 2	143	245	379	435	460
Dilution 3	211	322	383	423	450
Dilution 4	171	236	305	365	402
Dilution 5	180	197	262	316	325

polynomial's adjacent points. The required derivations are obtained by reading the points which will be estimated on the curves, generated by least squares method per first, second and third-order derivation on the interpolation curve. Suitable curve type for derivations is selected while curve fitting with least square method.

2.1.1. Application of the cubic spline extrapolation method in estimation of ultimate BOD

It is summarized that the using developed model in the BOD data which consist of 5 day measured extrapolation in the flow chart on the figure in detail. The flow chart consists of two phase which are interpolation phase, used in order to determine the data for extrapolation (5 day measured data) and extrapolation phase. Two hundred data are generated in interpolation phase. Then the interpolation is done between this data by cubic spline method. The derivation information is obtained from connecting data of cubic curves. The determined derivations are used describing the coefficients of curve forms which is found by least squares method in the flow chart, shown in Fig. 1. The extrapolation data which consist of next days of after 5 day is derived from created curve form. Thus, the 30 day BOD data is estimated by extrapolation curve which is determined from cubic polynomial coefficients. The flow chart and explanation of method is shown on Figs. 2 and 3.

The application of the method on a sample is given below on Fig. 4.

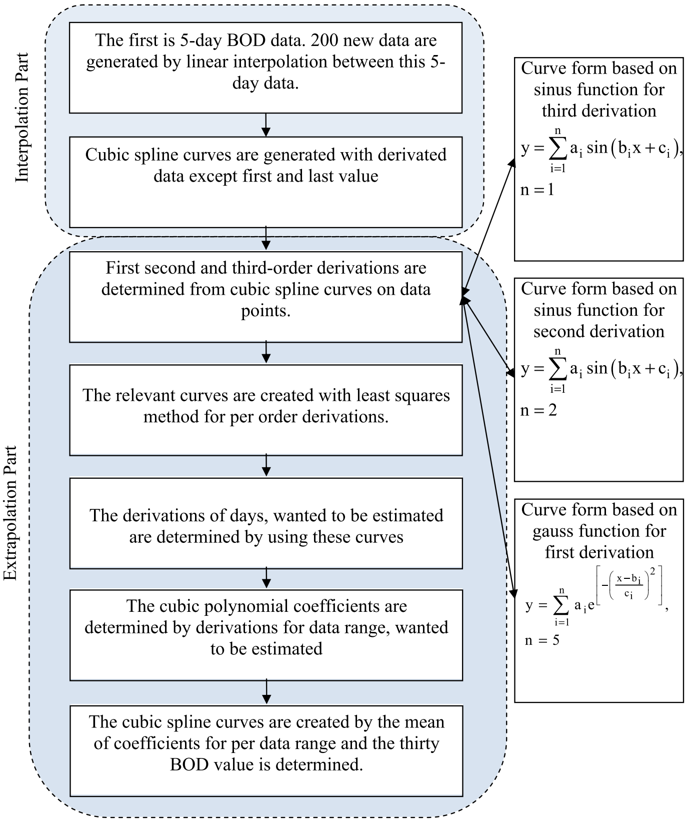

Fig. 2. Extrapolation of BOD value with the new approach.

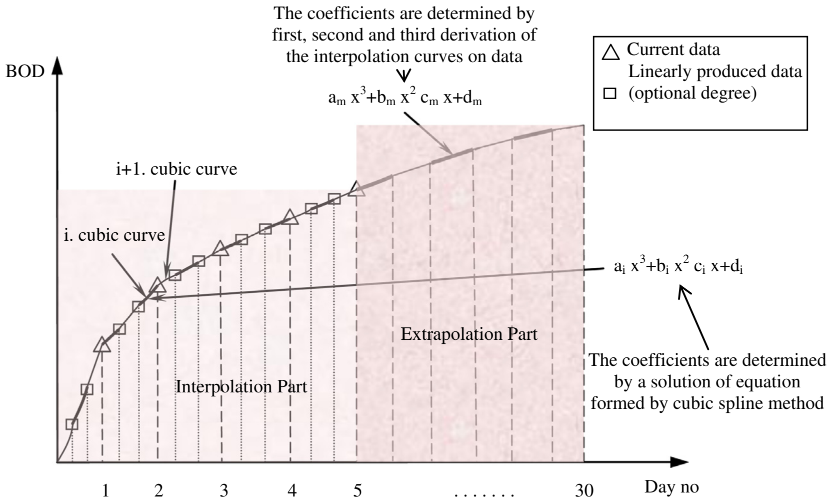

Fig. 3. Explanation of a new extrapolation method with diagram.

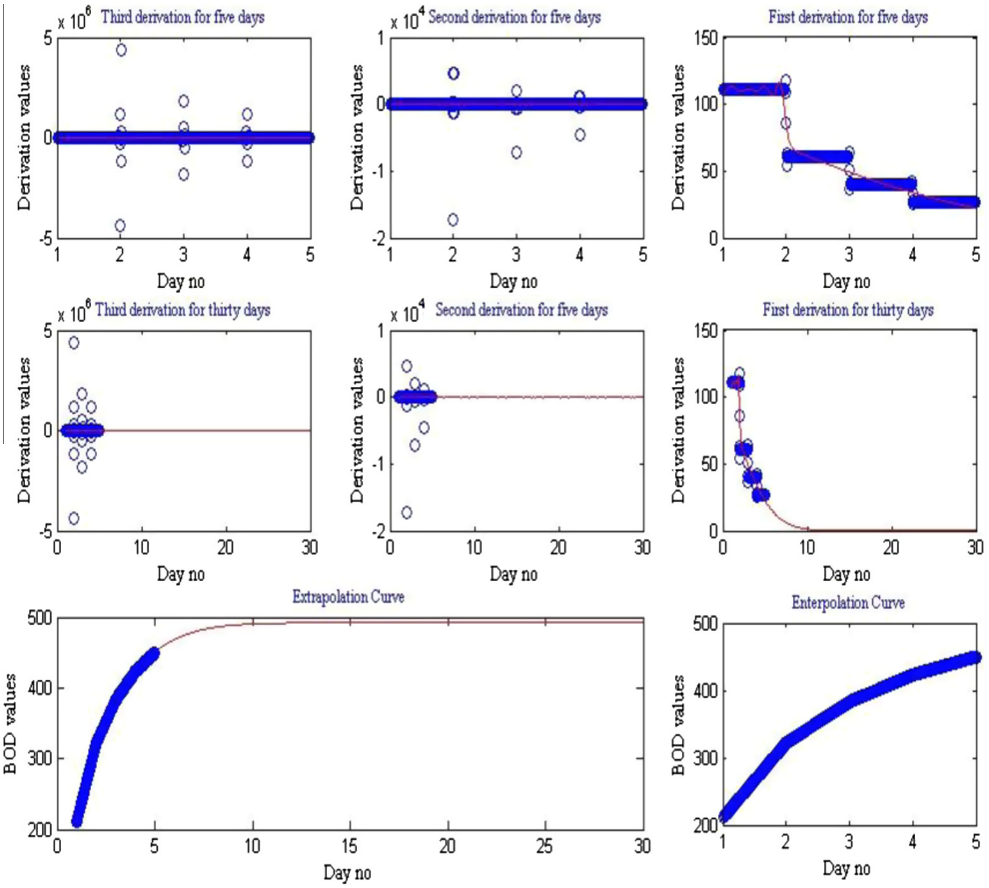

Fig. 4. The view of application of the developed model for dilution 3 sample.

