Application of Variable Pulsed Irrigation Algorithm (VPIA) for Runoff Losses Reduction: Case Study of Different Soil Types

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Application of Variable Pulsed Irrigation Algorithm (VPIA) for Runoff Losses Reduction: Case Study of Different Soil Types

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Abstract. The low-pressure sprinklers have been widely used to replace the high-pressure impact sprinklers in the lateral move sprinkler irrigation system due to its low operating cost and high efficiency. However, runoff losses under the low-pressure sprinkler irrigation machine can be significant. This study aims to evaluate the performance of the variable pulsed irrigation algorithm (VPIA) in reducing the runoff losses under low-pressure lateral move sprinkler irrigation machine for three different soil types. The VPIA uses the ON-OFF pulsing technique to reduce the runoff losses by controlling the number and width of the pulses considering the soil and the irrigation machine properties. Also, the VPIA aims to achieve a balance between four critical goals: reduce the runoff losses, deliver the highest possible irrigation depth, ensure a high level of water distribution uniformity in the direction movement, and with the lowest number of pulses. From a wide range of pulses numbers and widths tested applying a certain water depth to three soil types (Loamy Sand, Sandy Loam, Loam), the best solution that satisfies the algorithm goals was selected. A MATLAB code was written to simulate the soil infiltration rate, the sprinkler application rate, and to apply the proposed algorithm. The simulation results show a runoff reduction of at least 91.76% for Loamy sand, 90.7% for Sandy Loam, and 97.79% for Loam soils with a high level of distribution uniformity while delivering the highest possible irrigation depth using the lowest number of pulses.

Keywords: Variable pulse, Low-pressure sprinkler, Runoff losses, Sprinkler Irrigation System, MATLAB software

1. Introduction

Due to restrictions and limitations on agricultural water worldwide, one of the most effective ways to conserve water in this sector is to reduce the water losses and improve irrigation uniformity [1]. Efficient use of water, as well as crop production, is now a significant objective in the design and management of irrigation systems [2]. In the last decades, the self-propelled sprinkler irrigation has stood out as an efficient type of pressurised irrigation methods [3]. Currently, the self-propelled sprinkler irrigation machines irrigate more than 12.5 million hectares worldwide [4], and they become widely used to replace the other conventional irrigation methods such as the flood irrigation and some types of sprinklers irrigation [5]. Applying water on a regular and consistent basis is the most significant advantage of these machines [5]. Also, the self-propelled sprinkler can irrigate large fields efficiently with low labour costs, and it can be adapted to many different soils, and the changing terrain [6]. Furthermore, the self-propelled sprinkler systems are suitable for almost all crops, and all types of topography and they have a high level of automation [7]. Moreover, the application efficiency for the self-propelled sprinkler systems is the higher among all the other types of sprinkler systems [5].

The purpose of the sprinkler irrigation system is to distribute water evenly on the farm to supplement the soil moisture deficiency that doesn't replenish by rainfall [1]. If the irrigation water is not uniformly applied, then the under-watered areas will result in reduced crop yields, and the over-watered regions will result in reduced or loss of crop yields beside the increased pumping costs [1]. Therefore, the irrigation uniformity becomes very important because it observed that it has a direct function to the crop yield [1]. Improper irrigation applications lead to crop water stress and low yield [8, 9]. On the other hand, excessive irrigation can lead to pollution due to the loss of plant nutrients through deep percolation, runoff and soil erosion as well as oxygen stress [10-12]. This uneven distribution of the water will results in yield differences within the irrigated field, and variation in the economic return for various areas within the field [13]. Therefore, the great effort in the design and management of an irrigation system should be focused on dealing with problems related to the irrigation uniformity and reducing water losses.

Nowadays, the low-pressure sprinkler has been widely used to replace high-pressure impact sprinklers in the self-propelled sprinkler system due to its low operating cost and high efficiency [14]. The low-pressure sprinklers that operate closer to or below the crop canopy makes them more water efficient than high-pressure sprinklers [15]. The efficiency enhancement is believed to result from reduced water loss through evaporation and wind drift. The operating pressure is related directly to the wetting diameter of the sprinklers and will affect the instantaneous application rate. The high-pressure sprinklers have a wider wetting diameter compared to the low-pressure sprinklers. Therefore, to apply a certain water depth to a specific soil using the high-pressure sprinkler, the applied water will spread out on a wide area due to the wide wetting diameter and hence resulting in low instantaneous application rate [15]. If the low-pressure sprinkler used to apply the same water depth, the same amount of water would spread out on a smaller area resulting in higher instantaneous application rate.

The low-pressure sprinklers have a small wetting diameter, which results in high instantaneous application rate and causes surface runoff on most of the soil types except soils with high intake rate [16]. The magnitude of the runoff depends on several factors such as irrigation machine characteristics, soil type, crop type, cultivation practices, and topography [17, 18]. For any sprinkler irrigation systems, the surface runoff occurs when the water application rate exceeds the soil infiltration rate [19]. Therefore, the sprinkler application rate and the soil infiltration rate are the most critical factors that affect the amount of the runoff. Since the low-pressure sprinkler system has a high instantaneous application rate, the potential for increased surface runoff is higher especially with soil that has a low infiltration rate [20].

