EXPERIMENTAL STUDY TO ASSESS THE EFFECT OF FLOW THROUGH SUBMERGED BIOFILTER ON HYDRAULIC PROPERTIES OF POLLUTED STREAMS

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ABSTRACT

Lack of water is one of the major issues facing many countries in arid and semi-arid regions, like Egypt. Another stress on water resources is the pollution resulted from different sorts of pollutants from sewage, industrial wastewater, and agricultural drainage water. This demonstrates the significant obstacles that the Egyptian government must overcome in order to protect its water resources by reducing the streams pollution. When a water body is affected as in the case of most open drains in Egypt, efforts should be made to increase the waste assimilative capacity of the waterbody. A number of studies have recommended the use of submerged biofilters as one of the artificial methods to enhance the self-purification process in contaminated streams. However, the majority of these studies concentrated on the effectiveness of biofilters in removing contaminants from water bodies, and there is a lack of research on the hydraulic impacts on the waterway, such as raising the upstream water level and how this relates to the characteristics of the biofilters. The main aim of the current study is to investigate the hydraulic impacts of a star-shaped plastic media submerged biofilter on stream flow and determine a mathematical formula to anticipate these effects. The methodology includes doing an experimental work then utilize dimensional analysis and multi-linear regression analysis to correlate various parameters that affecting flow through the biofilter and develop a new formula for discharge through the used biofilter. The results were compared with three other formulas applied to various media including; Depuit, Fadhil and modified Fadhil formulas for verification of results. The results of the current study are closely matched with those of the other studies. Then the developed formula is used to calculate the flow through the biofilter (Q) as well as changes in the upstream water level (h_{us}), the biofilter and relative heading up (h_{us}/h_{ds}). The outcomes demonstrated that the upstream water depth (h_{us}) has a greater influence on the flow rate through the biofilter than does the relative heading up (h_{us}/h_{ds}). The derived formulas are also used to anticipate the upstream water depth (h_{us}) by determining the biofilters length (L), width (B), and discharge (Q). The features of contaminated streams may be improved by forecasting the hydraulic consequences of submerged biofilter use.

Keywords: contaminated streams, submerged biofilter, relative heading up, flow rate, dimensional analysis.

1 INTRODUCTION

Water is a valuable natural resource that is required for numerous purposes. Unconventional water resources are used for balancing water demands in urban areas with limited water resources. Egypt is one of the developing countries that using the unconventional water sources to face water scarcity. Egypt is one of the top ten countries that will face water scarcity in 2025 as a result of rapid population growth. Egypt's main supply of water is the Nile River, and agriculture uses the most water. The Nile River provides 97% of Egypt's water needs. The remainder is derived from nonrenewable groundwater aquifers and some rainfall (Abdel-Shafy and Aly, 2002). In order to overcome Egypt's water shortage, it may be necessary to use unconventional water sources such as agricultural drainage water (DW) and treated wastewater (TWW).

The use of a submerged biofilter is one of the suggested ways to improve the ability of open drains to purify them. Also, a number of researchers suggested different methods to evaluate this problem. Abd El-Rahman (2002) investigated the usage of submerged biofilter for depressing the organic content in waterways that had been contaminated by domestic wastes. He used three types of media as biofilters including; plate settler, tube settler, and plastic balls. According to Ramrez-Baca (2005), the submerged biofilter is an inexpensive device that can be built on-site and will improve the quality of water in small polluted rivers. Two stream models were built for his research, and crushed river stone was used to fill both the streams. The models were tested using a combination of primary and secondary effluents from a WWTP. Results showed that in streams that were heavily loaded with media, COD removal efficiency increased. El Monayeri et al. (2007 a and b) investigated the impacts of a submerged biofilter on the effectiveness of biological degradation and hydrodynamic design of streams in Egypt utilizing different media such as pall rings, stars, and gravel. The results showed that plastic media (pall rings and star shapes) are more efficient than gravel at removing BOD and COD, despite having the least impact on the hydraulics of the water flow in the channel.

