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Optimizing Height and Spacing of Check Dam Systems for Better Grassed Channel Infiltration Capacity

Ahmed Mohammed Sami Al-Janabi [1], Abdul Halim Ghazali [1], Badronnisa Yusuf [1], Saad Sh. Sammen [2], Haitham Abdulmohsin Afan [3], Nadhir Al-Ansari [4], Shamsuddin Shahid [5] and Zaher Mundher Yaseen [6,*]

1 Department of Civil Engineering, Faculty of Engineering, Universiti Putra Malaysia, UPM Serdang, Selangor 43400, Malaysia; huffad@yahoo.com (A.M.S.A.-J.); ahahalim@gmail.com (A.H.G.); nisa@upm.edu.my (B.Y.)
2 Department of Civil Engineering, College of Engineering, University of Diyala, Diyala Governorate, Iraq; Saad123engineer@yahoo.com
3 Institute of Research and Development, Duy Tan University, Da Nang 550000, Vietnam; haithamabdulmohsinafan@duytan.edu.vn
4 Civil, Environmental and Natural Resources Engineering, Lulea University of Technology, 97187 Lulea, Sweden; nadhir.alansari@ltu.se
5 School of Civil Engineering, Faculty of Engineering, Universiti Teknologi Malaysia (UTM), Johor Bahru 81310, Malaysia; sshahid@utm.my
6 Sustainable Developments in Civil Engineering Research Group, Faculty of Civil Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam
* Correspondence: yaseen@tdtu.edu.vn

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Featured Application: The application of this study contributes on the urban stormwater channels that reduce the required length of such channel and thereby reduce the land use, construction and maintenance-related costs.

Abstract: The check dams in grassed stormwater channels enhance infiltration capacity by temporarily blocking water flow. However, the design properties of check dams, such as their height and spacing, have a significant influence on the flow regime in grassed stormwater channels and thus channel infiltration capacity. In this study, a mass-balance method was applied to a grassed channel model to investigate the effects of height and spacing of check dams on channel infiltration capacity. Moreover, an empirical infiltration model was derived by improving the modified Kostiakov model for reliable estimation of infiltration capacity of a grassed stormwater channel due to check dams from four hydraulic parameters of channels, namely, the water level, channel base width, channel side slope, and flow velocity. The result revealed that channel infiltration was increased from 12% to 20% with the increase of check dam height from 10 to 20 cm. However, the infiltration was found to decrease from 20% to 19% when a 20 cm height check dam spacing was increased from 10 to 30 m. These results indicate the effectiveness of increasing height of check dams for maximizing the infiltration capacity of grassed stormwater channels and reduction of runoff volume.

Keywords: grassed channels; check dam system; stormwater; infiltration capacity; water resources modelling; modified Kostiakov model

1. Introduction

The use of grassed channels as a sustainable urban stormwater management tool has increased rapidly compared to other types of green stormwater management tools in recent years [1,2]. Grassed stormwater channel provides temporary storage and ecological water quality enhancement in addition to aesthetic benefits [3–5]. The most significant feature of grassed channels is the interaction between flowing water and the grass cover that diffuses the flow and lessens flow velocities [6,7]. This helps in increased infiltration and reduction of runoff volume, and thus lessening of flood risk in the downstream [8].

The construction of check dams in grassed stormwater channel enhances the infiltration process by temporarily blocking the flowing water and increasing the detention time [7,9]. Different materials are used for the construction of check dams such as soil, rocks, or bagged gravel or rock [4]. Check dams, therefore, can be (1) porous check dams—filtering water and trapping sediments, or (2) impervious check dams—dissipating flow energy and controlling water level [4,10].

Manning's equation [11] is generally used for the designing of grassed channel. The effect of the infiltration process on flow in a grassed stormwater channel is usually included by considering the infiltration flow rate along the channel cross-section. However, Manning's equation is only applicable for the flow condition when the water level, cross-sectional area, and velocity remain constant, in addition to fully rough and turbulent flow [12]. In urban areas, these assumptions are difficult to fulfil for a grassed stormwater channel as the flow depends on rainfall events; hence, it is ephemeral and intermittent [13,14]. Furthermore, the backwater, ponding, and energy dissipation resulting from check dam systems change the flow regime due to the rise in water depth and reduction of water velocity along the grassed channel [4,15,16].

Although some studies (e.g., [17–20]) have been conducted to assess interrelation between the infiltration rate and the water depth, the effects of backwater and ponding resulting from check dams on channel infiltration have not been investigated and ignored in channel design procedures [21]. However, the effect of channel water depth on infiltration may be ignored for shallow depths but not for higher depth caused by check dams [20,22].

Numerous models have been developed over the last century for prediction of infiltration rate (e.g., [17,23–27]), each with different required parameters. Hence, each model has different prediction accuracy when satisfying the condition of required parameters [28–31]. The modified Kostiakov model has been suggested in many studies (e.g., [28,29,31–34]) for the estimation of infiltration rate in unlined irrigation and drainage channels. A comparison among the performance of five infiltration models, namely, the Kostiakov, Horton, modified Kostiakov, Philip, and the Soil Conservation Service model (SCS), which conducted by [29] showed that none of the models consider the effects of variable channel cross-section. It has also been reported that adding three parameters of a channel trapezoidal section, namely, the water level, base width, and side slope to the modified Kostiakov model, it is possible to improve the prediction accuracy of the model [29]. Although the modified Kostiakov model showed significant improvement in the prediction accuracy of a channel infiltration capacity for a static condition, it has some limitations when used for flowing water conditions. It is important to improve the prediction accuracy of infiltration capacity in a grassed stormwater channel for better management of stormwater.

In this study, laboratory experiments were conducted to collect data for the development of an empirical infiltration model for better estimation of infiltration capacity of a grassed stormwater channel with check dams. Additionally, the model was used to assess the effects of check dam height and spacing on infiltration to provide new knowledge that can be used for designing check dams in grassed channel for better management of stormwater.

2. Materials and Methods

2.1. Experimental Tests

Laboratory experiments were conducted to determine the differences in channel infiltration capacity over time as a function of check dam height and spacing. The experiments were conducted at the Hydraulic Laboratory of Universiti Putra Malaysia using a trapezoidal channel fabricated from a perforated steel sheet mounted on a steel frame. The channel had a length of 10 m with longitudinal and side slopes of 0.3% and 3%, respectively, and a bottom width of 0.2 m, as depicted in Figure 1a.

(**a**) (**b**)

Figure 1. The trapezoidal channel model: (**a**) perforated steel sheets with steel frame (**b**); the channel with check dams during operation.

The simulation of the natural channel with a grass-covered boundary was performed by placing a thick topsoil layer (15 cm thick) evenly covered with cow grass (*Axonopus compressus*) of around 100 mm height on the channel base and side slopes (Figure 1b). The texture of the topsoil was composed of 76% sand, 8% silt and clay, and 16% organic matter.

Erosion from infiltrated water was prevented by placing a permeable sheet in between the soil and the perforated channel steel sheets. A check dam was installed at the end of the channel using a steel plate that could be fixed by an adjustable sandwich panel (Figure 2).

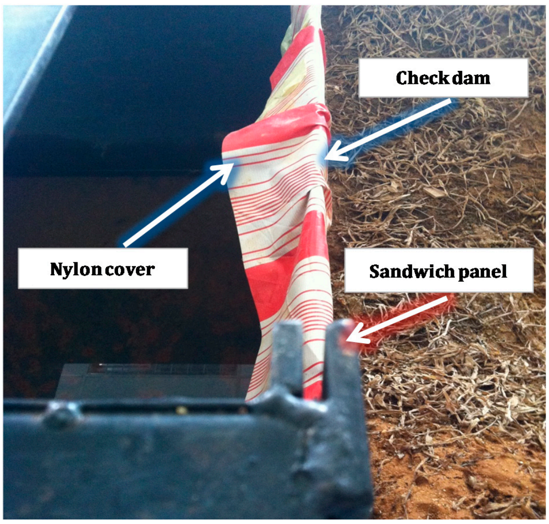
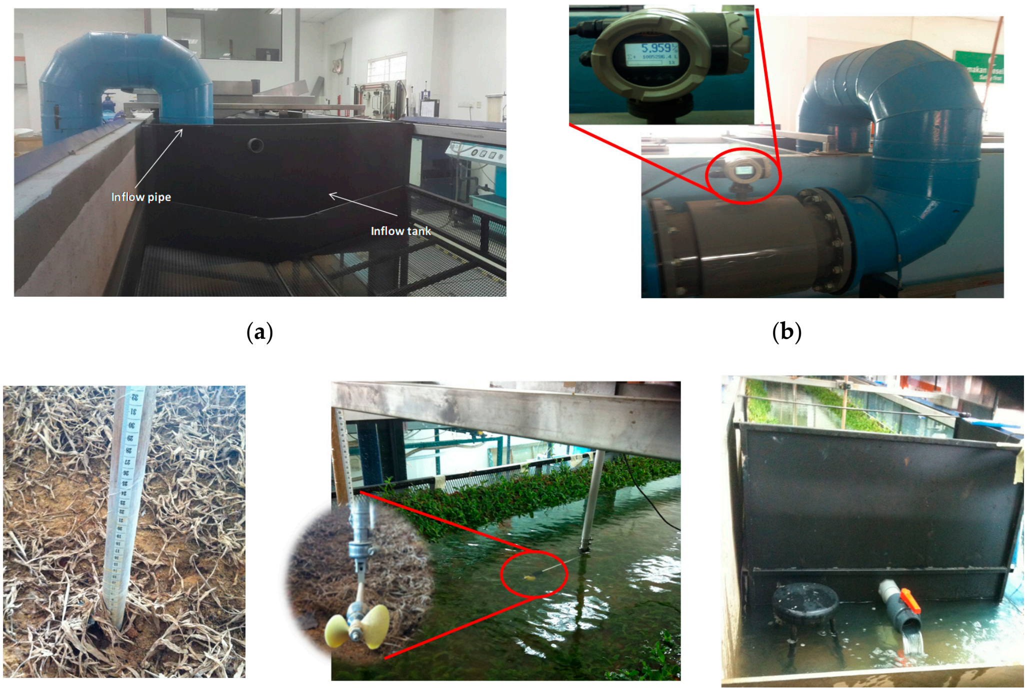


Figure 2. The check dam at the end of the channel downstream.

The water flow through the channel was monitored using different instruments. The instruments used to measure the water movements (inflow and outflow), water level, and flow velocity are presented in Table 1 and Figure 3.

Table 1. The instruments used in the experiments for the measurement of water movements.

Instruments	Application	Function
Upstream tank	Placed under the inflow pipe; some stones were placed in the bottom of it	Regulate inflow and reduce turbulence
Electronic flowmeter	Attached to the inflow pipe	Measure, regulate, and control the inflow rate
Staff gages	Fixed at three points along the channel as point 1: 5 m from upstream, point 2: middle of the channel, point 3: 5 m from downstream	Measure water level
Current meter	Movable among the three water level measurement points along the channel	Measure the mean flow velocities
Downstream tank with a valve	Placed after the check dam	Measure the outflow using the volumetric method



(a) (b)

(c) (d) (e)

Figure 3. The instruments used in the experiments: (**a**) upstream inflow tank; (**b**) electronic flowmeter; (**c**) staff gage; (**d**) current meter; (**e**) downstream tank with valve.

On the basis of the capacity of the channel and the capabilities of the laboratory instruments, the experiments considered a total of 15 tests; 3 cases of check dam heights, h_w = 10, 15, and 20 cm; and 5 inflow rates, Q_{in} = 0.0055, 0.0075, 0.0095, 0.0115, and 0.0135 m^3/s for each check dam height. The experiment was repeated for different Q_{in} for a given h_w and vice versa. The duration of each test was 1.5 h.

2.2. The Estimation of the Infiltration Rates

The infiltration flow rate was estimated using a mass-balance method. This method requires regular measurements of inflow and outflow rates. The measurements were conducted every 5 min for a period of 1.5 h. The equation of the mass-balance method is as follows:

$$Q_f = (Q_{in} - Q_{out}) - \frac{\Delta S}{\Delta t} \tag{1}$$

where Q_f = infiltration flow rate (m^3/s), Q_{in} = inflow rate (m^3/s), Q_{out} = outflow rate (m^3/s), and $\frac{\Delta S}{\Delta t}$ = change in channel storage (m^3/s) over a time interval, Δt.

The infiltration flow rate in a channel can be estimated using the following equation [29]:

$$Q_f = \frac{f}{360,000} PL \tag{2}$$

where f = infiltration rate (cm/h), P = wetted perimeter (m), L = channel length (m), and the 360,000 is the unit normalization factor (the unit of Q_f is m^3/s, whereas f is cm/h).

Equation (2) can be rewritten as follows to calculate the infiltration rate in a grassed channel:

$$f = \frac{360,000\, Q_f}{PL} \tag{3}$$

The modified Kostiakov model [27] for estimation of infiltration rate was adapted in the present study for the development of an improved model for the estimation of infiltration rate of a grassed channel with check dams. The infiltration capacity in unlined irrigation and drainage channels can be estimated using a modified Kostiakov model:

$$f_p = K_k\, t^{-\alpha} + f_c \tag{4}$$

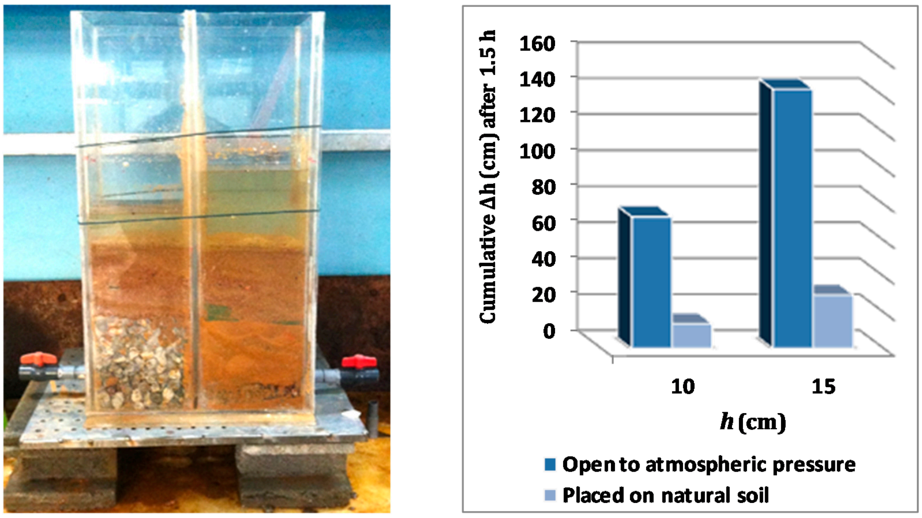
where f_p = infiltration rate (cm/h), t = time (h), f_c = final infiltration rate (cm/h), and K_k and α are non-dimensional constants.

The parameters K_k and α are usually obtained from experimental data and they do not have any physical meaning [28,35,36]. The experimental tests conducted by [37] revealed that K_k can have a value ranging from 0.225 to 1.1, and α can be between 0.458 and 0.669. However, the experimental tests conducted by [38] on a wide range of soil types revealed that the values of the parameters can have a much wider range, 7.76 to 333.92 for K_k and 0 to 0.77 for α. The estimation accuracy of the modified Kostiakov model can be significantly improved by adding flow velocity and channel cross-section parameters (i.e., mean velocity v, side slope m, base width b, and water level y), as follows [21,39]:

$$f_p = K_k\, y^{C1}\, b^{C2}\, m^{C3}\, v^{C4}\, t^{-\alpha} + f_c \tag{5}$$

where C1, C2, C3, and C4 are the constants for the introduced hydraulic parameters, y, b, m, and v, respectively. These constants were estimated from experimental data for the development of a new infiltration rate estimation model.

The laboratory temperature was maintained at 27 ± 1.5 °C so that water loss from the channel through evaporation could be minimized to an insignificant level. The aim of placing the topsoil layer on the perforated steel sheets was to ensure the drainage of the infiltrated water so that the soil remained unsaturated during the experiments. This is similar to the condition of a grass-covered stormwater channel with a deep groundwater table and a short period of rainfall. Infiltration during this condition normally ends before the wetting front reach to groundwater table [40] and thus the soil remains unsaturated during the period of a storm. However, the perforated steel sheets produced an opening to air drainage, which differs from field conditions where the presence of natural soil beneath the topsoil prevents such drainage. According to [21], the rate of infiltration through a topsoil layer placed on an open-air boundary is normally more than the infiltration through a topsoil layer placed on a natural soil. This was proved in a laboratory test using a model of two identical vertical columns (Figure 4a), one with holes in the bottom and a 15 cm thick topsoil layer placed on coarse gravel (open to atmospheric pressure), whereas the second column was without a hole and had a 15 cm thick topsoil layer placed on natural soil (fine sandy loam), having a final constant infiltration rate f_c of 2 cm/h. Two initial water levels h of 10 and 15 cm were considered in the experiment, and the decrease in the water head over time Δh was measured. The observed cumulative infiltration after 1.5 h was about fivefold higher for the topsoil open to the atmosphere compared to the value for the topsoil placed on natural soil (Figure 4b). This difference was due to low permeability of natural soil, which restricts the water penetrating through the topsoil.



(a) (b)

Figure 4. The laboratory conducted to measure the infiltration rates through a topsoil, open to atmospheric pressure and with natural soil boundaries: (**a**) the physical model with identical vertical columns (**b**); the cumulative infiltration after 1.5 h. [21]

3. Results

3.1. Flow Depth and Velocity for Different Check Dam Conditions

The flow in the channel could then be classified under three stages: (i) the flow at the startup, (ii) the peak flow, and (iii) the flow after shutting down the inflow pipe valve. Figure 5 depicts the typical hydrograph of the flow that occurred during the experiment, which exhibited three stages of flow.

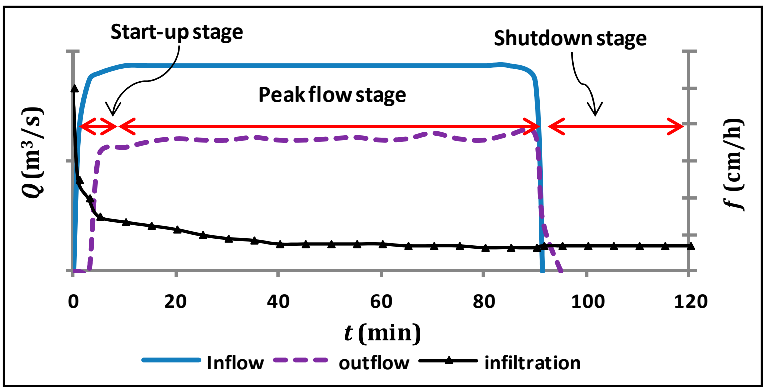


Figure 5. The typical hydrograph of flow along the channel during experiments, showing three flow stages.

The opening of the inflow valve initiated the startup stage, which continued until the maximum water depth in the channel was reached. The peak flow occurred at this stage. The inflow rate determined the extent of the startup phase. The outflow was only encountered when this phase was ended, and the water depth went beyond the check dam height. The mean velocity and water depth in the channel remained constant until the end of the second stage. The duration of this stage was determined by deducting the time of start-up and shutdown periods from 1.5 h (the overall time of the experiment). The shutting down of the inflow pipe valve initiated the third stage. The water flow through the channel was sustained for a limited period after shutting down the inflow pipe valve due to the channel longitudinal slope. The water level at this stage was gradually reduced to the height of the check dam in the downstream, causing a complete cessation of the outflow while sustaining the ponding water in the channel.

Table 2 presents the flow characteristics estimated for different experimental cases. The table shows that the time to downstream (i.e., the time lag between upstream and downstream of the channel), t_d (min), decreased with the increase of inflow rate, irrespective of check dam height in the downstream. The relationship between the inflow rate and the average value of t_d (min) for the grassed channels with a coefficient of determination, R^2, is shown in Figure 6a.

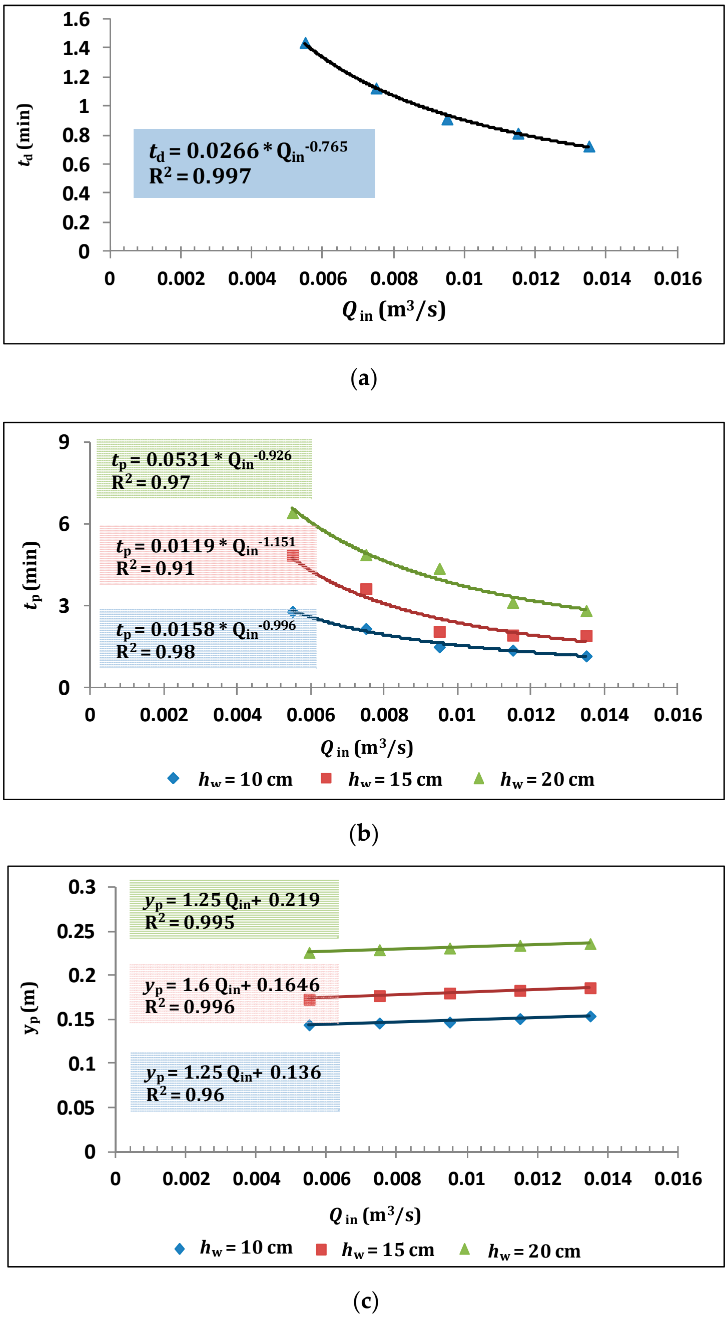


Figure 6. The experimental models developed to predict (**a**) the time to downstream t_d (min), (**b**) the time to peak t_p (min), and (**c**) the water level at peak flow y_p (m).

Table 2. The flow characteristics estimated for different experimental cases.

Case	Check Dam Height h_w (cm)	Inflow Rate Q (m^3/s)	Mean Velocity V (m/s)	Water Depth y (cm) at Peak			Time to Downstream t_d (min)	Time to Peak t_p (min)
				Point 1	Point 2	Point 3		
1	10	0.0055	0.06	12.9	14.4	15.4	1.5	2.8
		0.0075	0.08	13.2	14.6	16	1.33	2.17
		0.0095	0.1	13.7	14.7	16.3	0.87	1.5
		0.0115	0.115	14.1	15.1	16.6	0.8	1.38
		0.0135	0.13	14.6	15.4	17.1	0.73	1.17
2	15	0.0055	0.04	15.5	17.3	19	1.5	4.86
		0.0075	0.06	16.3	17.7	19.3	1.033	3.63
		0.0095	0.07	16.8	18	19.6	0.87	2.07
		0.0115	0.08	17.5	18.3	20	0.775	1.93
		0.0135	0.095	18	18.6	20.3	0.75	1.92
3	20	0.0055	0.025	20.3	22.6	24.3	1.32	6.42
		0.0075	0.035	20.9	22.9	24.6	1.016	4.88
		0.0095	0.045	21.1	23.1	25.4	1	4.38
		0.0115	0.05	21.5	23.4	24.9	0.87	3.13
		0.0135	0.06	22	23.6	25.2	0.7	2.83

The time taken to reach the peak, t_p (min), was found to vary with the inflow rate and downstream check dam height. Table 2 shows that t_p varied in the range of 1.17 to 6.4 min. It was found to decrease with the increase of inflow rate and increase with the increase of downstream check dam height. The relation between t_p (min) and the inflow rate for grassed channels at h_w = 10, 15, and 20 cm is shown in Figure 6b. The non-linear model developed to define the relationship is also shown in Figure 6b, which can be used for the estimation of t_p (min) from inflow for different dam heights. Table 2 shows increases in channel water level with the increase in the rate of inflow when all other factors are kept constant. The water level at peak flow was varied with inflow rate for different check dam heights, h_w (Figure 6c). A linear relationship between water level at peak flow and inflow rate was observed for different heights. The regression models are also shown in Figure 6c. The results showed a slight increase in water levels at peak flow with the increase in inflow rate.

3.2. Infiltration Rates versus Check Dam Conditions

The infiltration rate f_p and cumulative infiltration F for the grassed channel at varying inflow rates were estimated for different heights of check dam, h_w = 10, 15, and 20 cm, as shown in Figure 7a–c, respectively. The values of F for each inflow rate over time was consistently more for the higher values of h_w. For the sake of clarity, the values of F after 2 h for three heights of check dam are presented in Figure 8. The figure shows a clear increase in F after 2 h with the increase of h_w, irrespective of inflow rates. However, the changes in F for the three values of h_w showed more increase for higher flow rates due to the increase in water level and the associated decrease in velocity (Table 2).

3.3. Developing Infiltration Model for a Grassed Channel with Check Dam

The constants of the hydraulic parameters of Equation (5) were estimated from the observed values of f_p in a grassed channel at different time intervals for h_w = 10, 15, and 20 cm. The observed data were divided by 5 for the development of an infiltration model that had suitable natural conditions, as suggested by [21]. The observed data were classified for three stages, however, the data from the first two stages were considered. The data for the shutdown stage infiltration rate was not considered in model development because flow at this stage is under static condition when the velocity is equal to zero.

A nonlinear regression model was developed for the fitting of infiltration rate data and the estimation of the constants of the hydraulic parameters of Equation (5). The IBM SPSS software was used for this purpose. As b and m were kept constant in experimental tests, the related power values suggested by [29] were used for C_2 and C_3 (i.e., 0.01 for C_2 and 1.1 for C_3), whereas the difference values were used for C_1 and C_4.

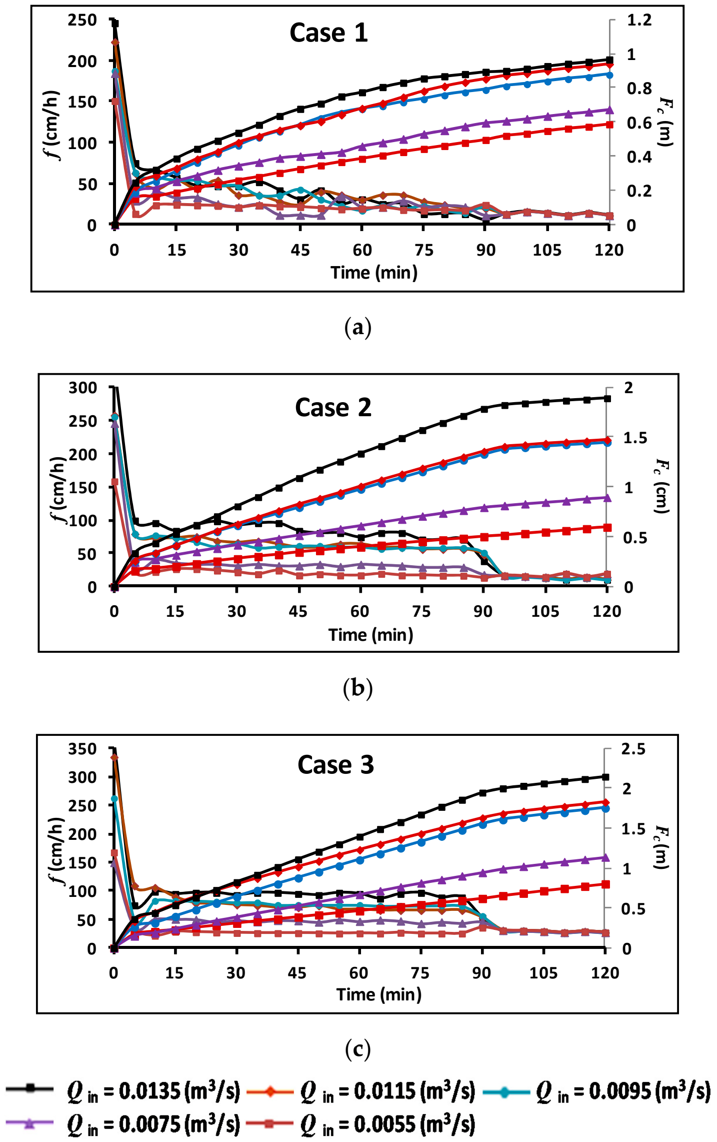


Figure 7. The changes in infiltration rate f_p and cumulative infiltration F with time in the grassed channel for different inflow rates: (**a**) h_w = 10 cm; (**b**) h_w = 15 cm; (**c**) h_w = 20 cm.

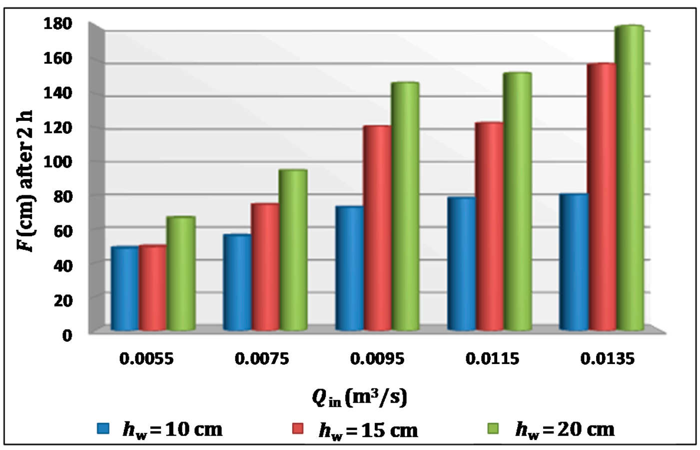


Figure 8. The values of cumulative infiltration, F, in the grassed channel after 2 h for different check dam heights.

The infiltration rate of natural soil (2 cm/h) was considered as the final constant infiltration rate, f_c [11]. The analysis of f_p was performed for the values of y, b, m, and v, and the time t. The results produced an improved version of the modified Kostiakov model with a coefficient of determination R^2 = 0.69, root mean square error (*RMSE*) = 3.1 cm/h, and values of 60 and 0.8 for the non-dimensional constants, K_k and α, respectively:

$$f_p = 60\, y^{1.5}\, b^{0.01}\, m^{1.1}\, v^{0.4}\, t^{-0.8} + 2 \tag{6}$$

This equation can be further simplified and generalized as

$$f_p = K_k\, F_{\text{hp}}\, t^{-\alpha} + f_c \tag{7}$$

where F_{hp} is a function that represents the four hydraulic parameters as

$$F_{\text{hp}} = y^{1.5}\, b^{0.01}\, m^{1.1}\, v^{0.4} \tag{8}$$

3.4. Influence of Check Dam Heights and Spacings on Infiltration Rate of Grassed Channel

The influence of check dam heights and spacings of a grassed channel on the amount of runoff reduction by infiltration process was evaluated using the newly developed model. It was assumed that the channel section was trapezoidal with a length = 60 m, bottom width = 0.2 m, side slope m = 3, and longitudinal slope = 0.3%. The channel was assumed to be uniformly covered with a similar type of soil and grass cover. A steady inflow rate of Q = 0.055 m^3/s was considered as a design discharge. The effects of check dam heights and spacing on the infiltration rate of grassed channel were investigated using five check dam system cases, as detailed in Table 3. Different sections were created in the grassed channel to represent the spacing between two check dams (Figure 9). The evaluation of the water depth, flow variations, and infiltration rates was performed at the middle of each channel section.

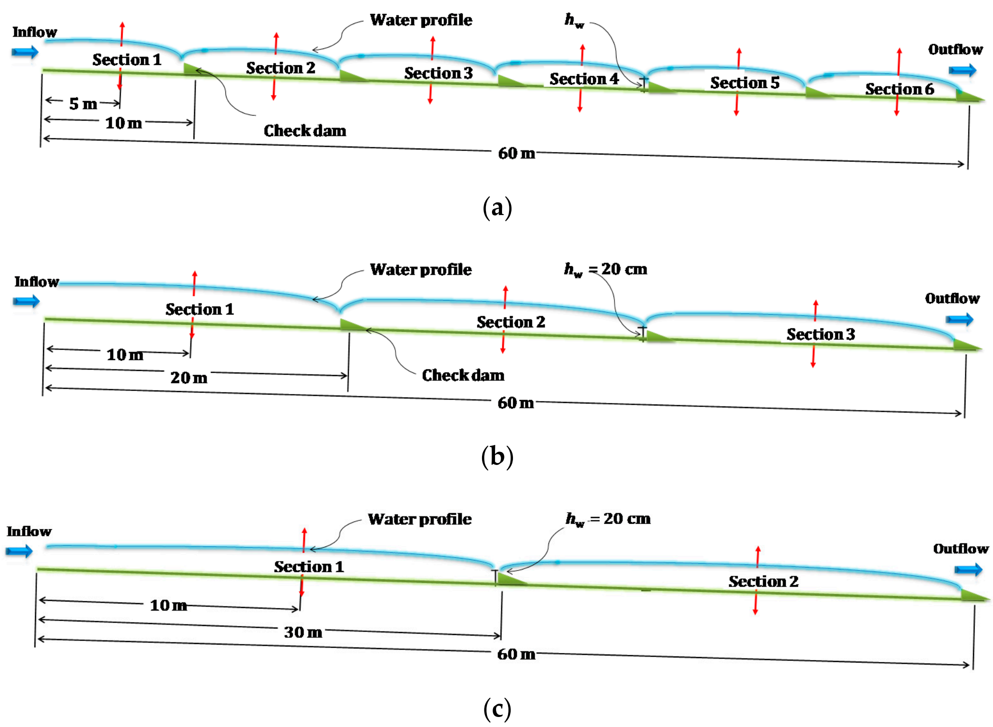
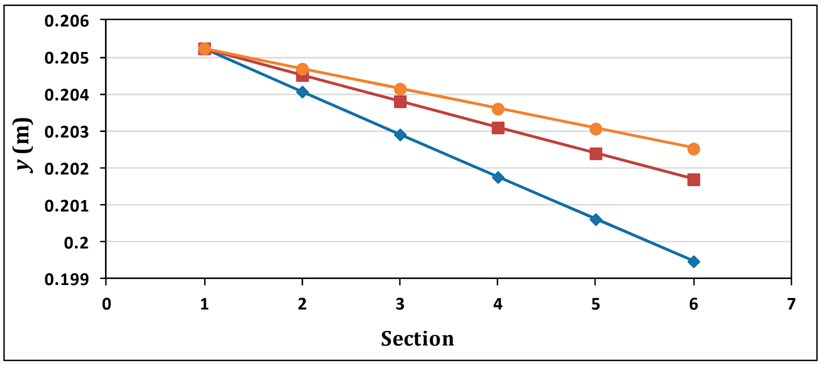


Figure 9. Side view of the channel for different check dam design cases: (**a**) case 1, case 2, and case 3; (**b**) case 4; (**c**) case 5.

Table 3. Details of the check dam system design cases used for the estimation of the effects of check dam heights and spacing on the infiltration rate of grassed channel.

Case	Height h_d (cm)	Spacing L_d (m)	Number of Sections
1	10	10	6
2	15	10	6
3	20	10	6
4	20	20	3
5	20	30	2

The values of t_d, t_p, and y for all design cases were calculated by fitted non-linear regression equations, as shown in Figure 6a–c. For example, the value of y (m) for Section 1 in case 1 was determined using the equation presented in Figure 6c. The obtained values of Q_{in} and y_p were 0.055 m^3/s and 0.2053 m, respectively. The depth was observed to decrease along the channel due to an infiltration-induced reduction of flow rate. The equations in Figure 6a,b were used to calculate the values of t_d and t_p at Section 1 for h_w = 10 cm, L = 10 m, and Q_{in} = 0.055 m^3/s. Obtained values were t_{d1} = 0.244 min (or 14.6 s), and t_{p1} = 0.284 min (or 17 s). The values of t_d and t_p for the rest of the sections were calculated in the same manner by considering the flow rates. Moreover, the flow variations at channel sections and related water levels were estimated from the infiltration rate at different times. Because Figure 6a,b was developed from a channel with 10 m spacing of downstream check dams, the values of t_d and t_p were multiplied by 2 and 3 in cases 4 and 5, respectively, in order to fit their spacing of 20 and 30 m (Figure 9). The differences in the water levels for different check dam design cases are shown in Figure 10. The figure shows a decrease in the water level in the downstream of the channel due to infiltration through the channel. However, the water level showed a time-dependent increase in each section due to the lower rate of infiltration along the channel over time.



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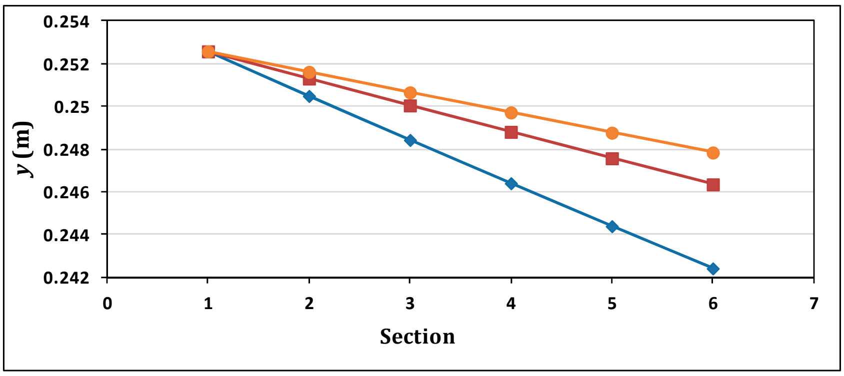
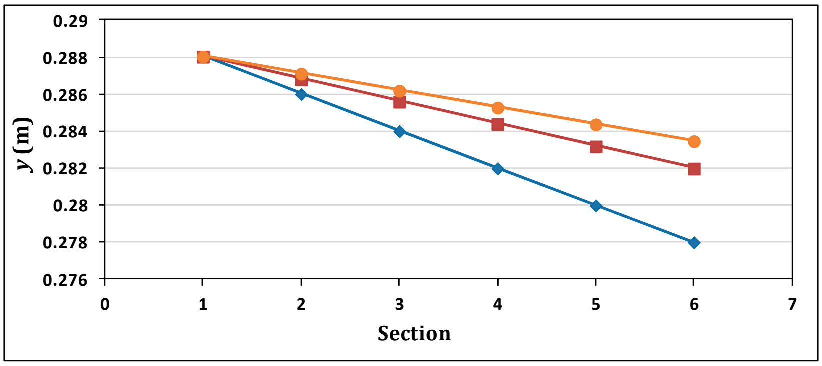


(**b**)

Figure 10. *Cont*.



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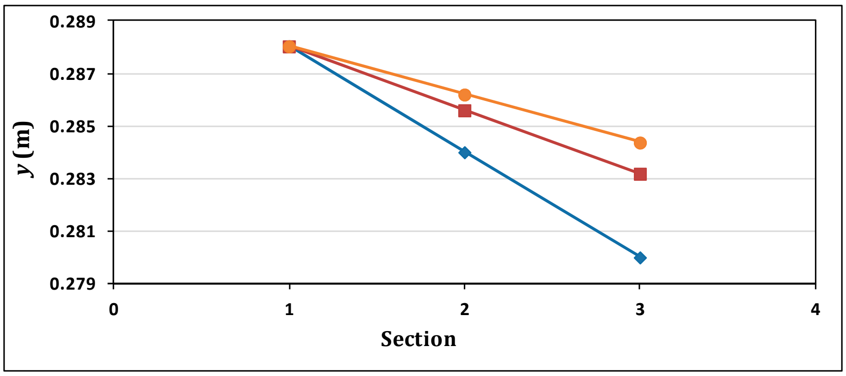

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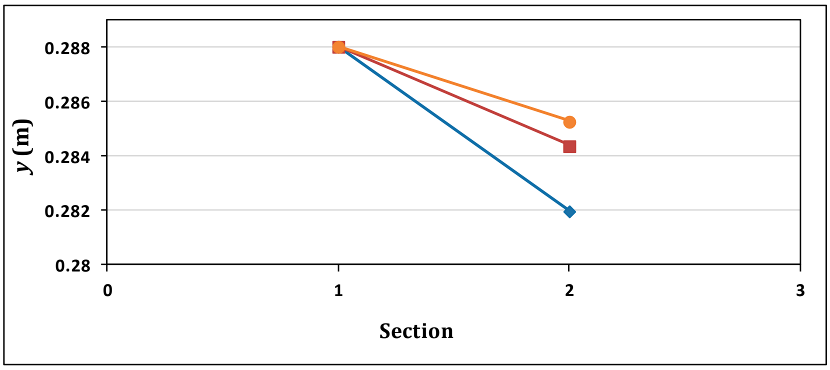

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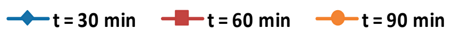
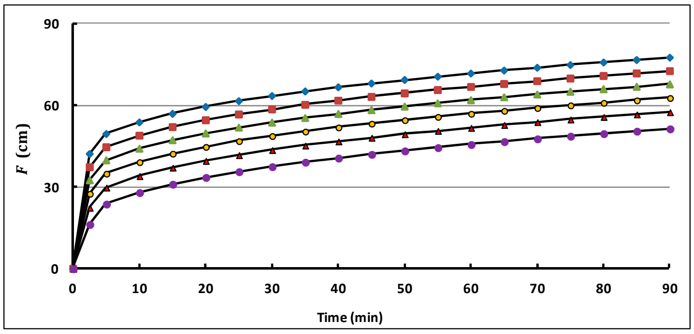


Figure 10. Water level along the channel sections for different times for different check dam design cases: (**a**) case 1; (**b**) case 2; (**c**) case 3; (**d**) case 4; (**e**) case 5.

Figure 11 presents the variations in F over time for the five considered cases. Figure 11a–c shows a higher value of F for a higher value of h_w at all channel sections. For the comparisons among Figure 11c–e, the values of F in all sections were summed at a specific time due to the differences of section lengths. The comparison revealed that a decrease in spacing of check dams had a very low impact on the infiltration rate. For more clarification, the total inflow, outflow, and infiltration volumes after 90 min for the five cases are presented in Table 4, whereas Figure 12 shows a comparison of the percentage of the total volume of conveyed water and the total volume of infiltrated water.



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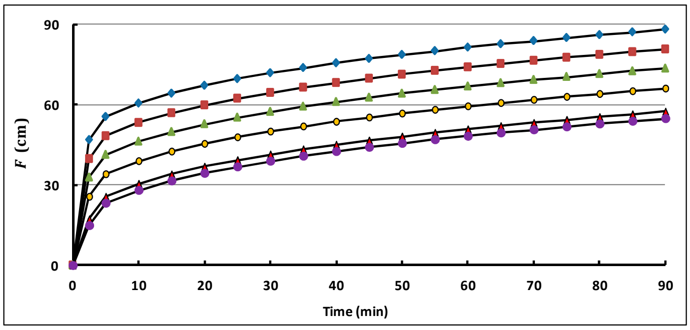
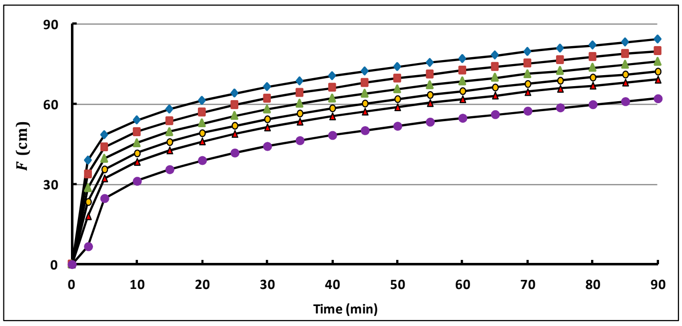
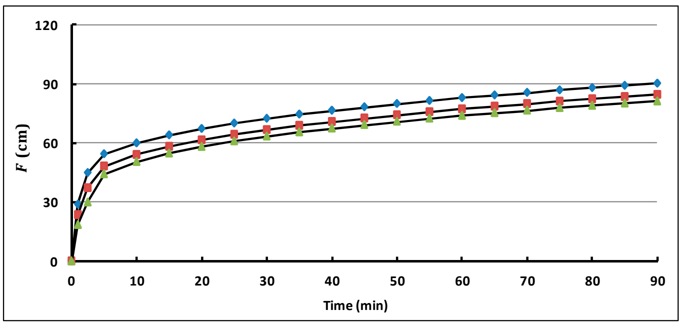


(**b**)

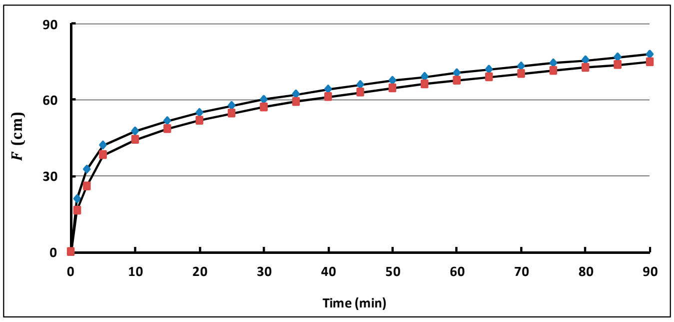


(**c**)



(**d**)

Figure 11. *Cont.*



(e)

Figure 11. The values of cumulative infiltration F for different times for the five check dam design cases: (**a**) case 1; (**b**) case 2; (**c**) case 3; (**d**) case 4; (**e**) case 5.

Table 4. The total inflow, outflow, and infiltration volumes after 90 min.

Case	Total Inflow Volume (m^3)	Total Outflow Volume (m^3)	Total Infiltrated Volume (m^3)
1	297	262.7	34.3
2	297	251.5	45.5
3	297	237.4	59.6
4	297	239	58
5	297	241	56

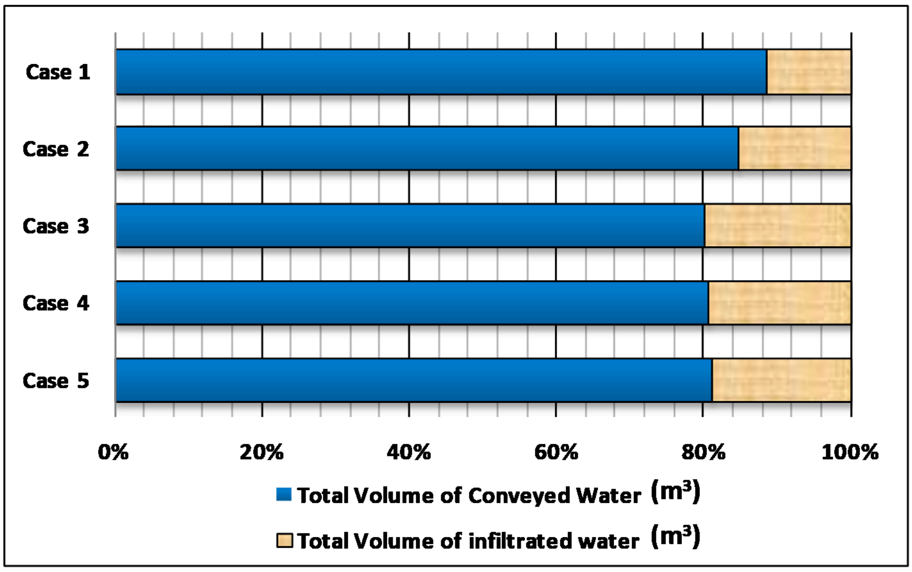


Figure 12. The percentage of the total volume of conveyed and infiltrated water.

Table 4 shows that the infiltrated water volume increased from 34.3 for h_w = 10 cm and spacing = 10 m (case 1) to 45.5 m^3 for h_w = 15 cm and spacing = 10 m (case 2), and 59.6 m^3 for h_w = 20 cm and spacing = 10 m (case 3). Therefore, the amount of infiltration was increased from 12% to 20% by increasing the height of the check dam from 10 to 20 cm at channel downstream, whereas increasing the spacing of 20 cm height check dams from 10 to 30 m caused a slight decrease in total infiltration from 59.6 to 56 m^3 (20% to 19%).

4. Conclusions

Check dams are commonly used in grassed stormwater channels for enhancement of channel infiltration capacity by temporarily blocking water flow and providing backwater ponding. The present study considered the application of a mass-balance method on a grassed channel model to assess the effects of varying check dam height on channel infiltration capacity. The results revealed that an increase in check dam height in channel downstream increased infiltration due to an increase in water depth and decrease in flow velocity. The observed data were used for the development of non-linear regression models to derive the relationship of inflow rate with the average value of time to downstream and the time taken to reach the peak for different check dam heights. The relationship between water level at peak flow and inflow rate was modeled for different check dam heights. A non-linear regression analysis was also conducted to derive an empirical infiltration model through the adaption of a modified Kostiakov model for accurate estimation of infiltration rate in grassed channels. The developed models were employed for the estimation of infiltration rate in a grassed channel for five different check dam system design cases. The infiltration rate in grassed channels was found to vary significantly with check dam height, whereas the effect of check dam spacing on infiltration rate was found negligible. The result showed an increase in channel infiltration from 12% to 20% by raising the check dam height from 10 to 20 cm. The results indicated that instead of increasing urban stormwater channel length, infiltration in a channel can be increased by raising the height of check dams. This can reduce the requirement of land for construction of an urban stormwater channel and the construction and maintenance-related costs. The results of this study can be used for designing of check dam system in grassed stormwater channels for better reduction of runoff.

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