2.2. Wastewater treatment models

Biological wastewater treatment is the essential operation for the processing of liquid waste. The primary objectives of biological processes are the degradation of various complex organic compounds in wastewaters which are usually characterized by a biochemical or chemical oxygen demand (BOD/COD) index. Activated sludge process and aerated lagoons are widely used processes for the biological treatment of municipal or industrial wastewaters [34].

Activated sludge wastewater treatment is a highly complex physical, chemical and biological process and variations in wastewater composition and flow rate, combined with time-varying reactions in a mixed culture of micro-organisms, make this process nonlinear and unsteady. For modeling the biological processes in the activated sludge plant, several models are proposed: ASM1, ASM2, ASM2d and ASM3 [35–38]. Due to the complexity of these models (for example: the ASM1 model contains 11 different components, 20 parameters and 8 processes), different versions of a reduced model for the activated sludge plant are proposed [39–43]. Development of a 4-measurable states activated sludge process model deduced from the ASM1 [44]. Computer modeling of the activated-sludge process has been an increasingly important tool to evaluate activated sludge systems because of its internal complexity [45].

Aerated lagoons are widely used due to their relatively low cost and maintenance requirements, minimum production of sludge and integration in the environment. The system is based on the degradation and uptake of organic matter by a microbial community under aerobic conditions [46].

2.3. The design parameters of activated sludge system

In general, all wastewater treatment units can be run in two ways as heavily loaded (high speeded) or low loaded (low speeded). The high speeded plants provide partial treatment. The partial treatment yield is accepted to be less than 80% and effluent BOD_5 is accepted to be higher than 30 mg/l. On the other hand the low speeded plants provide full treatment. The biological yield is 90% or more and the effluent BOD_5 is under the 20 mg/l in the low loaded activated sludge systems.

Normally, recycling rate varies between 0.33 and 1.0 (0.30 is for low loaded and 1.0 is for heavily loaded) The BOD_5 loading and aeration times in activated sludge plants are shown on Table 3.

$$\text{BOD load} = \text{flowrate} \times \text{influent BOD}, \tag{2}$$

$$V_1(\text{Basin volume according to BOD load}) = (\text{BOD load})/(\text{BOD loading}), \tag{3}$$

$$V_2(\text{Basin volume according to aeration time}) = \frac{\text{flowrate } \times \text{aeration time}}{24}. \tag{4}$$

The oxygen requirements for BOD removal without nitrification can be computed using Eq. (5) in Table 4.

$$\text{Required oxygen} = 1.5 \times \text{BOD load}/1000 \quad (1.5\ \text{kg } O_2/\text{kg BOD load}). \tag{5}$$

Provided oxygen = 44 g (1 diffuser 4 lb O_2/HP/day. Provided oxygen = 4 × 24 h/day = 96 lb O_2/HP/day = 44 kg O_2/HP/day)

$$N = \text{Required oxygen}/44 \quad (\text{HP}), \tag{6}$$

where N is compressor power.

In this study, activated sludge plant designs as a low speeded (0.5 kg BOD/m^3) with 6 h aeration time and high speeded (1.6 kg BOD/m^3) with 2.5 h aeration time [47]. The aeration tank designs for both rectangular and circular basin types. The length of tank is computed for the 5m depth, 10m width and 10 numbers of tanks. The wastewater flow rate is 35,000 m^3/day. Compressor power is calculated to compress the sufficient air for the biochemical oxygen demand. The calculations are made by the mean of C++ programming language.

The activated sludge plant design flow diagram is shown on Fig. 5 in C++.

BOD: g/m^3
BOD loading: g
Flow rate: 35,000 m^3/d
t: day (retention time)
V_1: m^3(volume for BOD load)
V_2: m^3(volume for retention time)

Table 3
The BOD_5 loading and aeration times in activated sludge plants.

System type	BOD loading (F/M)		Aeration time	Sludge recycling rate	Removal of BOD
	BOD (g/day/m^3)	BOD/SI (g/day/g)	(h)	(%)	(%)
High-speeded with full mixed	1600	0.5–1.0	2.5–3.5	100	85–90
Staged	480–800	0.2–0.5	5–7	50	90–95
Conventional	480–640	0.2–0.5	6–7.5	30	95
Contact stabilization	480–800	0.2–0.5	6–9	100	85–90
Prolonged aerated	160–480	0.05–0.2	20–30	100	85–95

Table 4
Typically air requirements in activated sludge plants.

Air diffuser system (diffuser)			Mechanical aeration system	
Air (m^3)/COD or BOD (kg)		Air (m^3)/wastewater (m^3)	O_2 (kg)/COD or BOD (kg)	
COD	BOD		COD	BOD
62–125	48–90	3.74–22.4	1.5–1.8	1.0–1.5