Most researchers have reported that self-propelled sprinkler systems have the problem of surface runoff. Ben-Hur, et al. [21] and Letey, et al. [8] suggested that the crop yield can be affected by the runoff in three ways: 1. The loss of runoff from the cultivated field is a loss from the water targeted for crop production. 2. The runoff will increase soil erosion and lead to a loss in fertiliser and nutrients that are washed out of the field. 3. The runoff water that accumulates in the low areas within the field will cause a poor distribution of water, reduce the water efficiency, and it can cause waterlogging that leads to either crop loss or a reduction in the crop yield. Kincaid, et al. [16] concluded that 22% of the applied water was lost under high-pressure centre pivot sprinkler systems spraying a field with silty loam soil. Addink [22] noted that the runoff was 65% under a low-pressure sprinkler machine, while it was 22% under a high-pressure sprinkler system when irrigating a field with very fine sandy soil. Addink [22] and Kincaid, et al. [16] reported no runoff happened under both low-pressure and high-pressure sprinkler system when irrigating a field with sandy soil.

Many research studies try to reduce the surface runoff losses under the linear move sprinkler system by increasing the soil infiltration rate and the surface storage capacity through applying specific tillage practices and adding some materials to the soil surface [21, 23-25]. These practices can decrease the runoff amount to some extent, but they will not eliminate it. Other researchers are focusing on reducing either the machine speed or the sprinkler discharge rate to minimise the surface runoff using different techniques [26-28]. However, the use of these methods often leads to a reduction in the applied depth for each pass of the irrigation machine, and the amount of the resulted runoff is not guaranteed to be at the lowest possible value. Also, some of these methods can affect the distribution uniformity and result in non-uniform water distribution especially for the lowest irrigation depths [29, 30]. In our previous work [31], we suggested the variable pulse irrigation algorithm (VPIA) based on the pulsing technique to reduce the runoff losses considering the sprinkler application rate, soil infiltration rate and surface storage capacity. We used a graphical method to reduce the runoff losses by varying the number and width of the OFF pulses taking advantage of the pulsing effect on the application rate and the soil infiltration rate considering the surface storage capacity. The VPIA was used to reduce the runoff losses resulted from the use of the LM sprinkler irrigation system to irrigate Sandy loam soil type. The results were promising as the runoff have been reduced for at least 90.7% while delivering a high and acceptable irrigation depth with a good level of distribution uniformity [31].

There is a significant difference in the runoff loses for different soil types according to differences in infiltration rate when the same sprinkler machine is used [17, 18]. Therefore, for some soils, the runoff will represent a substantial loss of irrigation water, and the irrigation process will be considered inefficient. So, this research will focus on applying the variable pulse irrigation algorithm (VPIA) for three different soil types (Loamy Sand, Sandy Loam, Loam) to reduce the runoff losses under a low-pressure linear move sprinkler irrigation system.

2. Materials

A MATLAB code was written to simulate the soil infiltration rate, the sprinkler application rate, and to apply the proposed algorithm. The simulation tests of the Variable Pulsed Irrigation Algorithm (VPIA) were performed using a linear-move (LM) irrigation system supplied with low elevation spray application (LESA) sprinklers designed by Lindsay (LINDSAY CORPORATION, Omaha, Nebraska, USA). The specifications of the LM irrigation system used in this study are consists of 3 spans, with a total length of 178 m and system flow rate of 25 L/sec. The nozzles are fitted on flexible drop hoses, with sprinklers set at 0.45 m above the soil surface, and the sprinklers were spaced 0.76 m apart. Each sprinkler was fitted with a 10-psi pressure regulator, and the wetting diameter of the sprinkler is 5.2m.

The soil types used in the simulation model are the Loamy Sand, Sandy Loam and Loam soils. To simulate the soil infiltration rate $q(t)$ and the accumulated infiltrated depth $I(t)$, Philip's Two-Term Model was used as follow [32]:

$$q(t) = 0.5St^{-0.5} + A \quad (1)$$

$$I(t) = St^{0.5} + At \quad (2)$$

Where: $q(t)$ is the infiltration rate in (mm/h); t is the time for infiltration in (h); S is the sorptivity in (mm/h$^{0.5}$); A is a constant in (mm/h); $I(t)$ is the cumulative infiltrated depth in (mm) at any time t. The sorptivity (S) and the constant (A) in Philip model for the three soil types were obtained from the Green-Ampt infiltration parameters proposed by Rawls, et al. [33] through applying the relations suggested by Rawls [34] and Philip [32] as follows:

$$S = (2K_{sat}\Delta\theta|\psi_f|)^{\frac{1}{2}} \quad (3)$$

$$\Delta\theta = \eta - \theta_0 \quad (4)$$

$$A = 0.38\, K_{sat} \quad (5)$$

Where: η is the total porosity in (cm^3/cm^3); θ_0: is the initial moisture content in (cm^3/cm^3); $|\psi f|$: is the wetting front soil suction head in (cm). We assume that $\Delta\theta = \theta_e$ in equations (1&2), where: θ_e is the effective porosity, and the surface storage capacity (SS) is 5mm. The calculated parameters of the used soils are listed in Table 1.

Table 1. Soil infiltration parameters for the three soil types, adapted from [33]

Soil Texture	Total Porosity η (cm^3/cm^3)	Effective porosity θ_e (cm^3/cm^3)	Wetting front soil suction head |ψf|(cm)	Hydraulic Conductivity K_{sat} (cm/h)	Sorptivity S ($cm/h^{0.5}$)	Constant A
Loamy Sand	0.437	0.401	6.13	2.99	3.8340	1.1362
Sandy	0.453	0.412	11.01	1.09	3.1446	0.4142
Loam	0.463	0.434	8.89	0.34	1.6198	0.1292