Abou El-fotoh et al. (2007) observed how the hydrodynamics of Egyptian streams and the effectiveness of the biological degradation process were impacted by submerged plastic media (pall rings, stars, and gravel). The findings showed that plastic media, such as pall rings and star shapes, are more effective than gravel at removing BOD and COD, while having the least impact on the hydraulics of water flow in the channel. EL-Gohary et al. (2007) examined the use of submerged biofilters in contaminated streams to boost the capability for self-purification at the discharging location in. The outcomes showed that submerged biofilter performance is influenced by total hydraulic loads. The pall rings media biofilter, which had the same overall surface area for biofilm production as the star shape and gravel biofilters, had the highest COD removal ratio whereas the COD removal ratio decreases as the total hydraulic loading increases. Salem (2016) examined the levels of pesticides and heavy metals in wastewater from three of Egypt's largest drains. According to the findings, certain heavy metal concentrations in water samples were greater than permitted.

There aren't enough studies that address hydraulic changes in the waterway, like raising the water level upstream the biofilters and how that relates to the biofilter specifications. The majority of recent studies focused on the effectiveness of the biofilters in removing pollutants from water bodies. The groundwater table, embankments, and the agricultural drainage system may all be negatively impacted by raising the water level upstream of the biofilter and raising the relative heading up in water streams. The flow through and over gravel gabion weirs (GGW), which are composed of gabion length and height on their upstream water depth, were the subject of a study done by Fadhil et al. (2015). His findings showed that increasing the biofilter length enhanced the gabion's upstream water depth. The findings indicated a linear relationship between the unit discharge through the gabion and the upstream water depth.

The goal of the current work is to investigate how the submerged biofilter affects water streams' hydraulics. The presence of these biofilters may lead to plausible changes in flow behavior, such as the upstream water levels and heading up. The influence of biofilter features on the upstream water level (h_{us}) and the heading up (h_{us}/h_{ds}) was assessed during the current investigation. A new formula was also created utilizing multi-linear regression analysis and dimensional analysis to calculate the discharge and upstream water depth.

2 METHOD AND MATERIALS

2.1 Description of the experimental model

The current experimental study was conducted in the hydraulic laboratory in Zagazig University using a channel of dimensions (1.0 m width, 10.0 m length and 0.45 m depth) as shown in Figure 1a. The channel is charged by water through a pump with a flow rate ranged between 5 to 70 L/s. A rulers graded is used to measure the upstream and downstream water depths as shown in Figure 1b. A rectangular weir is used to regulate and measure the discharge inter to the channel. The discharge (Q) intering the channel was determined by measuring the head (H) of water above the weir crest then used the weir formula ($Q=0.869^* H^{1.69}$) to determine the discharge. Where, the discharge measured in (L/s) and the head measured in (cm). To inspect the hydraulic effects of installing the biofilter on the flow through the channel, the heading up was calculated at different discharge.

(a) (b)

Figure 1. Longitudinal and cross section view of the used channel in the experimental study

2.2 Description of the submerged biofilter

The performance of the boifilter depends mainly on the type and characteristics of media such as; specific surface area, void ratio, surface roughness, geometry and configuration. The packing was placed in boxes of dimensions (1.0 m width, 0.26 m height, and 0.4 m length) as shown in Figure 2a and b. Then the biofilter was installed in the stream according to the experimental program. In the current study the random packed media used as biofilter is the star shape (see Figure 2c). It is not a common packing media, but it has been selected due to its high specific surface area (175.68 m^2/m^3), and void ratio (87%).

(a) (b) (c)

Figure 2. Star shape media and boxes used in the experimental study

2.3 Experimental Program

In the current study, various length of the biofilter are used from 0.4 to 2.0 m, with various flow rates (see Figure 3a). As indicated in Figure 3b, the length of the boxes is 1.0 m, representing the width of the channel (b), and the width of 0.4 m, used to calculate the needed length of the biofilter (e.g., to get a biofilter of length 1.2 m, this requires 3 boxes). For each flow rate, the water depth upstream (h_{us}) and downstream (h_{ds}) was measured. Figure 3 shows section elevation in the channel where star media was installed. Table 1 displays the operating parameters used in the experiment. The total number of runs conducted in the study was 36 runs for different lengths and flow rates as shown in Table 2.