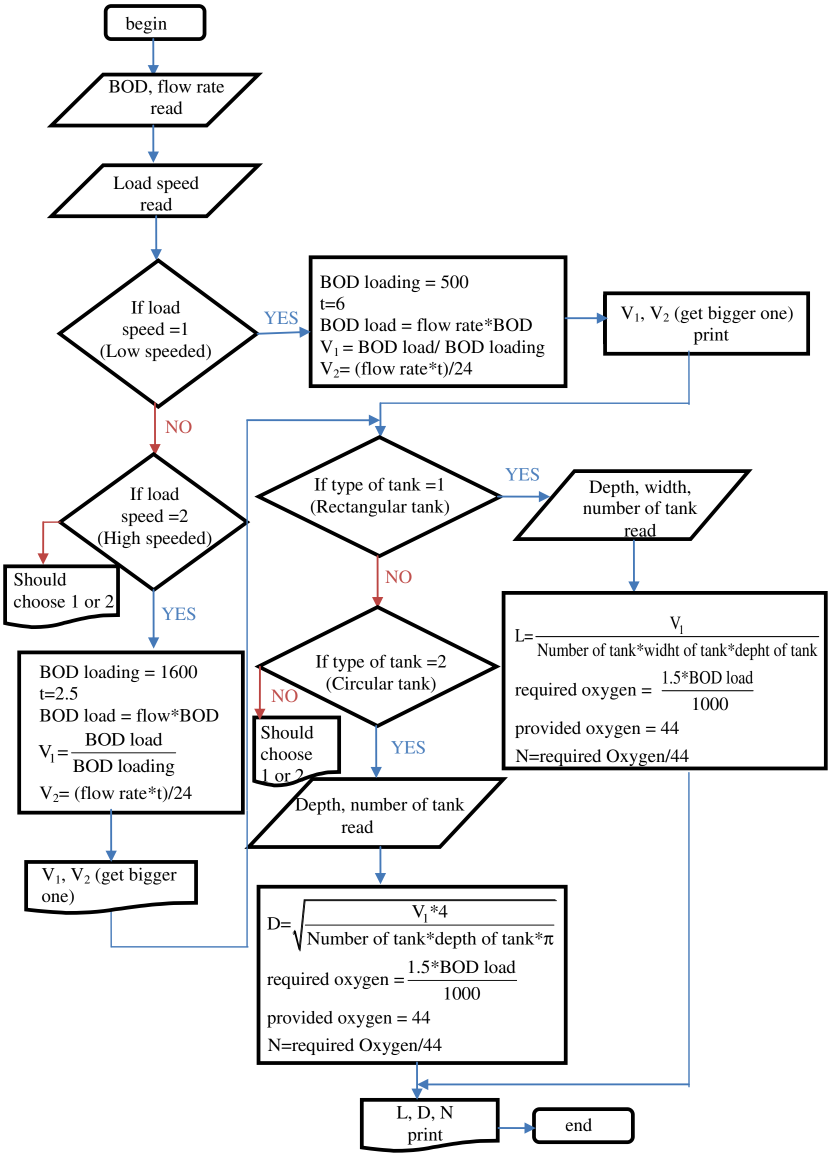

Fig. 5. The activated sludge plant design flow diagram.

V: volume (the bigger one in V_1 and V_2)
Type of tank: 1 (rectangular)
Type of tank: 2 (circular)
Depth of tank: 5 m
Width of tank: 10 m
Numbers of tank: 10

L: Length of tank
N: HP (horse power) (required compressor force)
D: m (diameter of circular tank)
Low speeded loading: 0.5 kg BOD/m^3
High speeded loading: 1.6 kg BOD/m^3.

2.4. The design parameters of aerated lagoons

The design of aerated lagoons is carried out according to following equations [48]:

$$t = \frac{S_0 - S}{S \cdot K_T} \tag{7}$$

$$V = t \cdot Q \tag{8}$$

K_T can be found with the following equation:

$$K_{T(^\circ C)} = K_{20(^\circ C)} . \gamma^{T-20}, \tag{9}$$

for 20 °C, $K_{T(^\circ C)} = K_{20(^\circ C)}$ ($\gamma = 1.085$ and $K_{20\,^\circ C} = 1.20$ day^{-1}).

S_0 = influent BOD$_5$ concentration, g/m^3
S = effluent BOD$_5$ concentration, g/m^3
K_T = overall, first-order, BOD$_5$, removal-rate constant, day^{-1} (vary from 0.3–3)
t = cell residence time, day
Q = flow rate, m^3/day.

The aerated lagoons design flow diagram is shown on Fig. 6 in C++.

S_0 = influent BOD$_5$ concentration, g/m^3
S = effluent BOD$_5$ concentration, g/m^3
K_T = overall, first-order, BOD$_5$, removal-rate constant, day^{-1} (vary from 0.3–3)
t = cell residence time, day
Q = flow rate, 35,000 m^3/day
V: volume, m^3
Type of tank: 1 (rectangular)
Type of tank: 2 (circular)
Depth of tank: 5 m
Width of tank: 10 m
Numbers of tank: 10
L: length of tank, m
N: HP (horse power) (required compressor force)
D: m (diameter of circular tank).

3. Results and discussion

Generally 5 day BOD of raw sewage varies in the 60–90% range of ultimate BOD. The reliability of the ultimate BOD values are dependent on the deviation of daily BOD values from the BOD curve, reliability of the mathematical methods, experimental period and number of observations. The calculated ultimate BOD (L, g/m^3) and reaction rate constant (k, day^{-1}) values obtained from the different mathematical methods (least squares method, log differences method, the slope method, graphical method, method of moments, sum of squares surface method) and the developed method are shown on Tables 5 and 6 for both respirometric and dilution techniques. The relationship between respirometric and dilution BOD values are given in Table 7.

As it is seen in Table 7 there is a satisfactory linear relationship between respirometric and dilution BOD values. Also, there is a strongly linear relationship in respirometric and dilution values, individually as shown on Tables 8 and 9.

The different mathematical methods and new developed method are compared with each other by correlation coefficient and results given in Tables 10 and 11, respectively for respirometric and dilution method.

As it seen in Table 10, the different mathematical methods provide consistent result with each other with high correlation coefficients for respirometric values. Moreover, if it is examined in more detail, it is seen that the LOG differences method does not provide consistent results according to other methods.