The application rate *q(t)* of the irrigation machine is an important factor that affects the amount of runoff (*RO*) and must be calculated correctly. Its shape is elliptical and perpendicular to the lateral as shown in Figure 1 [35]. The application rate is affected by the total flow rate (*Q*), machine speed (*V*) which related to the applied depth, and the sprinkler wetting radius (*R*). The following equations were used to calculate the application rate *P(t)*, peak application rate (P_P), time to reach the peak application rate (t_p), and the time (*T*) that the machine takes to irrigate any point of the soil inside the field fully [35]:

$$P(t) = \frac{P_p}{t_p}\sqrt{2\,t\,t_p - t^2} \quad (6)$$

$$P_p = \frac{4Q}{\pi RL} \quad (7)$$

$$t_p = \frac{R}{V} \quad (8)$$

$$T = 2t_P \quad (9)$$

Where: *P(t)* is the water application rate as a function of the time in (mm/h); t_p is the time after initial wetting that the peak application rate is reached in (h); *Pp* is the peak application rate for the elliptical pattern of the sprinkler package in (mm/h); *Q* is the total flow rate of the machine in (L/h); *R* is the wetted radius of the sprinkler in (m); *L* is the machine length in (meters); *V* is the average travel speed of the lateral in (m/h); and *T* is the time the machine takes to irrigate any point of the soil inside the field fully in (h).
The simulation tests run under the assumption of ideal weather conditions with irrigation of bare soil, and the evaporation and deep percolation losses were neglected. Every four sprinklers supposed to be grouped and fitted with electric solenoid valves to provide the variable pulse control.

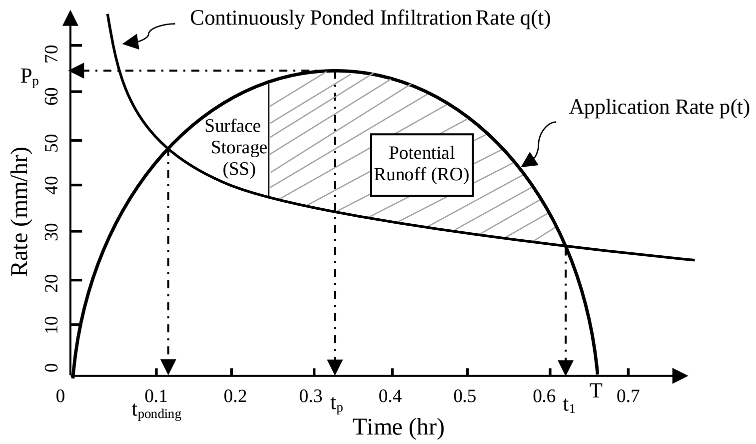

Figure 1. Application rate resulted from the overlap of individual sprinklers, adapted from [35].

3. The Variable Pulsed Irrigation Algorithm (VPIA)

The proposed variable pulsed irrigation algorithm (VPIA) based on the ON-OFF pulsing technique mainly aims to reduce the runoff losses that resulted from using the low-pressure linear move sprinkler irrigation system to irrigate different soil types while delivering the highest possible irrigation depth. Also, it aims to maintain a good uniform water distribution in the direction of the movement using the lowest number of pulses. The VPIA must determine the exact number and width of the OFF pulses that satisfy the aims of the algorithm. The selection of the number and width of the OFF pulses must balance between four critical needs: low runoff, high delivered infiltration depth, high level of distribution uniformity in the direction of movement, and a low number of OFF pulses.

3.1. The Required Data

Some factors related to the soil and the sprinkler irrigation machine must be supplied to the algorithm as an input data. According to the selected infiltration model, the soil data are the sorptivity (*S*), the constant (*A*) and the surface storage capacity (*SS*). The irrigation machine data are the total flow rate (*Q*), machine speed (*V*) which related to the applied depth, the sprinkler wetting radius (*R*), the machine length (*L*), and maximum permissible pulse range (n_{max}) and minimum time for the OFF and ON pulses (T_{OFFmin}, T_{ONmin}) that the nozzles and its plates can tolerate ensuring the safety and sustainability of the mechanical parts of the sprinklers.

3.2. Runoff Potential Estimation

The surface runoff occurs when the water application rate exceeds the soil infiltration rate [19]. The sprinkler application rate may exceed the soil infiltration rate because the latter was decreased through time due to the increase of the soil water content; at this point, the water will accumulate on the soil surface and results in ponding [35]. The water ponding starts when the application rate $p(t)$ overrides the soil infiltration rate $q(t)$ at a point of time called ($t_{ponding}$) as shown in Figure 1 [35]. The soil surface can temporarily store some of the excess water; this is called surface storage capacity (*SS*). As soon as the local surface storage (*SS*) is filled, the excess water will start to flow over the field as a runoff loss (*RO*). The potential runoff (*RO*) is represented by the dashed area as shown in Figure 1 [35].

Usually, the infiltration rate is measured using an instrument called infiltrometers, and the flooding infiltrometers type is widely used because their installation and use are easy and require less equipment [36]. The infiltration rate resulting from the use the flooding infiltrometers represents the continuously ponded infiltration rate because it is based on fixed inundation [36]. However, the water application rate for the linear-move sprinklers at a point rises and then drops instead of being constant as in the flood irrigation or stationary sprinklers [35]. Therefore, the prediction of runoff amount and ponding time will not be accurate if the continuously ponded infiltration rate curve $q(t)$ superimposed over the water application rate curve $p(t)$ of the moving sprinklers machine [37]. So, for accurate calculation of the runoff the sprinkler ponded infiltration rate $q(t-t_o)$ must be used instead of continuously ponded infiltration [37].

In our algorithm, the sprinkler ponded infiltration rate curve must be calculated to check the potential of runoff and its amount using an implicit equation that describes the infiltration rate (*q*) in terms of cumulative infiltrated depth (*I*) rather than time (*t*) as described by [37]. For further information and descriptions on the calculation of the sprinkler ponded infiltration rate and the potential runoff refer to [31, 37].

As a first stage, the speed range that generates a runoff under the linear move irrigation system must be determined. Therefore, for every speed, the sprinkler ponded infiltration rate curve is calculated, and the potential runoff (RO_S) that related to the specified soil type was determined by applying the steps described in [31, 37]. The results will be arranged in a table called the runoff potential table (RPT), as shown in Figure 2, to show at which speed the runoff starts and its amount along with the amounts of the applied irrigation depth (*dg*) and the actual infiltrated depth (*I*).

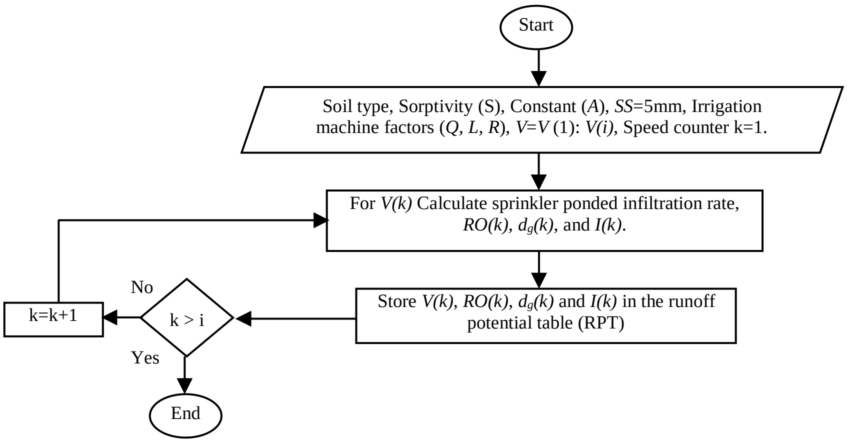

Figure 2. Flowchart for determining the runoff potentail table (RPT).

3.3. The Variable Pulsed Irrigation Algorithm (VPIA) Description

As different soil types have different infiltration rates which result in wide variation in the generated runoff (Table 1), this would necessitate different controlling of the sprinkler operating time to reduce the runoff amount to the lowest values. A VPIA was designed to ensure the delivering of an adequate irrigation depth with the lowest runoff losses using the pulsing technique. Also, the VPIA aims to assure a high level of distribution uniformity in the direction of movement which may result from using the pulsing technique. This will be achieved by finding the best number and widths of the OFF pulses that satisfy the algorithm goals, for different machine speeds and different soil types.

The VPIA must be applied when the runoff amount exceeds the allowable runoff threshold. In the VPIA, the runoff threshold is assumed to be 1% from the applied depth, which can be changed by the farmer or the irrigator to match the field and crop conditions. A graphical method was used to explain how the variable pulse algorithm work. For further detail see [31].

From the RPT, the total irrigation time (T) for the speeds that generate an unacceptable runoff must be calculated. The application rate time (T) will be divided into (n+1) equal ON pulses and (n) equal OFF pulses. The sequence of pulses starts with ON pulse and then OFF pulse alternately and ends with ON pulse. So, the suggested new shape of the application rate will be represented graphically by a pulsed application rate curve where the ON pulses represented by the dashed areas and the OFF pulses represented by the blank areas as shown in Figure 3.

According to the algorithm, the runoff will be reduced firstly by controlling the number of OFF pulses (n) by using several cases. Starting with the first case (case1) which includes the lowest number of pulses (n_{min}) that the sprinkler can endure (2 OFF pulses, suggested by the algorithm). Then continuing in the cases by increasing the number of the OFF pulses by 1, until the maximum allowable number of pulses (n_{max}) has reached (50 OFF pulses, suggested by the algorithm). Secondly by controlling the OFF pulses time (T_{OFF}) in each case. There are several steps in each case, where the number of steps is associated with T_{OFF}, starting with first step (step1) at which T_{OFF} is at its minimum value T_{OFFmin} (2 seconds suggested by the algorithm). Then the steps will be continuing by increasing the T_{OFF} by 1 second, until either the runoff amount become zero, or until the minimum allowable time of the ON pulses (T_{ONmin}) has reached. For every step in a case, the T_{OFF} will be set first; then the T_{ON} will be calculated using the following equation:

$$T=n*T_{OFF} + (n+1) *T_{ON} \tag{10}$$

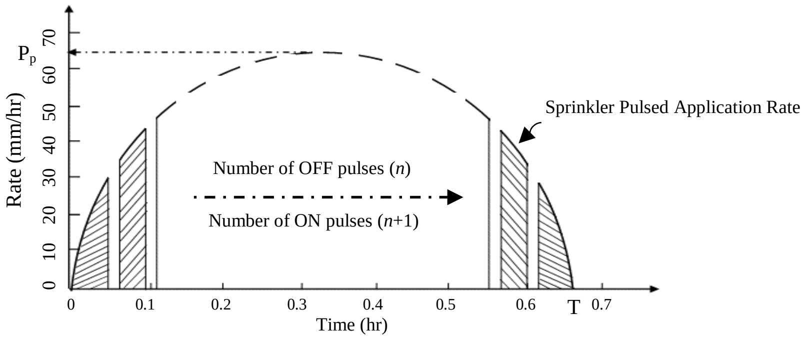

Figure 3. The suggested pulsation arrangement and its effect on the

The first stage in our algorithm is to find the nominated values of T_{ON} and T_{OFF} that gives the lowest amount of runoff at the first soil point and after that determining the runoff solution table (RST). After setting the cases numbers that match the n_{min} and n_{max} for each selected machine speed, we need to nominate the T_{OFF} and T_{ON} values that should reduce the runoff value for every case. The T_{OFF} and T_{ON} selection criterion will be based on their values that make either the runoff amount of the first soil point equal to zero or T_{OFF} will be increased to a value at which T_{ON} has reached its minimum value.

In Figure 4, the flowchart for determining the RST is described. For each case, the steps will continue by increasing the T_{OFF} by one second until satisfying one of the previous conditions, and the final values of T_{OFF} and T_{ON} will be chosen as the best solution for this case. In every step, *I(t)* and *RO* will be calculated by following the procedure described in [31, 37], and by considering the pulsing effect on the infiltration rate and taking into account the surface storage capacity. The *I(t)* and *RO* that resulted from the final T_{ON} and T_{OFF} for each case will be stored in the RST as well.

According to VPIA, the sprinklers spray pattern will be altered to the suggested new pattern as shown in Figure 3. Due to the spatial differences between the successive soil points in the direction of movement, each point will receive a spray pattern that shifted and differs in shape from the spray pattern received by the first point. Therefore, these differences in the spray pattern will affect the water distribution uniformity especially for the successive points in the direction of the machine movement. Since, the results listed in RST represent the best solutions of *n*, T_{OFF} and T_{ON} for the first soil point (X_1), another test must be carried out to check the distribution uniformity and the runoff potential for the successive points (X_2: X_i) when applying each solution from this table to the successive test points.

Figure 5 shows the flow chart for determining the uniformity check table (UCT) which will give us an indication of the level of uniformity after applying each of the solutions listed in RST. To perform the uniformity check, several hypothetical test points Xi should be distributed in one line parallel to the direction of the machine movement. The pulsed application pattern that resulted from every case solution listed in the RST will be applied to the successive test points after reshaping it to match the effect of the time delay between the test points. The amount of $I_i(t)$ and RO_i for each test point must be calculated and listed in the UCT. Also, the values of RO_i and the $I_i(t)$ for all the test points will be averaged and listed in the UCT as well. Therefore, the UCT will give us an indication about the level of uniformity for all the suggested solutions listed in the RST.

The final stage in the VPIA is to select a unique solution among all the solutions listed in the UCT for each speed to achieve algorithm goals. The UCT will be copied to a new table called the solution table (ST) to be used for applying the selection criteria. Therefore, multiple criteria will be applied to identify this unique solution, where each of these criteria must meet one of the algorithm's objectives as follows:

1. To achieve the main objective of reducing runoff losses, cases, where the amount of runoff at any test point is higher than the acceptable threshold, will be excluded from the ST. In VPIA, the runoff threshold was set at 1% from the applied depth. This threshold can be adjusted or changed by the farmer or the irrigator.
2. For the remaining cases from the first criterion, to assure a high degree of distribution uniformity in the direction of movement, cases, where the variance in the infiltration depths between its steps is higher than the accepted threshold will be excluded from the ST. In VPIA, the allowable

variance was set at 1% from the applied depth. This threshold can be adjusted or changed by the farmer or the irrigator as it depends on the desired level of uniformity.

3. The remaining cases after applying the two-previous criterion will be rearranged according to their infiltration depth in descending order. Therefore, the case with the highest infiltration depth will be the first in the ST. To ensure delivering a high infiltration depth, cases with infiltration depth below 1% from the highest infiltration depth, will be excluded from the ST.
4. To reduce wear and tear in sprinklers and valves, reduce maintenance costs, and extend the life of the sprinklers and valves, the case with the lowest number of pulses between the cases resulting from the application of the third criterion will be selected as the best unique solution for the specified speed.

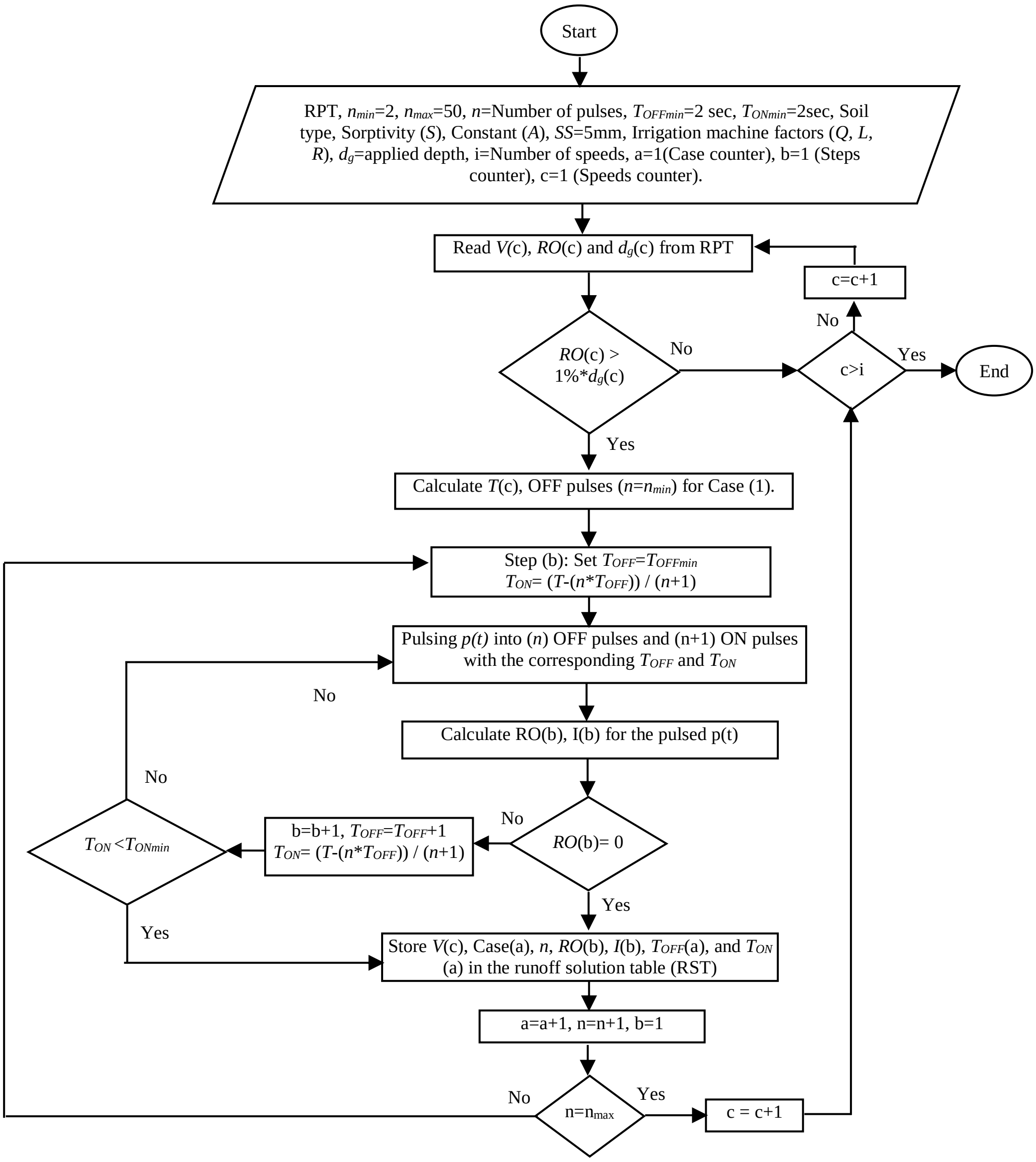

Figure 4. Flowchart for determining the runoff solution table (RST).

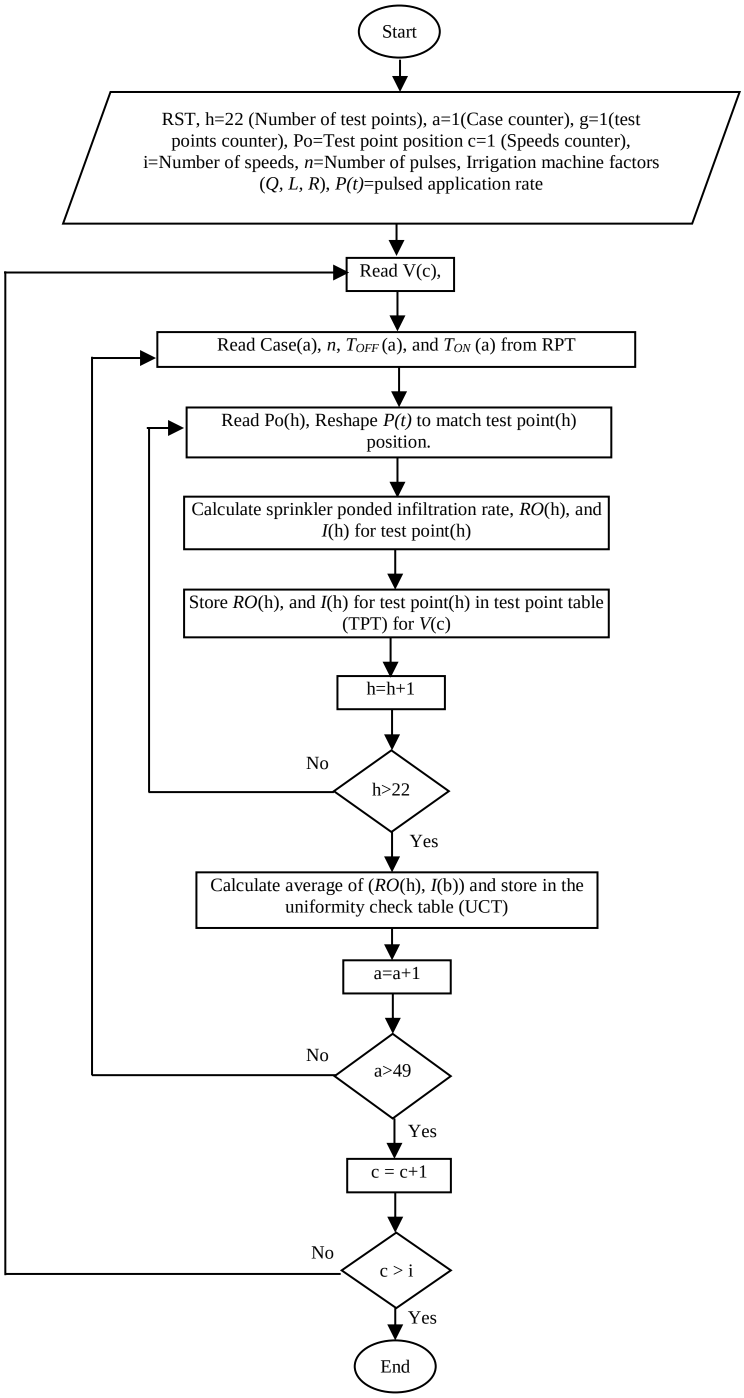

Figure 5. Flowchart for determining the uniformity check table (UCT).

4. Simulation Results

To examine the performance of the proposed algorithm, we simulate the soil infiltration rate and the application rate before and after pulsing using a code written in MATLAB software. The MATLAB code was written to apply the VPIA on the selected sprinkler system described in table 2, to irrigate a three different soil types Loamy Sand, Sandy Loam and Loam. Since the sprinkler irrigation machine has a range of speeds, the algorithm will be applied for the speeds at which the runoff exceeds the allowable threshold. The runoff threshold is set to 1% from the applied depth in our algorithm. Therefore, the supplied irrigation depth (d_g) along with the runoff loss (*ROs*) and the infiltration depth

(*I*) of each soil type for the speed range of the used irrigation machine are calculated and listed in the runoff potential table (RPT) as shown in Table 2.

From the RPT it seems that for the three soils, the runoff starts at different speed ranges when applying different irrigation depths due to the difference in the infiltration rate of each soil. Therefore, the VPIA will be applied to all the speeds that have resulted in an amount of runoff exceeds the threshold for every soil type individually.

Working on the first soil type (Loamy Sand) as an example of how the VPIA is applied. The speed of 20 m/h to apply 25 mm irrigation depth is the first speed at which the runoff is exceeding the threshold (0.68mm > threshold (0.25mm)). The total time (*T*) that the machine needs to irrigate any single point of the soil at this speed is (*T*=936 seconds). Therefore, the application rate will be pulsed within this time using several pulsing cases. Starting with the first case (Case1) at which the application rate will be pulsed with 2 OFF pulses and 3 ON pulses. In each case a wide range of steps with different pulses widths will be tested, where the time of the OFF pulses will start from (T_{OFF}=2 seconds) as a first step. Then the steps will continue by increasing the time of the OFF pulses by one second for each next step until the runoff equal to zero or the minimum allowable ON time (T_{ONmin}) is reached. Considering that all these calculations are made to the first test point (X_1). Also, the amount of surface storage capacity (*SS*=5mm) is considered when calculating the surface runoff and the infiltration depth. The results of case1 with *n*=2 and for the 20 m/hr speed are shown in Table 3.

Table 2. Runoff potential table (RPT)

Machine speed (*V*) m/h	Applied Depth (d_g) mm	Loamy Sand		Sandy Loam		Loam	
		Runoff (*ROs*) mm	Infiltrated depth (*I*) mm	Runoff (*ROs*) mm	Infiltrated depth (*I*) mm	Runoff (*ROs*) mm	Infiltrated depth (*I*) mm
166	3	0	3	0	3	0	3
108	4.5	0	4.5	0	4.5	0	4.5
100	5	0	5	0	5	0	5
83	6	0	6	0	6.1	0	6.1
58	8.5	0	8.5	0	8.6	0	8.6
50	10	0	10	0	10	0	10
42	12	0	12	0	12	1.54	10.46
33	15	0	15	0	15	3.83	11.17
25	20	0	20	1.55	18.45	7.79	12.21
20	25	0.68	24.32	4.65	20.35	11.85	13.15
17	30	3.26	26.74	7.92	22.08	16	14
15	33	4.88	28.12	9.95	23.05	18.53	14.47

From Table 3, it is shown that for Case 1, it takes 13 steps to get a zero runoff with T_{OFF}= 14 sec, T_{ON}=296 sec, and infiltrated depth I_1= 24.10mm as the best solution for this case. In our algorithm, we suggested that the maximum allowed number of OFF pulses is 50 pulses, which the user can change to match the sprinkler and nozzle specifications. Therefore, the same calculations will be repeated for all other 48 cases, and the results of all the solutions that give zero runoff will be listed in the RST.

The solutions listed in the RST represents the best solutions for different cases with different pulses numbers that give zero runoff for the first test point (X_1). Therefore, the next stage in the algorithm is to check the runoff and the distribution uniformity when applying the new pulsed application rate of each of these solutions to the successive points in the direction of movement.

Several hypothetical test points must be used to check the runoff losses and the distribution uniformity in the direction of movement. The number of the test points and the distance between them depends on the sprinkler wetting diameter and the aimed level of accuracy for the calculations. According to the sprinkler wetting diameter (5.2 m) of the used system, 22 test points (X_1: X_{22}) are suggested to be used and placed in one line in the direction of movement. These points are spaced 0.25

meter apart along the line, except the last point will be placed at 0.2 m distance from the previous point to match the width of the wetting diameter.

Starting with the first solution of Case1 that listed in the RST (Number of OFF pulses=2, T_{OFF}= 14 sec, T_{ON}=296 sec), the runoffs and infiltration depths will be calculated for all other 21 test points after applying the new and shifted pulsed application rate. The new results of the runoffs and infiltration depths for all the test points are shown in Figure 6- A&B and must be stored in a new table. The average value of runoffs and depths for the test points will be calculated and listed in the same table. The same calculations will be applied for all the cases listed in RST, and the results of the average runoffs and average depths for the test points will be calculated and listed in the UCT. The new results of the average runoffs and the average infiltration depths for all the cases points are shown in Figure 7- A&B.

Table 3. The runoff and infiltration depth of first test point for Case1 with speed of 20 m/h for Loamy Sand soil.

Step Number	T_{ON} (sec)	T_{OFF} (sec)	Infiltrated Depth after pulsing (mm)	Runoff after Pulsing (*ROa*) (mm)
Step 1	304	2	24.32	0.59
Step 2	303.33	3	24.31	0.54
Step 3	302.67	4	24.27	0.51
Step 4	302	5	24.26	0.43
Step 5	301.33	6	24.24	0.38
Step 6	300.67	7	24.23	0.36
Step 7	300	8	24.21	0.28
Step 8	299.33	9	24.20	0.23
Step 9	298.67	10	24.18	0.21
Step 10	298	11	24.17	0.13
Step 11	297.33	12	24.15	0.08
Step 12	296.67	13	24.14	0.06
Step 13	296	14	24.10	0

The final stage of the VPIA is to apply the selection criteria to choose one unique solution among the solutions listed in the ST for the selected speed of 20m/hr. By applying the first criterion, the following cases will be excluded because they have a runoff that higher than 0.25 mm in one or more of their test points, (Case1, Case2, Case3). All the remaining cases after applying the first criterion are passed the second criterion of the distribution uniformity, which means that the difference between the highest and lowest infiltration depths for the test points of all the cases are within the threshold of 0.25 mm. The remaining cases will be sorted after applying the previous two criteria according to the infiltration depth in descending order. Since Case6 has the highest infiltration depth of (24.176mm), it will be the first case in the new list. To apply the third criterion, the new infiltration depth threshold will be set at 1% lower than the highest depth of (24.176mm), which become (23.934mm). Therefore, all cases that have an infiltration depth lower than (23.934mm) will be excluded. All the remaining solutions in the ST are good solutions that gives low runoff and good and accepted uniform depth along the direction of movement for the Loamy Sand soil. However, we must select only one solution among these solutions. Therefore, to select a unique solution among all these solutions, the fourth criterion will be applied by selecting the case with lowest pulses number, which will be Case4 with the following factors: (number of OFF pulses: 5 pulses, T_{ON}=147.67sec, T_{OFF}=6 sec). Therefore, for the selected speed of 20m/h, when applying Case4 factors to generate the pulsed application rate, the new average runoff will have decreased from 0.68mm to 0.056 mm, while the new average delivered infiltration depth will be decreased from 24.32mm to 24.134mm.

The VPIA procedure will be applied to all the speeds that generate a runoff higher than the threshold values for all the soil types.

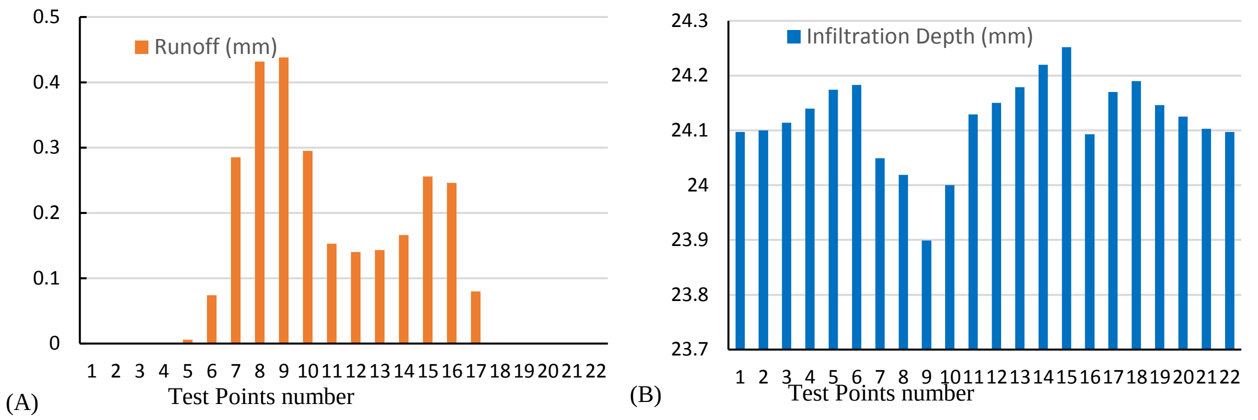

Figure 6. The runoffs and infiltration depths for all the test points after applying the best solution of Case1

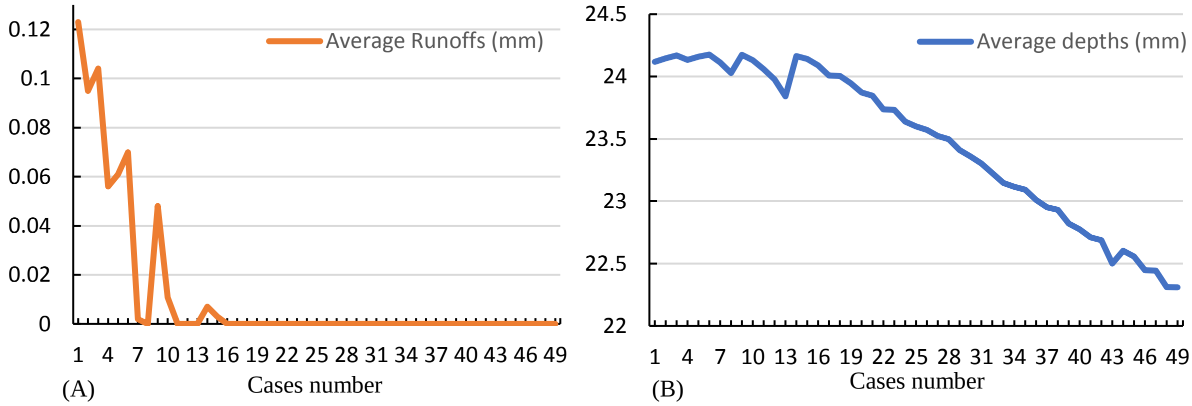

Figure 7. The avarage runoffs and the avarage infiltration depths for all the test points after applying the best solution of all the Cases

5. Discussion

According to the VPIA, the runoff reduction is controlled by the number and the width of the OFF pulses within the total time (T). Regarding the results listed in Table 3 for the first test point, Figure 8-A shows that for Case1 which includes 2 OFF pulses, the runoff is reduced by gradually increasing the width of the OFF pulses till it reaches zero value. However, the infiltration depth for the same point will decrease because of increasing the width of the OFF pulses as shown in Figure 8-B. Therefore, the OFF pulses will have a significant impact on reducing the runoff loses, because first, it reduces the amount of the supplied water and secondly, it gives extra time for the surface water (accumulated water over the soil surface) to infiltrate into the soil. However, a sort of balance between the amount of surface runoff and the infiltration depth within the accepted limits must be achieved by selecting the appropriate number and width of the OFF pulses.

According to the results shown in Figures 6-A&B, it is obvious that the solution of case1 is not a good solution because it causes an undesirable amount of runoff (> 0.25mm) in several of the test points even if it gives zero runoff for the others. Also, this solution has led to the unequal distribution of water for the successive test points. Therefore, we must try other cases solutions by increasing the number of OFF pulses and repeat the same procedures. