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Assessment of household greywater discharge from village houses using Streeter–Phelps model in stream

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ABSTRACT

The present study aimed to assess the effect of greywater discharged into the drainage system on DO concentrations using the Streeter–Phelps model. The result revealed that biochemical oxygen demand (BOD_5) was 172 mg/L, chemical oxygen demand (COD) was 400 mg/L and pH was 4.5. The highest BOD_5 loading rate for daily flow rate was observed at Drain (III) with the values of 63 kg/d and 369 m^3/d. These drains have a high frequency of household activities and number of occupants leads to high amount of pollutant loading rate produced from greywater drainage. Moreover, the assessment of greywater pollution modelling was measured using Streeter–Phelps model. The DO deficit (D_t) and time critical (t_c) were 3.54 and 3.80 mg/L and 0.007/d, respectively, as recorded at the distance of 10 m upstream ($Station_1$) of the discharge point. The findings show that the degradable organic matter and travel time as a critical oxygen deficit point occurred at 10 m upstream as the kinetics of BOD reaction. Hence, the greywater discharge with mixing stream showed no risk of pollution occurrence near the river flow in this study.

Keywords: Greywater; Deoxygenation; Reaeration; Self-purification; Stream; Streeter–Phelps model

1. Introduction

Greywater sources play a critical role in the variation of pollutant concentration levels compared with blackwater. Major contaminants reported within the effluents of these domestic residential include a very high loading of organic pollutants from household activities [1]. Mohamed et al. [2] claimed that the biochemical oxygen demand (BOD_5) in greywater ranged from 117 to 178 mg/L in combined discharges of kitchen, bathroom and laundry greywater in Malaysia. The range is considerably higher than the safe level of water quality stipulated in the Environment Quality Regulations 2009 and the BOD_5 (50 mg/L) for standard effluent discharge. Moreover, greywater from kitchen had acidic pH [3] due to the presence of many organic materials from food, dishes, oil and grease [4,6,8]. It also has been reported that the raw greywater discharged from kitchen have high concentrations of COD [3,8]. Dwumfour-Asare et al. [9] revealed that kitchen activities also have high concentrations of BOD_5 (average 370 mg/L) due to high organic matter, while BOD_5 concentration in the laundry greywater is 269 mg/L, while bathroom greywater has only 139 mg/L.

In villages, greywater and blackwater are separated from the sewerage network, in which the sewage goes to the septic tank whilst the greywater is disposed into the nearest drainage. This is a common practice in many of the village

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houses in Malaysia. Dwumfour-Asare et al. [9] reported that commonly, the raw greywater from household activities (kitchen, laundry and bathroom) in village house is discharged directly into streams or rivers. The direct discharge of greywater into drainages has potential negative effect on the environment and human health [10]. The process of dissolved oxygen reduction is due to the decomposition of organic waste and lack of oxygen supply for the aquatic organism in the water [20]. The excess nutrients could lead to the growth of large algae populations known as an algal bloom [21]. Therefore, the direct discharge of greywater to the natural water system could potentially contribute to the eutrophication phenomenon due to excess nutrients in the greywater [7]. Stagnant drainage water which contains greywater could lead to unpleasant odours from the release of nutrients and provide a breeding environment for insect pests [4]. Furthermore, low water flow and stagnant water contribute to the presence of *Anopheles larvae* in drains [5]. Some of the wastes, especially greywater discharge, which is non-biodegradable and acidic were also found to interrupt the auto-purification processes of streams and rivers [13].

The value rate of river quality depends on the self-purification process of the river which relies on the water body velocity, depth, discharge and temperature [11]. The Streeter–Phelps model (oxygen sag curve model) is a water quality modelling tool used to evaluate water pollution. The model has been used to predict the decrease of DO in the Harsit Stream (Turkey) due to the municipal and industrial wastewaters contamination and then the degradation of BOD. The Model transport simulation using the Streeter–Phelps model is also used to predict the changes in surface water quality at a certain distance after mixing of the effluent discharged in the stream [12]. It is considered as an effective tool and treatment innovation for future management of water streams [13]. Moreover, the Streeter–Phelps model is also used by engineers to simulate the hydrological processes of streams or rivers. Maamar et al. [14] stated that Streeter–Phelps model was used to investigate the quality of the Wadi Cheliff River mainly to study the need for self-purification, hydraulic properties and physicochemical characteristics. The study revealed that the Wadi Cheliff River has a normal capacity but limited ability to purify itself from many pollutants due to domestic or industrial wastewater discharge. These could happen due to the presence of wastes (non-biodegradable), which slows down the self-purification processes in the river. The dry season indicates that the flow is low, thereby generating low flow velocity and temperatures higher than 29°C decreases the solubility of the DO [14].

Moreover, the prediction of DO movement levels in a water body after the discharge of organic waste showed that the mathematical equation in the Streeter–Phelps model was accepted as an efficient tool to the analysis of pollution status in streams or rivers [15]. Maroneze et al. [16] explained that the total change in oxygen shortage was equal to the difference between the two rates of deoxygenation (K_d) and reaeration (K_r) at any time. The changes in the oxygen content of polluted stream or rivers were studied through the Streeter–Phelps model. The model used the DO sag curve profile to predict the DO movement with reasonable accuracy in the contaminated water bodies [1]. Therefore, measurement of the DO in the stream from the greywater discharge of the household activities was studied. In the current work, the Streeter–Phelps model was used in describing the DO decreases in a stream. A certain distance by BOD depletion identified the critical DO level at certain distance of drainage as affected by the greywater discharge.

2. Materials and methods

2.1. Study area

The current study was conducted at Parit Raja Darat village, Parit Raja, Batu Pahat, Johor, Malaysia with the location coordinates (2.024 N and 102.618 E). All the data were collected once every weekend during dry seasons in a period of 11 months.

2.2. Collection of greywater samples

The information in the case study was acquired using questionnaire to obtain household demographic profiles and household activity practices data from respondents. The form was distributed to the villagers, as much as 48 houses, representing five drains for greywater sampling. The 48 houses were chosen from site investigation which showed that the pollution of wastewater came from the greywater discharge from five drains based on drainage lines and number of houses. Grab samples and measurement of fieldwork were used to determine the variation of greywater pollutants loading rate (BOD_5) in the morning (8.00 a.m. to 12.00 p.m.). The time selected represents the peak household activities period and ensures that the collected samples reflect the actual constitutes of the greywater. Most occupants preferred spend their time at home during the weekend in the morning. The samples were collected once every weekend, with a total of 45 samples between October 2016 and August 2017. Grab sampling was taken from the last point of household greywater discharge through drain before mixing with the stream as shown in Fig. 1. Sampling was conducted three times from each of the drains. Samples were tested for quality parameters based on pH, BOD_5 and COD. The experiments were conducted in three replicates collected to improve reliability of data. Samples were collected in a polyethylene container and stored in ice box at 4°C. All samples were transported to the laboratory within 24 h to preserve or maintain the quality of sample and analysed for characterization according to APHA (2012).

2.2.1. Greywater flow measurement

Greywater flow measurement was measured at the drains to get the flow rate in unit m^3/s. Velocity greywater discharge was determined by using automatic current meter. The current meter measured the direct flow in greywater. Samples were carried out in three replicates to reduce error. All data were recorded in the table. The distance, width (drain and water) and depth of water of each sources greywater were measured by using a measuring tape. The calculation of drain area was calculated by using geometry formulas based on drain shape at sampling site as follows:

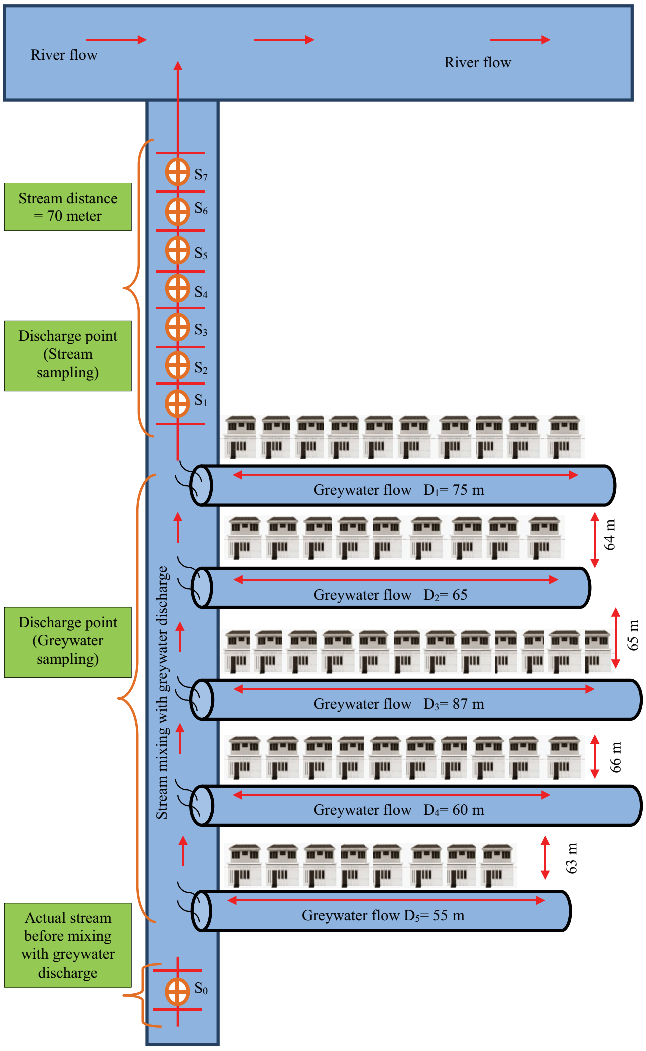

Fig. 1. Sampling location of greywater discharge and stream flow.

$$(a)\text{Discharge}, Q\left(\frac{\text{m}^3}{\text{s}}\right) = V(\text{velocity})\left(\frac{\text{m}}{\text{s}}\right) \times (A)\text{Area}\left(\text{m}^2\right) \quad (1)$$

$$(b)\text{Velocity}, v\left(\frac{\text{m}}{\text{s}}\right) = \text{Automatic current meter} \quad (2)$$

(c)Cross section area

$$\text{For } D_1 \text{ to } D_5, A\left(\text{m}^2\right) = \frac{1}{2}\left(b_1 \times b_2\right) \times h(\text{trapeziod}) \quad (3)$$

$$\text{For } D_5, A\left(\text{m}^2\right) = \frac{\pi r^2 \text{e}}{360}(\text{sector of a circle}) \quad (4)$$

2.2.2. Greywater pollution loading measurement

Organic pollutant loading depends on its flow rate, Q (m/s^3), and its pollutant strength (BOD$_5$) through greywater that was discharged into the drains. The time periods of work measurements are during the peak operational time (activity). Hence, by depending on the five drains in each of the household activities higher greywater pollutant loading rate (BOD$_5$) could be predicted. The organic pollutant loading was calculated as per formula given by EPA [24] by using Eq. (5).

$$\text{OL}\left(\frac{\text{kg}}{\text{day}}\right) = \frac{Q\left(\frac{\text{m}^3}{\text{day}}\right) \times \text{BOD}_5\left(\frac{\text{mg}}{\text{L}}\right)}{1{,}000} \quad (5)$$

2.3. Stream sampling

After greywater sampling, stream sampling was conducted by grab method in the evening (5.00 p.m to 7.00 p.m) on the same day. The time selected represent the time where the stream is completely diluted with greywater after peak time where household activities were carried out in the house. Stream flow measurement was analyzed by using Streeter–Phelps model from the upstream of the household discharge until downstream at 70 m distance (Fig. 1). Thus, stream distance at 70 m was selected because the stream flow was approaching river area for this study. To collect water quality samples of point contamination, seven sampling stations namely S_1, S_2, S_3, S_4, S_5, S_6 and S_7, were decided and each station was within 10 m. Initial DO deficit at S_0 was collected to distinguish the actual condition of normal stream flow without mixing greywater discharge (Fig. 1). All samples and fieldwork measurements were conducted three times at each station to get the average values. Simultaneously, the depth, width and velocity for each station were measured and recorded by using a measuring tape. Thus, water samples were taken at different sampling stations. Stream samples on each station were collected in 1.5-L sampling bottles that were was labelled with proper identification and taken to a laboratory to analyse. The stream samples were tested for quality parameters (BOD$_5$, DO, temperature and pH). Lastly, after all the data were collected, calculations can be done to put in Streeter–Phelps model to get the DO (D_t) and time (t_c) critical and comparison between measured and simulated DO with respect to distance. The Streeter–Phelps formulas, namely Eqs. (6)–(12), as the first order kinetic equations of the oxygen uptake rate (BOD) in stream.

2.4. Theory

The Streeter–Phelps model Eq. (6) was used to measure the movement condition of dissolved oxygen (DO) of stream [17].

$$D_t = \frac{K_d L_0}{K_r - K_d}\left(e^{-K_d t} - e^{-K_r t}\right) + D_0\left(e^{-K_r t}\right) \quad (6)$$

where D_t is oxygen deficit in stream after exertion of BOD for time (mg/L); L_0 is initial ultimate BOD after stream and greywater have mixed (mg/L); K_d is deoxygenation rate constant, d^{-1} (per d); K_r is reaeration rate constant, d^{-1} (per d); t is time of travel of greywater discharged downstream (per d); D_0 is dissolved oxygen after stream and greywater mixed (mg/L).

Eq. (7) for the determination of deoxygenation (K_d) using Hydroscience empirical equation is known as organic water pollution model for normal flow stream [30] and ultimate BOD_5 (L_0), using mathematical Eq. (8), at temperature of 20°C [22].

$$K_d = 0.3 \times \left(\frac{H}{8}\right)^{\Lambda-0.434} \quad 0 \le H \le 8 \tag{7}$$

$$L_0 = 1.46\text{BOD}_5 \tag{8}$$

where K_d is the removal of oxygen by microorganisms during biodegradation (per d); H is the depth of the stream (m), L_0 is BOD of the mixture of stream water and greywater (mg/L); BOD is pollutant load after stream and greywater have mixed (mg/L). The second method for deoxygenation (K_d) and ultimate BOD_5 (L_0) is shown as follows.

Eqs. (9) and (10) for the determination of deoxygenation (K_d) and ultimate BOD_5 (L_0) use the Thomas slope method [20]. Furthermore, long-term BOD analysis results will be used to determine the value of carbon deoxygenation rate (K_d) and final BOD (BOD_u).

$$K_d = 2.61\frac{a}{b} \tag{9}$$

$$L_0 = \frac{1}{2.3K_d a^3} \tag{10}$$

Note: Plotting $(t/y)^{1/3}$ as a function of t, the slope (b) and the intercept (a) of the line of best fit can be used to estimate the values of K_d and L_0

Eq. (11) for the determination of reaeration (K_r) uses the O′ Conner Model method [19].

$$K_r = \frac{3.9V^{0.5}}{H\left(\frac{3}{2}\right)} \tag{11}$$

where K_r is the replenishment of oxygen at the interface between the stream and the atmosphere (per d); V is stream velocity (m/s); H is depth of stream.

Eq. (12) for the determination of critical time of the deficit [17] shows the lowest point on the DO sag curve profile which is called the critical point

$$t_c = \frac{x(\text{m})}{v\left(\frac{\text{m}}{\text{s}}\right)} \tag{12}$$

where t_c is travel time (m/d) from the basic relationship between time, distance and velocity; x is stream distance (m); v is velocity of stream (m/s).

3. Results and discussion

3.1. Physicochemical parameters of raw greywater

The physicochemical parameters of the raw greywater were tested at five different drains and conducted from October 2016 to August 2017. The questionnaire contained factors that influence greywater quality including a household demographic profile such as the type and number of occupants (adults, teenagers, children and baby). However, the household activity analysis was obtained based on the frequency of bathroom, laundry and kitchen usage per d are presented in Table 1.

The typical concentrations of physicochemical parameters in raw household greywater were characterized. The results of these parameters namely; BOD_5, COD and pH were compared with previous studies (raw greywater at Parit Raja) (Table 2). Fig. 2 presents the bar charts of BOD_5 concentrations in greywater. Based on Fig. 2, D_3 samples have the highest BOD_5 concentration which is 172 mg/L. The high BOD_5 might be due to the presence of organic fractions from food scraps, oil and grease in the greywater discharge. These findings are similar to those obtained in a study by Mohamed et al. [7], and Sultana and Alamgir [8], who found that the high concentration of BOD_5 is due to the presence of food waste in raw greywater. The detectable organic concentrations were due to the high frequency of bathing and laundry from household activities. This could be caused by activities such as cleaning and washing of occupant clothes which wash away organic wastes from the human body. Mohamed et al. [2] observed that BOD_5 concentration was high in households with occupants comprising largely of babies and children.

Hence, the high content of BOD_5 in greywater might lead to DO depletion that could disrupt aquatic organisms. The BOD_5 from D_2 was low at 106 mg/L. The results indicated a slightly lower value compared with previous studies conducted by Mohamed et al. [2] of 117–178 mg/L. The low levels of BOD_5 at D_2 were due to the low frequency of household activities from bathroom and laundry greywater. Also, the number of people including children and baby in D_2 was 5 compared with 24 people at D_3 (Table 1). Fig. 3 presents the concentrations of COD in the greywater samples collected at the five drains.

The range of COD results in all drains ranged from 208 to 400 mg/L. The highest COD concentrations were obtained at D_3 due to the presence of high organic compounds from household uses. This happened due to the high frequency of bathing, kitchen and laundry activities in the houses (Table 1). However, the high frequency from laundry sources in D_3 is caused by a lot of washing using soap and detergents. Another reason is the higher number of occupants with 63 households and presence of children and babies in 23 households compared with other drains. Do-Couto et al. [21] had stated that the high organic compounds in COD concentration were influenced by sources such as food waste, oils and grease, detergent and other cleaning products from bathing, kitchen and laundry sources. It can be observed that the results of BOD_5 and COD concentrations were based on laboratory analyses. The value of BOD_5 range was from 106 to 172 mg/L which is less than the COD value which was between 208 and 400 mg/L. The results

Table 1
Summary (extracted from questionnaire) of the houses profile that discharge their greywater into the drains

Segments	Data	D_1	D_2	D_3	D_4	D_5
Demographic profile	Number of houses	10	9	12	9	8
	Type of occupants	Family	Family + student	Family	Family + student	Family
	Numbers of occupants	43	40	63	51	37
	Number of adults	19	25	23	26	16
	Number of teenagers	15/13–16 years	10/13–18 years	16/14–16 years	15/13–16 years	14/14–18 years
	Number of childrens and babies/age (years)	9/3 months-5 years	5/4 months-12 years	24/2 months-12 years	10/5 months-12 years	7/4 months-9 years
Household activites (high frequency)	Frequency of dishwashing per day	2	2–3	2–3	2	2
	Frequency of taking bath per day	2–3	2	2–3	2	2–3
	Frequency of clotheswashing	2 times/week	1 time/week	2 times/week	2 time/week	2 times/week

Table 2
Physicochemical characteristics of raw greywater collected from five drains at Parit Raja Darat village, Parit Raja, Johor in the period between October 2016 and August 2017 (n = 45, ±SD).

Drain/open channel	D_1	D_2	D_3	D_4	D_5	Previous studies (Raw greywater at Parit Raja)	
Drain distance before mixing Parameter	(75 m)	(65 m)	(87 m)	(60 m)	(55 m)	Mohamed et al. [17]	Mohamed et al. [2]
BOD_5 (mg/L)[a]	165 ± 10	106 ± 9	*172 ± 15*	158 ± 8	169 ± 12	75	117–178
COD (mg/L)[b]	358 ± 12	208 ± 14	*400 ± 10*	267 ± 14	377 ± 13	149	221–334
pH	6.2 ± 0.5	5.5 ± 0.4	*4.5 ± 0.1*	5.8 ± 0.6	6.0 ± 0.8	4.6	6.5–6.7

[a]The units for all parameters are expressed in mg/L except for pH; Standards A: discharge upstream of water supply sources; Standards B: discharge downstream of water supply sources; the highest value for each parameter is highlighted in the italics.

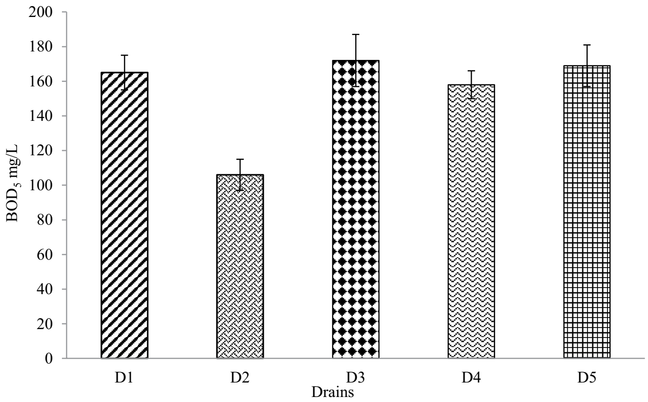

Fig. 2. BOD_5 concentrations of raw greywater.

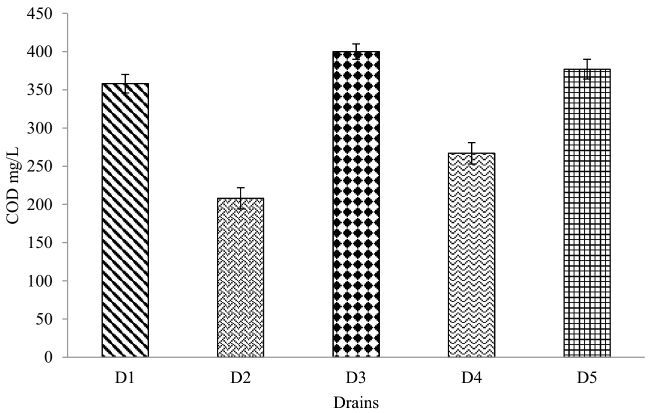

Fig. 3. COD of raw greywater.

show that the measured value of COD is higher than that of measured BOD_5.

Similarly, Sultana and Alamgir [8] stated that the value of COD was higher than that of BOD_5 value in raw greywater due to high organic matter which can be oxidized chemically rather than biologically in water. Thus, measured COD in this study is an indication of the polluting strength of the raw greywater generated from the three sources within the five drains investigated. Therefore, discharging greywater with high BOD_5 and COD concentrations into drain may negatively impact the low dissolved oxygen and pH values, which could disrupt aquatic life [22]. It can also lead to foul odours in the drain and the increased organic matter degradation time and creates unfavourable conditions for the environment [4]. Next, Fig. 4 presents the results of the measured pH in the investigated greywater samples.

The pH values in all drains were acidic, ranging from 4.5 to 6.2 which are in the range (pH = 4.9 to 6.8) reported by Mohamed et al. [7]. The acidity level for D_3 was 4.5 due to the high frequency of dishwashing from kitchen activities and bathing from the houses profiled. Therefore, the acidic pH was due to the presence of lots of food waste at D_3 in greywater flow. Abedin and Rakib [23] and Bakare et al. [3] confirmed that the fair acidity of kitchen greywater was due to the presence of organic acids produced by degradable organic compounds. Therefore, the acidic pH

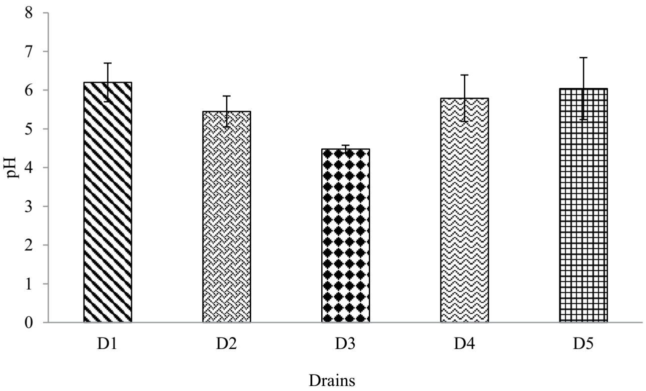

Fig. 4. pH of raw greywater.

may have negative impacts on soil or plants when raw greywater is discharged directly to the environment [23]. Hence, it indicates that number of house occupants and their activities influence quality of physicochemical characteristics of raw greywater collected from five drains.

3.2. Raw greywater pollutant loading rate

In this section, the organic loading rate represents BOD_5 as pollutant strength through the five drains, which is shown in Table 3. Shankhwar et al. [24] stated that organic loading rate can be measured through the parameters BOD and flow rate of the greywater discharge. The greywater pollutant load was measured to show pollution level when greywater was discharged into the drains. The analysis of organic loading rate is summarized in Fig. 5.

Fig. 5 shows that the raw greywater concentration and organic pollutants originated from greywater discharge through household activities. The figure shows that the organic loading and flow rates were from 30 to 63 kg/d and 210 to 369 m^3/d, respectively. The values are considered acceptable due to good agreement with the findings of Shankhwar et al. [24]. The BOD_5 loading rate was typically ranged from 33.31 to 83.34 kg/d while the flow rate was between 560 and 865 m^3/d. It can be observed that the analysis of daily flow rate in this study was slightly lower compared with Shankhwar et al. [24]. This was due to the variables which depend on the water velocity of the discharged greywater into the drain. Shankhwar et al. [24] demonstrated that such conditions had influenced the socioeconomic and cultural factors.

The high value of total greywater load and flow rate was found at D_3 due to the higher organic load from household activities with value of 63 kg/d and 369 m^3/d, respectively, compared with other drains. From the results of the house profile in Table 1, D_3 had 63 occupants with 24 babies and children aged 2 months to 12 years old. Hence, these drains have higher frequency of bathing and laundry for cleaning activities and kitchen for dishwashing compared with other drains. Most occupants preferred cooking food two to three times per day in their houses. While, the people in the house frequently take bath two or three times a day due to the warm climate. This indicates that warm climate may lead to higher frequency of bathing in the house (Table 1). While, they were doing laundry work on weekend in the morning. Another reason is the occupants only spend their time at home during the weekend. Hence, the high frequency of household activities and number of occupants leads to high amount of pollutant loading rate produced from greywater drainage in this study. Shankhwar et al. [24] stated that the amount of organic load content was proportional to the water production whereas the higher organic load was due to the high production rate of water from households. Based on pollutant load data obtained in this study (Table 3), it can be concluded that flow rate and pollutant strength (BOD_5) play a vital role in BOD_5 loading rate through greywater discharge which contributing catchment area for each drain. Thus, the higher the number of occupants and activity in a house, the higher the greywater BOD_5 loading rate produced from kitchen, laundry and bathroom.

Table 3
Greywater BOD_5 loading rate for each drain

Open channel	BOD_5 concentration (mg/L)	Flow, Q (m^3/d)	BOD_5 loading rate (kg/d)
D_1	165	314	52
D_2	106	287	30
D_3	172	369	63
D_4	158	287	45
D_5	169	210	35

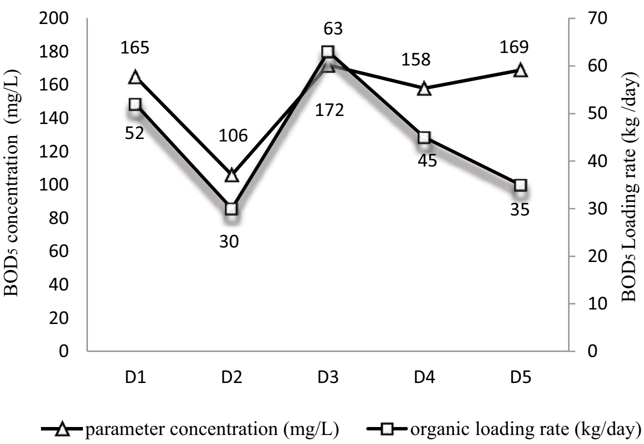

Fig. 5. BOD_5 concentration (mg/L) vs. organic load (kg/d) for each drain.

3.3. Stream characteristics with mixing greywater discharge

The results of hydraulic and physicochemical parameters were collected at intervals from each station along the streams that were mixed with greywater discharge is shown in Tables 4 and 5. Stream samplings and measurement of hydraulic properties were conducted three times at each point to get the average values. In this study, the hydraulic and physicochemical characteristics were measured to determine the parameters: ultimate BOD (L_0), time (t_c), deoxygenation (K_d) and reaeration (K_r) coefficients of the stream.

The stream depth was measured from 0 to 70 m ranging from 0.460 to 0.680 m, respectively. The result of stream depth in this study depends on the cross-section of a stream area. It can be observed that the depth of the sampling site in the stream was shallow in this study. While, the velocity flow in the stream was measured from 0.009 to 0.016 m/s, respectively. According to the previous studies by Omole and Longe [26] and Maamar et al. [14], the stream velocities in the range of 0.046–0.40 m/s and 0.43–1.43 m/s were slightly higher than what is recorded in this study. The changes of stream velocity might be due to the dependency of the variables on temperature, travel time and the rate of effluent discharged from household activities [12].

On the other hand, the flow rate in the stream was 0.026–0.046 m^3/s from a distance of 0–70 m, respectively. The results were compared with Omole and Longe [26] and Maroneze et al. [16] who reported that the flow rate for the stream was in the range of 0.09–0.43 m^3/s and 1.5–22.40 m^3/s, respectively. Even though the stream flow rate for this study is slow moving than the flow rate results reported by other researchers, this difference could be due to different geographic locations of sampling.

The characterization of the stream in terms of BOD_5, DO, pH and temperature were conducted to measure the level of pollutants. The stream characteristics were determined according to the procedures described in APHA [25]. Thus, the range of concentrations of stream quality was within the

Table 4
Hydraulic parameters of stream mixed with greywater discharge from five drains (n = 24)

Stations	Distance (m)	Depth, h (m)	Width, w (m)	Velocity, v (m/s)	Area, $A = w \times h$ (m^2)	Flow rate, $Q = A \times V$ (m^3/s)
0	0	0.580	3.611	0.018	2.094	0.0377
1	10	0.460	3.551	0.016	1.633	0.026
2	20	0.490	4.091	0.014	2.005	0.028
3	30	0.530	4.303	0.012	2.281	0.027
4	40	0.680	5.247	0.009	3.568	0.032
5	50	0.590	5.679	0.010	3.351	0.034
6	60	0.520	6.343	0.012	3.299	0.040
7	70	0.470	6.903	0.014	3.244	0.045

Table 5
Physicochemical parameters of stream mixed with greywater discharge from five drains (n = 24)

Stations	Distance (m)	BOD (mg/L)	DO (mg/L)	pH	Temperature (°C)
0	0	20.90	5.10	5.31	25.8
1	10	25.67	3.55	4.35	27.4
2	20	24.48	4.09	4.61	26.8
3	30	22.84	4.30	4.83	27.5
4	40	21.80	5.25	5.22	26.6
5	50	18.36	5.68	5.63	25.6
6	60	19.70	6.34	5.37	26.5
7	70	17.61	6.90	5.49	26.5

range of values reported in the literature. When the domestic wastewater from household activities is discharged into the stream as the receiving waters, the critical dissolved oxygen deficit values occurred. It can be observed that the highest DO loss observed was 3.55 mg/L at 10 m distance from upstream. Hence, it indicates that DO deficit occurred at 10 m upstream using laboratory analysis. The results showed that high DO loss influenced the high concentration of BOD, which favoured the abundant decomposition of microorganisms and disruption of aquatic life survival in the stream [1]. Hence, the results are supported by other studies as reported by Yustiani et al. [30]. In the study, the DO loss as an organic pollution factor was due to the reduction of the oxygen amount needed by microorganisms during the decomposition of organic materials.

In this study, the highest BOD value in the stream was 25.67 mg/L, which represents the highest concentration of waste load at S_1 (upstream) compared with other stations. This section indicates the occurrence of degradation and decay of the organic matter of the BOD in the stream. The BOD values were confirmed by the research conducted by Uzoigwe et al. [17] and Deborah et al. [27] who observed that the stream mixed with domestic effluents were 12.18–18.0 mg/L and 38 mg/L, respectively. Besides that, the rate of which the oxygen is supplied to the polluted stream depends on several of factors as stream depth, stream velocity, oxygen deficit and water temperature as reported by Omole and Longe [26].

The pH values from S_0 to S_7 were 4.35–5.63, respectively, which is in the acidic range. In addition, it is in good agreement with the range 4.93–5.76 reported by Uzoigwe et al. [17]. The highest pH value of 4.35 was obtained at S_1 and it shows that the acidic stream was mixed with greywater contamination through household activities. In another research, Omole et al. [11] observed that acidic pH may destroy the environment of aquatic life as living things cannot survive for long above the normal pH range of fresh water [11].

Furthermore, the temperature of all the samples collected ranged from 26.5°C to 27.5°C in the dry season. Thus, the dry season lead to high temperature can have a significant impact on DO depletion and rate of increasing BOD. The rising temperatures can also lead to high decomposition of biodegradable organic matter in the effluent stream and also destroys aquatic life in water [19]. Maamar et al. [14] reported that domestic discharge contains many pollutants in the dry seasons. In this case, contamination flow was generated at low velocity and temperature may reach up to 29°C in dry seasons.

3.4. Development of Streeter–Phelps model

In this section, the research shows the movement condition of dissolved oxygen (DO) when greywater was discharged into the streams. The DO estimation was calculated using a mathematical equation from the Streeter–Phelps model. The model was applied to seven stations along the stream before they were mixed with a river nearby. The analysis of DO deficit estimation was summarized according to Tables 6 and 7.

Table 6
Dissolved Oxygen (DO) deficit level of empirical equation in deoxygenation rate (n = 24)

Station	Distance (m)	K_d (per d)	L_0 (mg/L)	K_r (per d)	Time (per d)	K_r–K_d (per d)	$e^{-K_d t}$	$e^{-K_r t}$	$(e^{-K_d t}) - (e^{-K_r t})$	DO (mg/L)	DO ($e^{-K_r t}$)	D_t (mg/L)
0	0	0.937	30.514	1.185	0	0.248	1	1	0	5.10	5.10	5.10
1	10	1.036	37.480	1.581	0.007	0.545	0.993	0.989	0.004	3.55	3.511	3.80
2	20	1.008	35.740	1.345	0.017	0.337	0.983	0.977	0.006	4.09	3.996	4.64
3	30	0.974	33.346	1.107	0.029	0.133	0.972	0.968	0.004	4.30	4.162	5.14
4	40	0.874	31.828	0.660	0.051	0.214	0.956	0.967	0.011	5.25	5.078	6.51
5	50	0.930	26.805	0.861	0.058	0.069	0.947	0.951	0.004	5.68	5.402	6.85
6	60	0.982	28.762	1.139	0.058	0.157	0.945	0.936	0.009	6.34	5.934	7.55
7	70	1.027	25.711	1.432	0.058	0.405	0.942	0.920	0.022	6.90	6.348	7.78

Table 7
Dissolved oxygen (DO) deficit level of Thomas slope method in deoxygenation rate (n = 24)

Station	Distance (m)	K_d (per d)	L_0 (mg/L)	K_r (per d)	Time (per d)	K_r–K_d (per d)	$e^{-K_d t}$	$e^{-K_r t}$	$(e^{-K_d t})-(e^{-K_r t})$	DO (mg/L)	DO $(e^{-K_r t})$	D_t (mg/L)
0	0	0.870	18.510	1.185	0	0.315	1.000	1.000	0	5.100	5.10	5.100
1	10	0.113	39.530	1.581	0.007	1.468	0.999	0.989	0.010	3.550	3.511	3.541
2	20	0.237	21.536	1.345	0.017	1.108	0.996	0.977	0.019	4.090	3.996	4.084
3	30	0.356	14.337	1.107	0.029	0.751	0.990	0.968	0.022	4.300	4.162	4.312
4	40	0.373	15.733	0.660	0.051	0.287	0.981	0.967	0.014	5.250	5.077	5.363
5	50	0.340	13.136	0.861	0.058	0.521	0.980	0.951	0.030	5.680	5.402	5.659
6	60	0.356	14.337	1.139	0.058	0.783	0.980	0.936	0.044	6.340	5.934	6.221
7	70	0.326	12.059	1.432	0.058	1.106	0.981	0.920	0.061	6.900	6.348	6.565

In this study, the deoxygenation (K_d) result was analysed using the Thomas slope method and empirical equation for normal flow stream [28,30]. Tables 6 and 7 show that the value of deoxygenation (K_d) ranged from 0.874 to 1.036 per d and 0.113 to 0.870 per d, respectively. It can be observed that the high deoxygenation rate at S_1 (upstream) will stimulate higher BOD when the DO depletion is very high in the stream. The results were compared with Yustiani et al. [30]; Uzoigwe et al. [17]; Singh and Sharma [1]; Yustiani et al. [30] who reported deoxygenation (K_d) coefficients of 0.423–0.536, 0.566, 0.38–0.55 and 0.422–0.462 per day, respectively. It shows that deoxygenation (K_d) process occurred in the degraded organic matter which was discharged into the stream. The deoxygenation (K_d) values differed due to the higher temperature, the influence of microbial metabolism, composition and concentration of the organic load from the contaminated water [16]. Other than that, the depth of sampling site in a stream or river is influenced by the differential value of the deoxygenation rate [30]. This is due to the observation that the depth of a stream or river may affect the life of the microorganisms and reduce oxygen supply which reduces the deoxygenation rate.

The ultimate BOD (L_0) result ranged from 25.714 to 37.481 mg/L and from 12.059 to 39.530 mg/L based on the empirical equation and Thomas slope method. The results indicate that ultimate BOD (L_0) value in the upstream water part is greater than those in downstream water. This stream condition can be caused by severe pollution occurred in the upstream area where the greywater from household activities was discharged into the stream. In the downstream water, the organic matter had been decomposed by the microorganisms and thus the ultimate BOD tends to be lower while DO level tends to be higher. Hence, it was considered acceptable since Nas and Evin [12] and Yustiani et al. [18], reported ultimate BOD (L_0) values from 6.50 to 35.25 mg/L and 23.32 to 38.50 mg/L, respectively. The important part of the ultimate BOD (L_0) was the total amount of oxygen consumed after all BOD were exerted and all the organic materials had been decomposed after an independent specified period of time [29].

The result of reoxygenation (K_r) coefficient ranged from 0.660 to 1.581 per d, as calculated from the O' Connor Model. Maroneze et al. [16] observed that the results of reoxygenation (K_r) were between 2.5 and 7.4 per d, which are slightly higher compared with this study. This variation is due to the influence of temperature, depth, velocity and stream geometry on the stream condition [19]. These factors influenced the reoxygenation (K_r) process for self-purification of the stream. The aeration process was important because it helped to increase the DO content by aerating the water for the removal of the organic matter in water bodies [12]. Maroneze et al. [16] explained that the Streeter–Phelps model and the experimental data refer to the station's sources and the kinetic coefficients of deoxygenation (K_d) and reoxygenation (K_r). These coefficients obtained in the field and the laboratory were used as calibration parameters. Consequently, the deoxygenation (K_d) and reoxygenation (K_r) processes controlled the DO contents.

Next, the estimated average of travel time from all stations was between 0.007 and 0.058 per d in the stream using the mathematical equation. It was considered acceptable because according to Omole et al. [11], Maamar et al. [14], and Uzoigwe et al. [17] obtained estimated time travel values in the range of 0.009 to 0.031, 0.005 to 0.130 and 0.07 to 0.43 per d, respectively. The travel time from the starting point was required to show the critical oxygen deficit point which is known as the time critical. After all the data were obtained, the calculation using the Streeter–Phelps model was applied from S_0 until S_7 for the estimation of dissolved oxygen in the stream. Furthermore, the value of DO deficit (D_t) and time critical (t_c) that was obtained at the distance of 10 m upstream of discharge point were 3.54 and 3.80 mg/L and 0.007 per d. Hence, Figs. 6 and 7 clarify the analysis of DO estimation.

3.5. Comparison between measured and simulated (DO)

The comparison between the measured (laboratory testing) and the simulated DO (mathematical equation) was carried out to establish the greywater pollution modelling using the Streeter–Phelps model. The plots of the measured and simulated DO were dissimilarity in terms of the graph pattern and are shown in Figs. 6 and 7. The difference for this graph based on the simulated DO of deoxygenation rate using empirical equation and Thomas slope method were calculated.

The summary of DO movement condition is illustrated in Figs. 6 and 7 based on DO sag curve profile as a guide. Three zones could be clearly identified: the first zone shows the active degradation and decomposition from S_0 to S_1 at

0 to 10 m distance in the stream known as upstream. This represents the zone of heavy pollution in a high concentration of suspended solids, BOD and turbidity in stream effluents [26]. It can be observed that the highest rate of deoxygenation process is obtained in the water body at 0–10 m distance compared with other distances. This high coefficient was caused by shallow water depth in the upstream water [16,18]. It can be seen that the concentration of DO in the upstream was lower than the DO concentration in the downstream using the laboratory analysis and mathematical equation. This condition happened because stream quality in the upstream section was deteriorated due to a large amount of greywater discharged from household activities [30]. These expressions show that degradation and decomposition process occurs at 0 to 10 m distance in stream.

The second zone was the recovery stage where the gradually degraded condition had started from S_2 until S_5 at 20 to 50 m distance in the stream known as downstream. Next, the stream flow became zone of cleaner water whereas the BOD level decreased correlatively with the increase in the DO level. It can be observed from Figs. 6 and 7 that the S_6 to S_7 had the highest DO value of 7.55–7.78 and 6.22–6.57 mg/L which is very close to the saturated dissolved oxygen level of 8.40 mg/L of the stream [14]. It is shown that the high reaeration process for self-purification in the stream with the presence of organic substance concentration was low. The self-purification capacity in the stream was dependent on wastewater discharge, travel time, water temperature and aeration, where the oxygen was obtained from the atmosphere by aeration in the stream [12].

Overall, the results of DO movement were influenced by the differential value based on laboratory analysis and the mathematical equation. This variation is due to the atmospheric pressure of the velocity that was effected in the stream, which could not be measured accurately. The stream velocity was affected by the base flow of the stream that caused the difference in DO obtained from the Streeter–Phelps model in this study. The results were supported by the findings of Omole et al. [11], where the auto-purification of the stream occurred with the presence of velocity and cross-sectional area in the stream or river. The precision of the DO measurements for self-purification processes was influenced by temperature and water flow in water bodies, as proven by Li et al. [31].

Besides that, the value of simulated DO in Fig. 6 (ranged with the formula) was greater than (from 3.80 to 7.78 mg/L) the measured DO using laboratory analysis. However, the results of the laboratory analysis were between 3.55 and 6.90 mg/L. The results show that the rate of DO movement is higher in the mathematical equation solution. Fig. 7 also compares between mathematical models with laboratory analysis. The results show that the rate of DO movement is very close to the value of mathematical equation (from 3.54 to 6.57 mg/L) with laboratory analysis in the range 3.55–6.90 mg/L. The validity of the Streeter–Phelps model in this study proved that the regression of Thomas slope method indicates a good fitting compared with empirical equation for deoxygenation rate in simulated DO. Furthermore, the result of simulated DO using the mathematical equation from the Streeter–Phelps model determined by using laboratory analysis was consistent with that measured in the field.

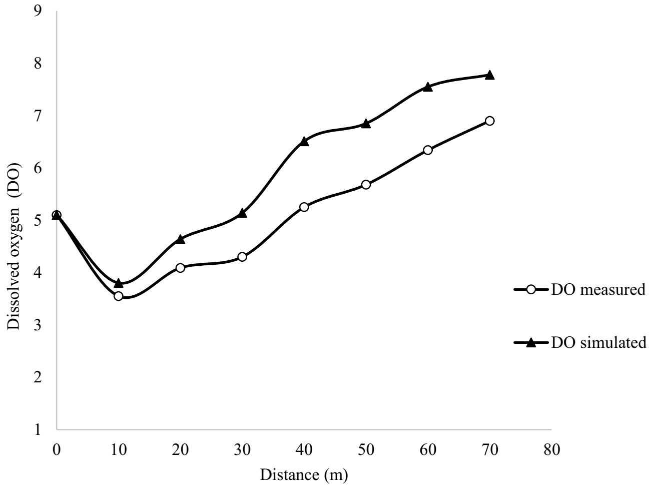

Fig. 6. Simulated (empirical equation) and measured DO sag curve of the stream.

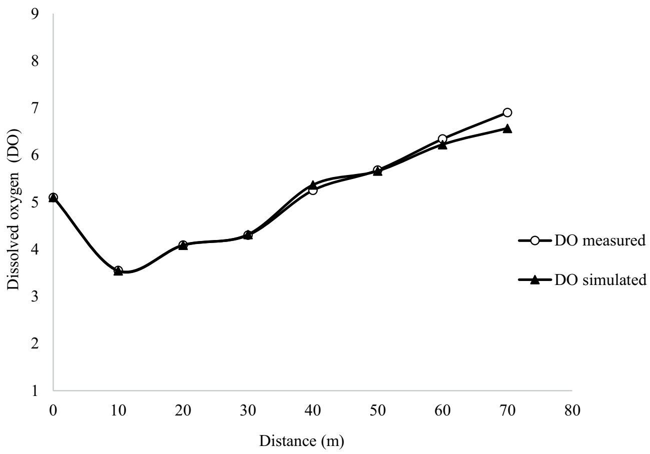

Fig. 7. Simulated (Thomas slope method) and measured DO sag curve of the stream.

Therefore, the findings conclude that the value of DO deficit (D_t) and time critical (t_c) was obtained at the distance of 10 m upstream of discharge point were 3.54 and 3.80 mg/L and 0.007 per d by using the Streeter–Phelps model. It also shows that the kinetics of BOD reaction of the degradable organic matter and travel time as a critical oxygen deficit point occurred at 10 m upstream. Hence, the river was not polluted near the stream flow with the effluent in this case of study. Therefore, the DO measurements in this study indicate that there is no significant effect on the river conditions after mixing with greywater discharged in the stream.

4. Conclusion

The curve of the measured and simulated DO has shown a gradual increase in DO movement which indicates a rapid self-purification along the stream. Hence, it was found that the DO deficit (D_t) and critical time (t_c) were 3.54 and 3.80 mg/L and 0.007 per d. It shows that the process of degradable and decomposition of organic matter and travel time as a critical oxygen deficit point were obtained at the distance of 10 m upstream of discharge point. However, the DO measurement in this study indicated no significant effect of river condition after mixing with greywater discharge in stream. This is because lower mixing effect of greywater discharge from five drains. Thus, no pollution occurred near the stream flow with effluent in this study.

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