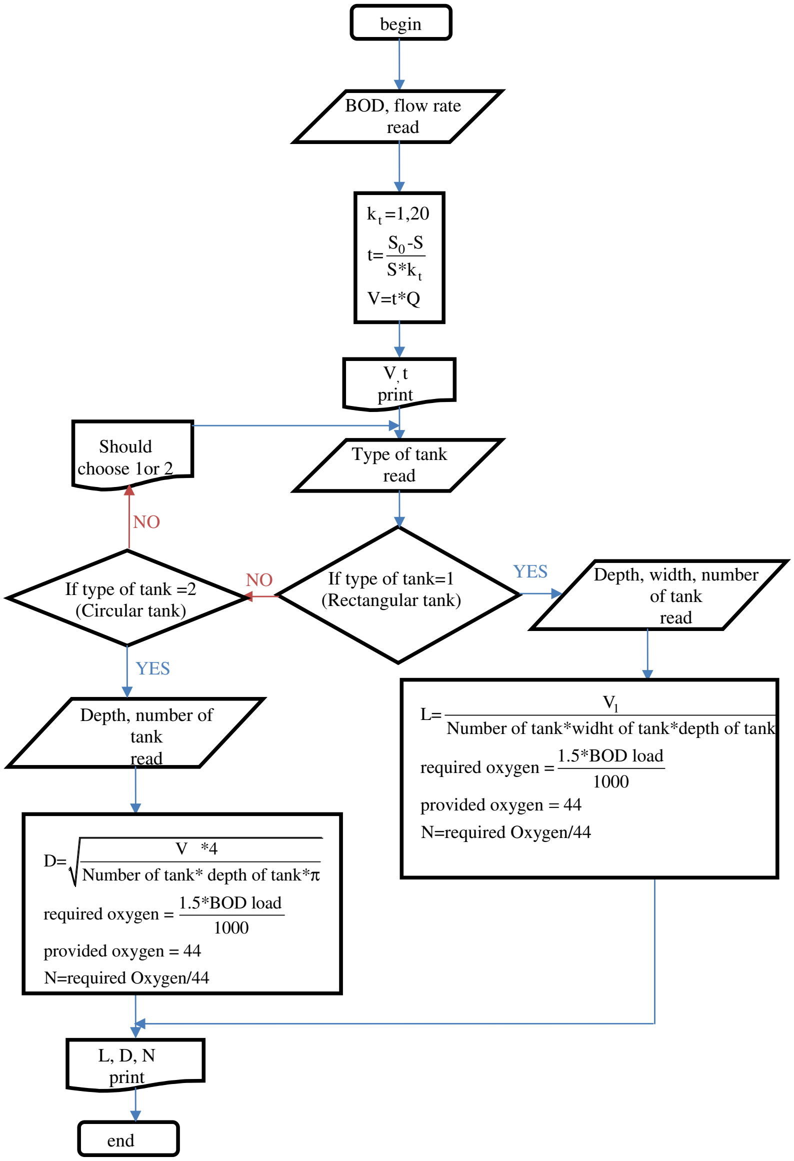

Fig. 6. The aerated lagoons design flow diagram.

Table 5
k (d^{-1}) and *L* (g/m^3) values, determined by different methods (respirometric).

Sample	y_1	y_2	y_3	y_4	y_5	Graphical		L. Squares		Moment		Log. Diff.		Series		D. M.
						k	*L*	*k*	*L*	*k*	*L*	*k*	*L*	*k*	*L*	*L*
	g/m^3	g/m^3	g/m^3	g/m^3	g/m^3	d^{-1}	g/m^3	d^{-1}	g/m^3	d^{-1}	g/m^3	d^{-1}	g/m^3	d^{-1}	g/m^3	g/m^3
Res 1	188	244	308	344	388	0.520	414.7	0.487	410.8	0.539	398.4	0.394	422.7	0.484	416.1	423.2
Res 2	200	276	344	374	398	0.564	435.9	0.609	415.8	0.610	411.7	0.427	437.4	0.567	422.6	415.2
Res 3	166	222	288	322	346	0.511	380.0	0.478	380.9	0.534	365.1	0.380	393.5	0.491	377.7	403.9
Res 4	144	222	266	288	322	0.507	352.1	0.596	327.7	0.539	336.2	0.372	367.5	0.526	339.2	333.3
Res 5	100	188	210	254	288	0.350	346.2	0.395	327.9	0.365	335.9	0.232	405.3	0.433	308.7	307.2

D. M.: The developed method.

For dilution values, given on Table 11, the different mathematical methods also provide consistent method as it is seen above. Furthermore, in contrast to respirometric values, all methods provide closer correlation coefficients, even LOG differences method. But the developed method does not give good correlation coefficients (Fig. 7).

Table 6
k (d^{-1}) and L (g/m^3) values, determined by different methods (dilution, %2).

Sample	y_1	y_2	y_3	y_4	y_5	Graphical		L. Squares		Moment		Log diff.		Series		D. M.
						k	L	k	L	k	L	k	L	k	L	L
	g/m^3	g/m^3	g/m^3	g/m^3	g/m^3	d^{-1}	g/m^3	d^{-1}	g/m^3	d^{-1}	g/m^3	d^{-1}	g/m^3	d^{-1}	g/m^3	g/m^3
Dil 1	143	342	398	439	455	0.318	614.1	0.469	531.0	0.40	547.5	0.197	775.1	0.477	505.3	459.9
Dil 2	143	245	379	435	460	0.223	719.9	0.248	679.7	0.24	680.2	0.120	1062.8	0.260	651.2	479.5
Dil 3	211	322	383	423	450	0.532	499.3	0.611	470.0	0.57	472.0	0.395	512.2	0.562	476.2	492.1
Dil 4	171	236	305	365	402	0.419	452.8	0.324	499.2	0.41	449.2	0.298	498.4	0.395	458.9	437.3
Dil 5	180	197	262	316	325	0.557	351.7	0.315	421.4	0.58	335.6	0.434	349.1	0.553	343.0	325.2

D. M.: The developed method.

Table 7
The correlation coefficients between respirometric and dilution values.

1	0.91424
0.91424	1

Table 8
The correlation coefficients of respirometric values between each other.

1	0.98866	0.99532	0.98551	0.97765
0.98866	1	0.99687	0.99421	0.97933
0.99532	0.99687	1	0.98754	0.97458
0.98551	0.99421	0.98754	1	0.99131
0.97765	0.97933	0.97458	0.99131	1

Table 9
The correlation coefficients of dilution values between each other.

1	0.94934	0.9837	0.92688	0.86493
0.94934	1	0.98676	0.98726	0.97253
0.9837	0.98676	1	0.97872	0.93702
0.92688	0.98726	0.97872	1	0.98331
0.86493	0.97253	0.93702	0.98331	1

Table 10
The comparative of different mathematical methods by correlation coefficients with regard to each other for respirometric values.

Graphical	Least squares	Moment	Log differences	Series	Developed method
1	0.96879	0.99692	0.82206	0.96605	0.88767
0.96879	1	0.97986	0.78744	0.97386	0.96094
0.99692	0.97986	1	0.84256	0.96469	0.90055
0.82206	0.78744	0.84256	1	0.67478	0.59686
0.96605	0.97386	0.96469	0.67478	1	0.96458
0.88767	0.96094	0.90055	0.59686	0.96458	1

Table 11
The comparative of different mathematical methods by correlation coefficients with regard to each other for dilution values.