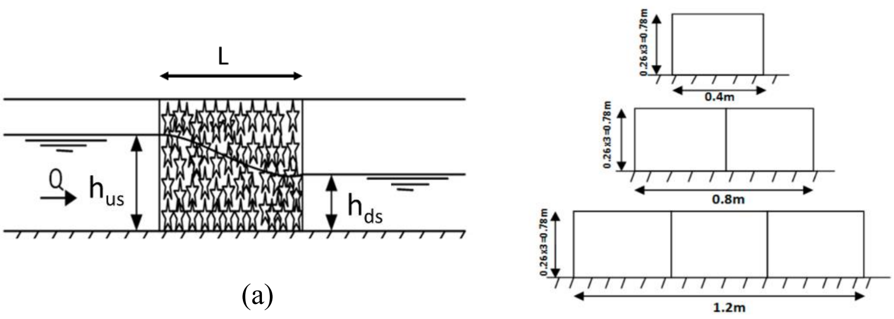


Figure 3. Longitudinal cross section and side view of boxes used in the experimental study

Table 1: The operational conditions used in the experimental work

No of run	Flow rate(L/S)	Length(m)	Measured parameters	Calculated parameters
1	16.5 - 60.4	0.4	H_{us} , h_{ds}	The heading up (h_{us}/h_{ds})
2	14.1 - 62.1	0.8		
3	20.6 - 64.6	1.2		
4	2.8 - 67.6	1.6		
5	2.4 - 62.4	2.0		

2.4 The measured heads upstream/downstream and the relative heading up

In the current study the flow through the installed media in the stream is passing totally through the biofilter. Table 2 shows the obtained results for different water depths upstream and downstream the biofilter and the resulting relative heading up (h_{us}/h_{ds}). Figure 4 depicts the relationship between discharge flowing through a biofilter with various lengths and relative heading up (0.4, 0.8, 1.2, 1.6, 2 m). It is clear that for each length, the relationship between (h_{us}/h_{ds}) and Q is linear. With longer biofilters, the relative heading up (h_{us}/h_{ds}) value rises for the same discharge.

Table 2: The recorded depths upstream and downstream water and the relative heading up (h_{us}/h_{ds})

L (m)	Flow rate (L/s)	Upstream water depth (h_{us}) m	Downstream water depth (h_{ds}) m	Relative heading up (h_{us}/h_{ds})
0.4	16.50	0.509	0.505	1.008
	28.60	0.545	0.535	1.019
	34.60	0.559	0.548	1.020
	41.10	0.580	0.561	1.034
	45.50	0.591	0.570	1.037
	48.50	0.602	0.580	1.038
	52.30	0.610	0.585	1.043
	56.30	0.617	0.590	1.046
	60.40	0.627	0.598	1.048
0.8	14.10	0.508	0.501	1.014
	20.00	0.526	0.516	1.019
	31.70	0.560	0.541	1.035
	37.60	0.578	0.552	1.047
	41.50	0.593	0.561	1.057
	46.20	0.606	0.569	1.065

	47.00	0.617	0.575	1.073
	51.50	0.628	0.583	1.077
	55.50	0.639	0.589	1.085
	62.10	0.657	0.600	1.095
1.2	20.60	0.526	0.515	1.021
	26.80	0.543	0.527	1.030
	31.70	0.568	0.540	1.052
	39.70	0.588	0.551	1.067
	45.11	0.610	0.563	1.083
	46.60	0.620	0.570	1.088
	48.50	0.635	0.578	1.099
	54.30	0.650	0.585	1.111
	57.92	0.662	0.590	1.122
	64.60	0.680	0.600	1.133
1.6	2.80	0.462	0.461	1.002
	6.90	0.481	0.479	1.004
	13.90	0.508	0.499	1.018
	67.60	0.710	0.610	1.16
2.0	2.30	0.470	0.467	1.006
	15.50	0.520	0.505	1.030
	62.40	0.690	0.590	1.170

According to Figure 4, increasing the discharge from 2.3 to 62.4 L/s resulted in the highest relative heading up values at L=2 m, which ranged from 1 to 1.17. However, for the biofilter lengths (L=1.6 m, L=1.2 m, L=0.8 m, L=1.2 m, L=0.8 m, and L=0.4 m), the relative heading up values ranging from 1 to 1.16, 1.02 to 1.13, 1.014 to 1.095, and 1.008 to 1.048 respectively.