Graphical	Least squares	Moment	Log differences	Series	Developed method
1	0.92886	0.99059	0.98191	0.96247	0.73749
0.92886	1	0.96117	0.97002	0.96453	0.58312
0.99059	0.96117	1	0.98151	0.98987	0.74937
0.98191	0.97002	0.98151	1	0.95504	0.61535
0.96247	0.96453	0.98987	0.95504	1	0.77288
0.73749	0.58312	0.74937	0.61535	0.77288	1

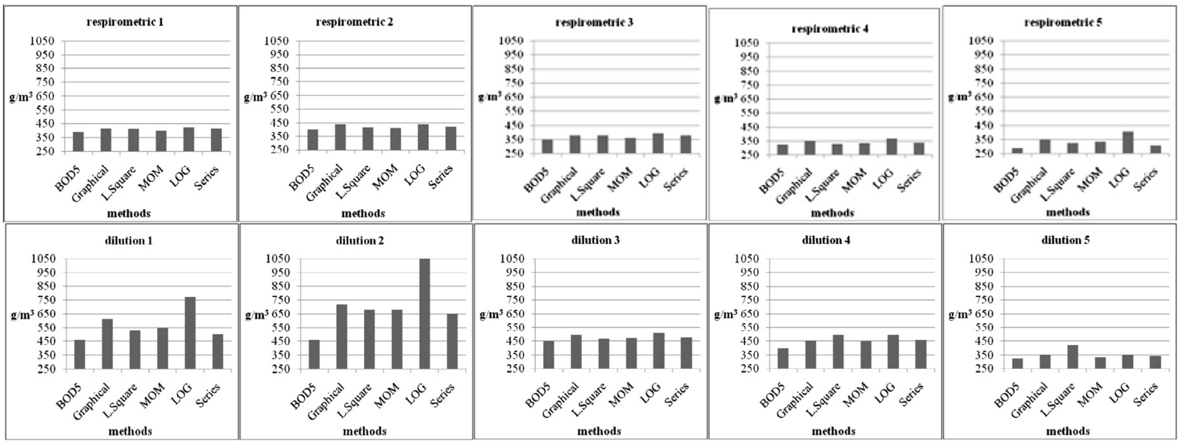

Fig. 7. Comparing of the ultimate BOD values, determined from different methods for respirometric and dilution techniques.

3.1. Activated sludge plant design results depending on the BOD parameters variations

The activated sludge and aerated lagoons are designed by using the C++ programme and the design results are shown on Tables 12–15 for both respirometric and dilution technique values. Also, the graphical presentations in a reference plane of results are given in Figs. 8–10.

BOD: g/m^3
BOD loading: g
Flow rate: 35,000 m^3/d
t: day (retention time)
V_1: m^3(volume for BOD load)
V_2: m^3(volume for retention time)
V: volume (the bigger one in V_1 and V_2)
Type of tank: 1 (rectangular)
Type of tank: 2 (circular)
Depth of tank: 5 m
Width of tank: 10 m
Numbers of tank: 10
L: length of tank
N: HP (horse power) (required compressor force)
D: m (diameter of circular tank)
Low speeded loading: 0.5 kg BOD/m^3
High speeded loading: 1.6 kg BOD/m^3.

3.2. Aerated lagoon design depending on the BOD parameters variations

S_0 = influent BOD$_5$ concentration, g/m^3
S = effluent BOD$_5$ concentration, g/m^3
K_T = overall, first-order, BOD$_5$, removal-rate constant, day^{-1} (vary from 0.3–3)
t = cell residence time, day
Q = flow rate, 35,000 m^3/day
V: volume, m^3
Type of tank: 1 (rectangular)
Type of tank: 2 (circular)
Depth of tank: 5 m
Width of tank: 10 m
Numbers of tank: 10
L: length of tank, m
N: HP (horse power) (required compressor force)
D: m (diameter of circular tank).

Table 12
Activated sludge plant design results depending on the BOD parameters variations (respirometer).

Sample	BOD$_5$ g/m^3	Method	uBOD g/m^3	Loading type	*t* h	*V* m^3	*L* m	*D* m	*N* hp
Respirometric 1	388	–	–	Low	6	27160.00	54.32	26.30	462.95
				High	2.5	8487.50	16.97	14.70	462.95
		Graphical	417.4	Low	6	29218.00	58.44	27.28	498.03
				High	2.5	9130.63	18.26	15.25	498.03
		The least square	410.8	Low	6	28756.00	57.51	27.07	490.16
				High	2.5	8986.25	17.97	15.13	490.16
		Moment	398.4	Low	6	27888.00	55.78	26.65	475.36
				High	2.5	8715.00	17.43	14.90	475.36
		Log differences	422.7	Low	6	29589.00	59.18	27.46	504.36
				High	2.5	9246.56	18.49	15.35	504.36
		Series	416.1	Low	6	29127.00	58.25	27.24	496.48
				High	2.5	9102.19	18.20	15.23	496.48
Respirometric 2	398	–	–	Low	6	27860.00	55.72	26.64	474.89
				High	2.5	8706.25	17.41	14.89	474.89
		Graphical	435.9	Low	6	30513.00	61.03	27.89	520.11
				High	2.5	9535.31	19.07	15.59	520.11
		The least square	415.8	Low	6	29106.00	58.21	27.23	496.12
				High	2.5	9095.63	18.19	15.22	496.12
		Moment	411.7	Low	6	28819.00	57.64	27.07	491.23
				High	2.5	9005.94	18.01	15.15	491.23
		Log differences	437.4	Low	6	30618.00	61.24	27.93	521.90
				High	2.5	9568.13	19.14	15.61	521.90
		Series	422.6	Low	6	29582.00	59.16	27.45	504.24
				High	2.5	9244.38	18.49	15.35	504.24
Respirometric 3	346	–	–	Low	6	24220.00	48.44	24.84	412.84
				High	2.5	7568.75	15.14	13.89	412.84
		Graphical	380.0	Low	6	26600.00	53.20	26.03	453.41
				High	2.5	8312.50	16.62	14.55	453.41
		The least square	380.9	Low	6	26663.00	53.33	26.06	454.48
				High	2.5	8332.19	16.66	14.57	454.48
		Moment	365.1	Low	6	25557.00	51.11	25.52	435.63
				High	2.5	7986.56	15.97	14.26	435.63
		Log differences	393.5	Low	6	27545.00	55.09	26.49	469.52
				High	2.5	8607.81	17.21	14.81	469.52
		Series	377.7	Low	6	26439.00	52.88	25.95	450.66
				High	2.5	8262.19	16.52	14.51	450.66
Respirometric 4	322	–	–	Low	6	22540.00	45.08	23.96	384.20
				High	2.5	7043.75	14.09	13.40	384.20
		Graphical	352.1	Low	6	24647.00	49.29	25.06	420.12
				High	2.5	7702.19	15.40	14.01	420.12
		The least square	327.7	Low	6	22939.00	45.88	24.16	391.01
				High	2.5	7168.44	14.34	13.51	391.01
		Moment	336.2	Low	6	23534.00	47.07	24.49	401.15
				High	2.5	7354.38	14.71	13.69	401.15
		Log differences	367.5	Low	6	25725.00	51.45	25.60	438.49
				High	2.5	8039.06	16.08	14.31	438.49
		Series	339.2	Low	6	23744.00	47.49	24.59	404.73
				High	2.5	7420.00	14.84	13.75	404.73
Respirometric 5	288	–	–	Low	6	19320.00	38.64	22.19	329.32
				High	2.5	6037.50	12.07	12.40	329.32
		Graphical	319.9	Low	6	22393.00	44.79	23.88	381.70
				High	2.5	6997.81	13.99	13.35	381.70
		The least square	303.2	Low	6	21224.00	42.45	23.25	361.77
				High	2.5	6632.50	13.26	13.00	361.77
		Moment	309.8	Low	6	21686.00	43.37	23.50	369.65
				High	2.5	6776.88	13.55	13.14	369.65
		Log differences	366.3	Low	6	25641.00	51.28	25.56	437.06
				High	2.5	8012.81	16.02	14.29	437.06
		Series	308.7	Low	6	21609.00	43.22	23.46	368.33
				High	2.5	6752.81	13.50	13.12	368.33

Table 13
Activated sludge plant design results depending on the BOD parameters variations (dilution technique).

Sample	BOD$_5$ g/m^3	Method	uBOD g/m^3	Loading type	*t* h	*V* m^3	*L* m	*D* m	*N* hp
Dilution 1	455	–	–	Low	6	31850.00	63.70	28.49	542.90
				High	2.5	9953.13	19.91	15.92	542.90
		Graphical	614.1	Low	6	42987.00	85.97	33.09	732.73
				High	2.5	13433.40	26.87	18.50	732.73
		The least square	531.0	Low	6	37170.00	74.34	30.77	633.58
				High	2.5	11615.60	23.23	17.20	633.58
		Moment	547.5	Low	6	38325.00	76.65	31.25	653.28
				High	2.5	11976.60	23.95	17.47	653.28
		Log differences	775.1	Low	6	54257.00	108.51	37.18	924.83
				High	2.5	16955.30	33.91	20.78	924.83
		Series	505.3	Low	6	35371.00	70.74	30.02	602.91
				High	2.5	11053.40	22.11	16.78	602.91
Dilution 2	460	–	–	Low	6	32200.00	64.40	28.64	548.86
				High	2.5	10062.50	20.12	16.01	548.86
		Graphical	719.9	Low	6	50393.00	100.79	35.83	858.97
				High	2.5	15747.80	31.49	20.03	858.97
		The least square	679.7	Low	6	47579.00	95.16	34.82	811.00
				High	2.5	14868.40	29.74	19.46	811.00
		Moment	680.2	Low	6	47614.00	95.23	34.83	811.60
				High	2.5	14879.40	29.76	19.47	811.60
		Log differences	1062.8	Low	6	74396.00	148.79	43.54	1268.11
				High	2.5	23248.80	46.50	24.34	1268.11
		Series	651.2	Low	6	45584.00	91.17	34.08	777.00
				High	2.5	14245.00	28.49	19.05	777.00
Dilution 3	450	–	–	Low	6	31500.00	63.00	28.33	536.93
				High	2.5	9843.75	19.69	15.84	536.93
		Graphical	499.3	Low	6	34951.00	69.90	29.84	595.76
				High	2.5	10922.20	21.84	16.68	595.76
		The least square	470.0	Low	6	32900.00	65.80	28.95	560.79
				High	2.5	10281.30	20.56	16.18	560.79
		Moment	472.0	Low	6	33040.00	66.08	29.01	563.18
				High	2.5	10325.00	20.65	16.22	563.18
		Log differences	512.2	Low	6	35854.00	71.71	30.22	611.15
				High	2.5	11204.40	22.41	16.90	611.15
		Series	476.2	Low	6	33334.00	66.67	29.14	568.19
				High	2.5	10416.90	20.83	16.29	568.19
Dilution 4	402	–	–	Low	6	28140.00	56.28	26.78	479.67
				High	2.5	8793.75	17.59	14.97	479.67
		Graphical	452.8	Low	6	31696.00	63.39	28.42	540.27
				High	2.5	9905.00	19.81	15.89	540.27
		The least square	499.2	Low	6	34944.00	69.89	29.84	595.64
				High	2.5	10920.00	21.84	16.68	595.64
		Moment	449.2	Low	6	31444.00	62.89	28.30	535.98
				High	2.5	9826.25	19.65	15.82	535.98
		Log differences	498.4	Low	6	34888.00	69.78	29.81	594.68
				High	2.5	10902.50	21.80	16.67	594.68
		Series	458.9	Low	6	32123.00	64.25	28.61	547.55
				High	2.5	10038.40	20.08	15.99	547.55
Dilution 5	325	–	–	Low	6	22750.00	45.50	24.07	387.78
				High	2.5	7109.38	14.22	13.46	387.78
		Graphical	351.7	Low	6	24619.00	49.24	25.04	419.64
				High	2.5	7693.44	15.39	14.00	419.64
		The least square	421.4	Low	6	29498.00	59.00	27.41	502.81
				High	2.5	9218.13	18.44	15.32	502.81
		Moment	335.6	Low	6	23492.00	46.98	24.46	400.43
				High	2.5	7341.25	14.68	13.68	400.43
		Log differences	349.1	Low	6	24437.00	48.87	24.95	416.54
				High	2.5	7636.56	15.27	13.95	416.54
		Series	343.0	Low	6	24010.00	48.02	24.73	409.26
				High	2.5	7503.13	15.01	13.83	409.26

Table 14
Aerated lagoons design results depending on the BOD parameter variations (respirometric).

Sample	BOD_5 g/m^3	Method	uBOD g/m^3	S_0 g/m^3	S g/m^3	Flow rate m^3/d	t d	V m^3	L m	D m	N hp
Respirometric 1	388	–	–	388.0	30	35000	9.94	348056	696.11	94.17	462.95
		Graphical	417.4	417.4			10.76	376639	753.27	97.96	498.03
		Least square	410.8	410.8			10.58	370222	740.44	97.12	490.16
		Moment	398.4	398.4			10.23	358167	716.33	95.52	475.36
		Log differences	422.7	422.7			10.91	381792	763.58	98.62	504.36
		Series	416.1	416.1			10.72	375375	750.75	97.79	496.48
Respirometric 2	398	–	–	398.0	30	35000	10.22	357778	715.55	95.47	474.88
		Graphical	435.9	435.9			11.27	394625	789.25	100.27	520.11
		Least square	415.8	415.8			10.71	375083	750.16	97.75	496.12
		Moment	411.7	411.7			10.60	371097	742.19	97.23	491.23
		Log differences	437.4	437.4			11.31	396083	792.16	100.45	521.90
		Series	422.6	422.6			10.90	381694	753.39	98.61	504.24
Respirometric 3	346	–	–	346.0	30	35000	8.77	307222	614.44	88.47	412.84
		Graphical	380.0	380.0			9.72	340278	680.55	93.11	453.41
		Least square	380.9	380.9			9.74	341153	682.30	93.23	454.48
		Moment	365.1	365.1			9.30	325792	651.58	91.10	435.63
		Log differences	393.5	393.5			10.09	353403	706.80	94.88	469.51
		Series	377.7	377.7			9.65	338042	676.08	92.80	450.66
Respirometric 4	322	–	–	322.0	30	35000	8.11	283889	567.78	85.04	384.20
		Graphical	352.1	352.1			8.94	313153	626.30	89.32	420.12
		Least square	327.7	327.7			8.26	289431	578.86	85.87	391.00
		Moment	336.2	336.2			8.50	297694	595.39	87.09	401.15
		Log differences	367.5	367.5			9.37	328125	656.25	91.43	438.49
		Series	339.2	339.2			8.58	300611	601.22	87.51	404.72
Respirometric 5	288	–	–	288.0	30	35000	7.16	250833	501.66	79.94	343.63
		Graphical	319.9	319.9			8.05	281847	563.69	84.74	381.70
		Least square	303.2	303.2			7.58	265611	531.22	82.26	361.77
		Moment	309.8	309.8			7.77	272028	544.05	83.25	369.64
		Log differences	366.3	366.3			9.34	326958	653.91	91.26	437.06
		Series	308.7	308.7			7.74	270958	541.91	83.08	368.33

Table 15
Aerated lagoons design results depending on the BOD parameter variations (dilution technique).

Sample	BOD_5 g/m^3	Method	uBOD g/m^3	S_0 g/m^3	S g/m^3	Flow rate m^3/d	t d	V m^3	L m	D m	N hp
Dilution 1	455	–	–	455.0	30	35000	11.80	413194	826.38	102.60	542.89
		Graphical	614.1	614.1			16.22	567875	1135.75	120.28	732.73
		Least square	531.0	531.0			13.91	487083	974.16	111.39	633.58
		Moment	547.5	547.5			14.37	503125	1006.25	113.22	653.26
		Log differences	775.1	775.1			20.69	724403	1448.81	135.85	924.83
		Series	505.3	505.3			13.20	462097	924.19	108.50	602.91
Dilution 2	460	–	–	460.0	30	35000	11.94	418056	836.11	103.20	548.86
		Graphical	719.9	719.9			19.16	670736	1341.47	130.72	858.97
		Least square	679.7	679.7			18.04	631653	1263.31	126.85	811.00
		Moment	680.2	680.2			18.06	632139	1264.28	126.90	811.60
		Log differences	1062.8	1062.8			28.68	1004110	2008.22	159.94	1268.11
		Series	651.2	651.2			17.25	603944	1207.89	124.04	777.00
Dilution 3	450	–	–	450.0	30	35000	11.66	408333	816.66	101.99	536.93
		Graphical	499.3	499.3			13.03	456264	912.52	107.81	595.75
		Least square	470.0	470.0			12.22	427778	855.55	104.39	560.79
		Moment	472.0	472.0			12.27	429722	859.44	104.63	563.18
		Log differences	512.2	512.2			13.39	468806	937.61	109.28	611.14
		Series	476.2	476.2			12.39	433806	867.61	105.13	568.19
Dilution 4	402	–	–	402.0	30	35000	10.33	361667	723.33	95.99	479.65
		Graphical	452.8	452.8			11.74	411056	822.11	102.33	540.27
		Least square	499.2	499.2			13.03	456167	912.33	107.80	595.63
		Moment	458.9	458.9			11.91	416986	833.97	103.07	547.55
		Log differences	498.4	498.4			13.01	455389	910.77	107.71	594.68
		Series	449.2	449.2			11.64	407556	815.11	101.90	535.97
Dilution 5	325	–	–	325.0	30	35000	8.19	286806	573.61	85.48	387.78
		Graphical	351.7	351.7			8.93	312764	625.52	89.26	419.64
		Least square	421.4	421.4			10.87	380528	761.05	98.46	502.80
		Moment	335.6	335.6			8.48	297111	594.22	87.00	400.43
		Log differences	349.1	349.1			8.86	310236	620.47	88.90	416.54
		Series	343.0	343.0			8.69	304306	608.61	88.05	409.26

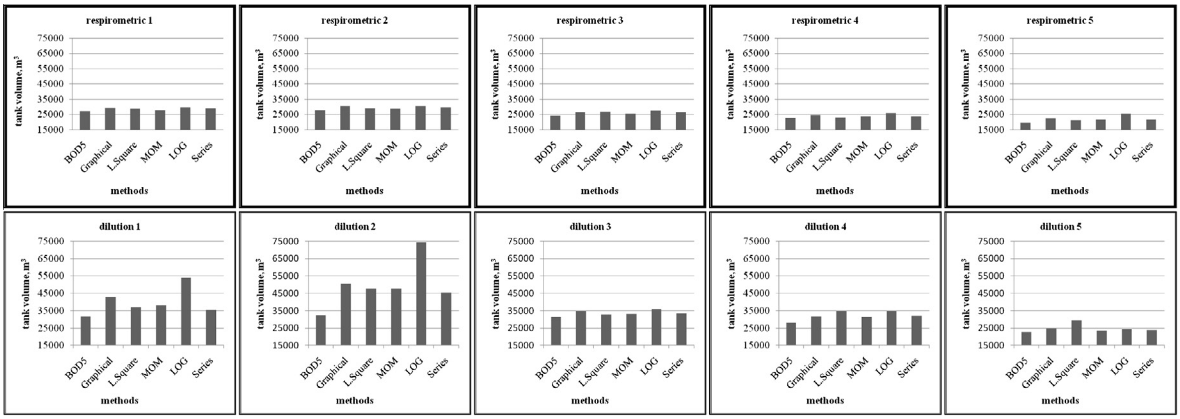

Fig. 8. The impacts of BOD parameter variations on the design of activated sludge plants (low loading).

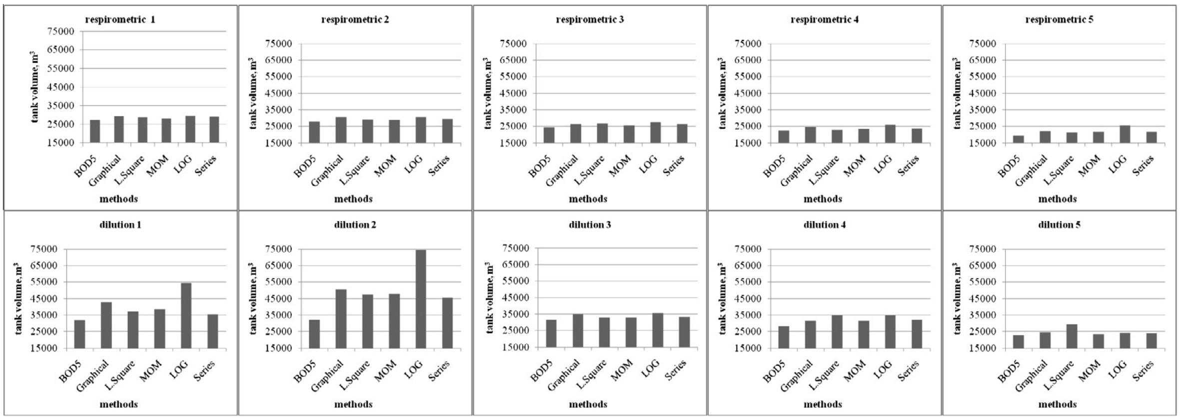

Fig. 9. The impacts of BOD parameter variations on the design of activated sludge plants (high loading).

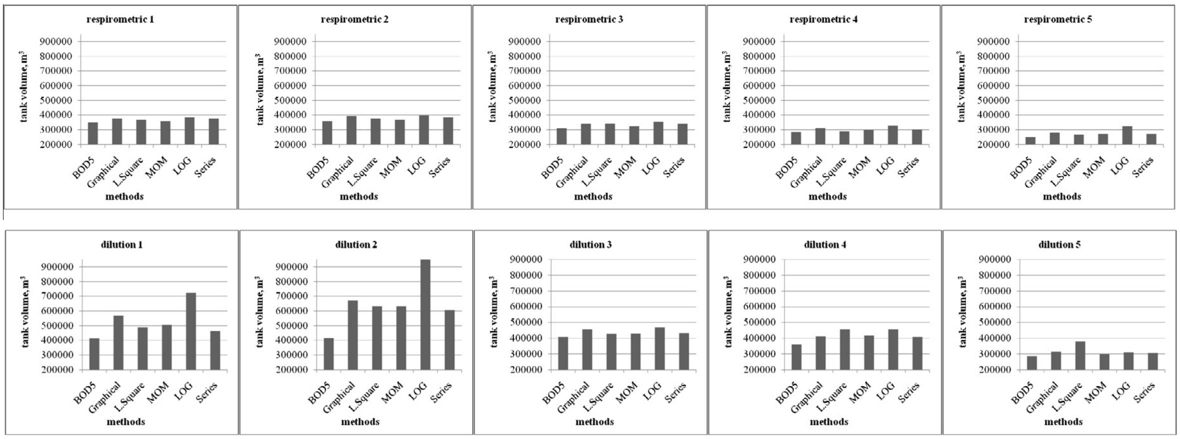

Fig. 10. The impacts of BOD parameter variations on the design of aerated lagoons.

Table 16
The increase range of active sludge tank volumes and compressor force depending upon the BOD parameter variations.

Sample	Tank volumes and required compressor force increase range between (%)
Respirometric 1	2.68–8.94
Respirometric 2	3.44–9.89
Respirometric 3	5.52–13.72
Respirometric 4	1.77–14.13
Respirometric 5	9.85–32.71
Dilution 1	11.05–70.35
Dilution 2	41.56–131.04
Dilution 3	4.44–13.82
Dilution 4	11.74–24.17
Dilution 5	3.26–29.66

Table 17
The increase range of aerated lagoons volumes and compressor force depending upon the BOD parameter variations.

Sample	Tank volumes and required compressor force increase range between (%)
Respirometric 1	2.90–9.69
Respirometric 2	3.72–10.71
Respirometric 3	6.04–15.032
Respirometric 4	1.95–15.58
Respirometric	5.89–30.35
Dilution 1	11.84–75.32
Dilution 2	44.46–140.19
Dilution 3	4.76–14.81
Dilution 4	12.69–26.13
Dilution 5	3.59–32.68

As it is seemed in Tables 16 and 17; the dilution 2 samples show enormous increasing range than the other samples.

4. Conclusions

Because, determine the ultimate BOD (L) instead of the only 5-day period used for BOD test are necessary to understand the organic strength of the wastewater, the different mathematical methods which is mentioned in this study have importance. So, these methods are investigated in detail and relative similarity or difference of these methods are provided.

The general conclusions drawn from the results of this work are as follows:

- When the laboratory test methods, which is used in order to determine BOD are compared, there are considerable variations between the domestic wastewater BOD values obtained from respirometer and dilution test methods. On the other hand, according to analyses result there is a satisfactory linear relationship between respirometric and dilution BOD values. Also, there is a strongly linear relationship in respirometric and dilution values, individually.
- When the mathematical methods, which are used in order to determine ultimate BOD are evaluated, the mathematical methods show significant changes. However, the mathematical methods provide consistent result with each other with high correlation coefficients, even new developed method. Although, the new developed method is not first order function origin, it gives good results with other methods. When considered from this point of view, the new developed method is vary from other methods. Moreover, if it is examined in more detail, it is seen that the LOG differences method in respirometric data and the new developed method in dilution data do not provide consistent results in regards to other methods.
- And finally, when it comes to the impacts of the BOD parameter variations on the WWTP, both activated sludge and aerated lagoons tank volumes and required compressor force increased in proportion to the BOD and ultimate BOD values. Analytical results show that, the volume of the activated sludge system and required compressor force change in the range 1.7–32.7% and 3.26–131.04% for respirometer technique and dilution technique, respectively, depending upon the variation of ultimate BOD values. And the volume of the aerated lagoons and required compressor force change in the range of 2.90–30.35% and 3.59–140.19% for the respirometer technique and dilution technique, respectively, depending upon the variation of ultimate BOD values.

Consequently, BOD parameters show significant changes depending on the different methods. Therefore, the changing of these parameters impact a lot of situation such as ultimate BOD estimation, the wastewater treatment plants design, the dimensions of the plants and cost of the plants. In view of this study, estimation of the BOD parameters (uBOD, k) are essential to provide more consistent and accurate estimations in regard to wastewater research and wastewater treatment plants design.

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