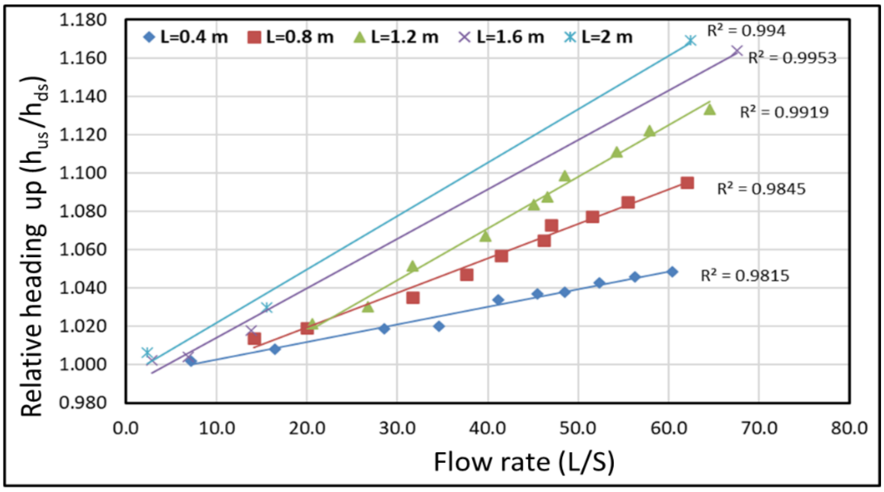


Figure 4. The relation between relative heading up at different flow rates and different lengths

3 DEVELOPMENT OF EMPERICAL EQUATIONS FOR DETERMINING THE FLOW RATE THROUGH THE BIOFILTER

Studying the impact of utilizing biofilters in water streams is the main goal of this study. There should be probable changes in the flow behavior as a result of the placement of these biofilters in the stream. The change in upstream water depth is the most significant variable resulted from installing the biofilter. The resulted relative heading up from putting the biofilter in water streams could cause sequences effects on groundwater level, embankments and deterioration of agricultural drainage network.

3.1 Previous formula used for determining the flow through the biofilter

Over the last decades, a number of empirical formulas have been used for determining the flow through different types of submerged biofilters. El-Saiad et al. (2021) studied a number of mathematical equations in the literature in order to determine which equation best captured the flow through a submerged biofilter. Based on El-Saiad main three equations were developed which are described as following:

1. Dupuit formula

$$Q = 0.785 * b * (h_{us}^2 - h_{ds}^2)L^{-1} \quad (1)$$

2. Fadhil formula

$$Q = 0.398 * b * h_{us}^{4498} * L^{-0.193} \quad (2)$$

3. Fadhil (modified) formula

$$Q = 1.64 * b * (h_{us}/h_{ds})^{12.14} * L^{-0.675} \quad (3)$$

where; Q is the flow rate (m^3/s), b is the biofilter width (m), h_{us} is the upstream water depth (m), h_{ds} is the downstream water depth (m), L is the biofilter length (m).

3.2 Developing a new formula for the discharge through the biofilter and determining the water depth upstream the biofilter

The flowthrough of the submerged biofilter is calculated using a new formula in the current study using measurements made in the laboratory (h_{us}, h_{ds} and relative heading up). A formula for the flow through the biofilter and the head upstream was created using dimensional analysis and multi-linear regression analysis.

3.3 Flow through the biofilter

The biofilter's upstream water depth is influenced by a variety of factors, including the fluid, media, discharge, and filter geometry parameters. Dimensional analysis can be used to determine a physically relevant relationship between the upstream water depth and other variables. The functional relationships of the flow rate through the biofilter (Q) may be expressed as:

$$Q = f\,(\rho, g, b, h_{us}, L) \quad (4)$$

where; Q is the flow rate (m^3/s), ρ is the density of water (t/m^3), g is the gravitational acceleration (m/s^2), h_{us} is the upstream water depth (m), b is the biofilter width (m), L is the biofilter length (m).

The flow through the biofilter depending on deferent parameters as presented in relationship (4), some transformations on the relationship (4) lead to the non-dimensional relation (5) as following:

$$\frac{Q}{g^{0.5}h^{2.5}} = \Phi\left(\frac{B}{h}, \frac{L}{h}\right) \quad (5)$$

In order to provide an explicit equation for flow rate (Q) via the biofilter, the dimensionless group in relation (5) is then correlated. An empirical equation connecting the flow rate through the biofilter

(Q) to the biofilter length (L), width (b), and upstream water depth (h_{us}), as indicated in equation (6) was developed by correlating the several dimensionless parameters shown in equation (4):

$$Q = 0.75 * b * h_1^{5.73} * L^{-0.13} \quad (6)$$

3.2.1 Upstream water depth

The developed formula (6) by multi-linear regression analysis can be utilized to obtain the upstream water depth (h_{us}) as following:

$$h_1 = 1.052 * Q^{0.174} * L^{0.023} * b^{-0.174} \quad (7)$$

4 RESULTS AND DISCUSSION

4.1 Flow through the biofilter

The discharge obtained by equation (6) is compared with the discharge determined by the empirical equations 1, 2, and 3. Figure 5 displays comparison between the calculated discharge through the biofilter utilizing the developed equation with the three equations. In comparison to other formulas, the equation of the flow through the gabion dam (Fadhil formula) is the one that is most like the submerged biofilter utilized in this study, as shown in Figure 5. It is evident that, the flow rate passing through the biofilter depends more on the water depth upstream the biofilter (h_{us}) than on the relative heading up (h_{us}/h_{ds}).

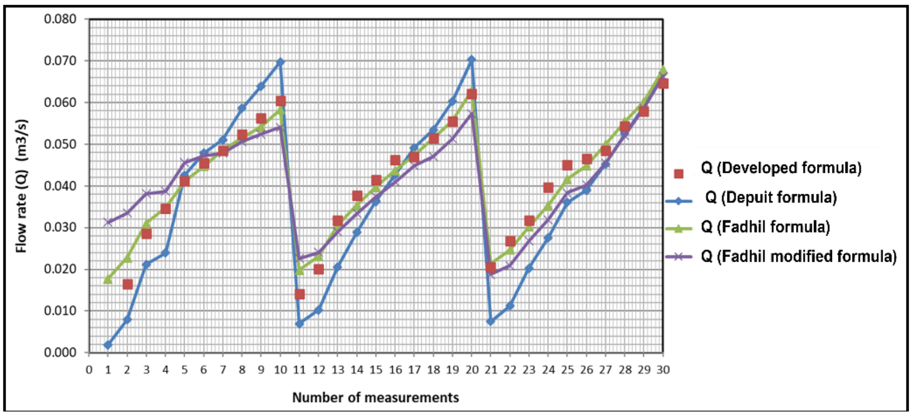


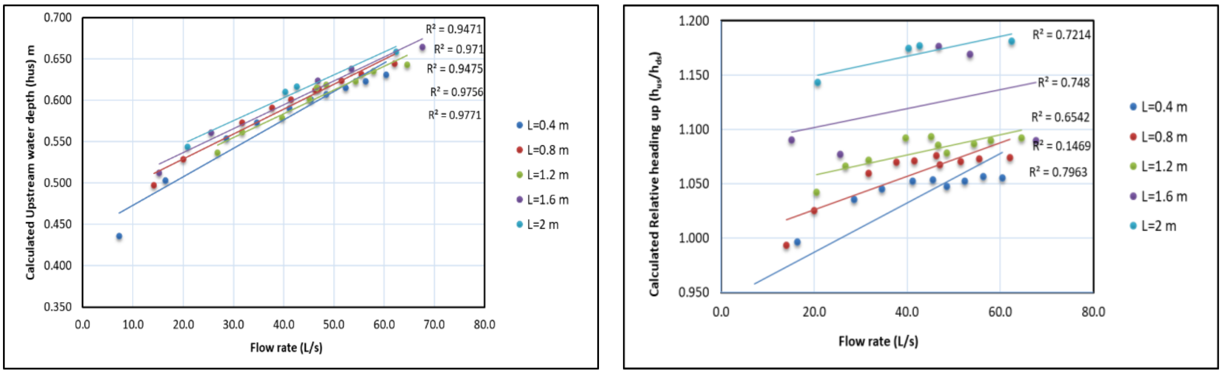
Figure 5. Comparison between discharge obtained from the developed formula with other formulas

4.2 Water depth upstream the biofilter

For various lengths and discharges, the upstream water level (h_{us}) is calculated using equation (7). Figure 6a depicts the relationship between the biofilter discharge (Q) at various biofilter lengths (0.4m, 0.8m, 1.2m, 1.6 and 2.0m) and the calculated upstream water depth (h_{us}). The connection between calculated upstream water depth (h_{us}) and discharge (Q) for all biofilter lengths is linear. With longer biofilters for the same discharge, the upstream water depth (hus) value increased.

Figure 6a shows that the length (L=2.0 m) gave the highest upstream water depth (h_{us}) when the discharge increased. However, the length (L=0.4 m), gave the lowest values of upstream water depth (h_{us}), when the discharge increased. The results reveal that the upstream water depth (h_{us}) is increasing linearly with increasing the discharge. The relationship between computed relative heading up (h_{us}/h_{ds}) and discharge (Q) for flow through the biofilter is linear for all biofilter lengths. Also, the relative heading up (h_{us}/h_{ds}) for the same discharge increased as the biofilter's length increase as shown in

Figure 6b. The length (L=2.0 m) provided the highest values of relative heading and the length (L=0.4 m) gave the lowest values of the relative heading.



(a) (b)

Figure 6. Calculated values of h_{us} and relative heading up for different lengths at different flow rates through the biofilter

Plotting the results of upstream water depths (h_{us}) estimated by Equation (7) against laboratory-measured values for flow through the biofilter is shown in Figure 7. As illustrated in Figure 7, the estimated upstream water depth (h_{us}) and the laboratory results correspond fairly well.

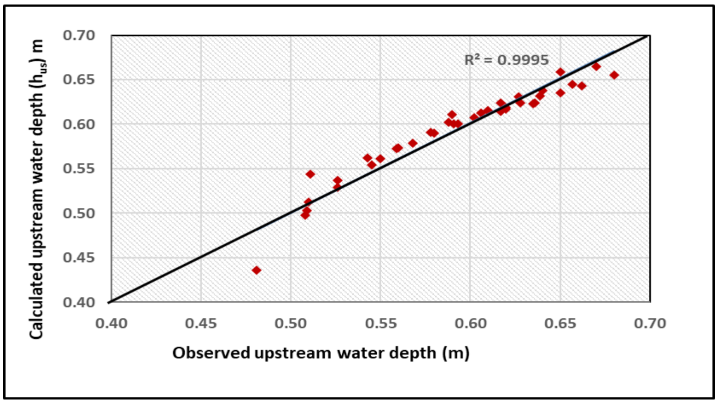


Figure 7. Calculated upstream water depths against measured upstream water depths for the flow through the biofilter

A new formula for calculating the upstream water depth for flow through the submerged biofilter of star-shaped plastic media was developed using multiple regression analysis based on the dimensional analysis. The formula relates the length, width, and flow rate through the biofilter to the upstream water depth. In distinction to other types of media, the used media (star shape) is cheap and available (El Monayeri et al., 2007). The upstream water depth for various biofilter lengths can be calculated using the developed formula. By reducing the amount of upstream water that affects the heading up, the biofilters dimensions may be improved as a result. Future research is advised to use optimization approaches to reduce the biofilter dimensions in order to decrease the heading up caused by the biofilter.

CONCLUSION

Shortage of water causes a great stress on many countries in arid regions such as Egypt. In addition to water contamination that losses large amounts of fresh water. Submerged biofilter has been used to improve the water quality in contaminated streams. Utilizing submerged filters enhanced the removal of contaminants from streams but affected the hydraulic characteristics of the stream such as increasing the upstream water depth. This study aimed to assess the hydraulic effects of using submerged biofilter on the flow in water streams. Experimental study has been carried out to determine the effect of using submerged biofilter on upstream water depths. Then dimensional analysis and multi-linear regression analysis were utilized to develop new empirical formulas for calculating discharge through the biofilter based on the experimental data. The developed formulas are compared with three empirical equations from the literature. The developed formula showed that using star shape biofilter increased the heading up and discharge through the biofilter and the relation is proportional to the lengths of biofilter. Star shape biofilter with length 2 m, gave the highest values of relative heading up and length 0.4 m, gave the lowest values of relative heading up which reveal that increasing the biofilter length increases the heading up. The results the discharge through the biofilter obtained by the developed formula was compared with three empirical equations (Depuit formula, Fadhil formula and modified Fadhil formula). The results showed that Fadhil formula is the closest one to the submerged biofilter used in this study followed by modified Fadhil formula and the last one is Depuit formula. The results approved that the flow rate through the biofilter depends on the upstream water depth (h_{us}) more than on the relative heading up (h_{us}/h_{ds}). The developed formulas were used to predict the upstream water depth (h_{us}) by knowing the discharge (Q), length (L) and width (B) of the biofilter. The developed equations can help in predicting the hydraulic effects of using submerged biofilter in polluted streams which can be used for enhancing the polluted stream characteristics. In order to maximize the effectiveness of installing biofilters in contaminated streams, optimization approaches could be used to minimize the biofilters dimensions.

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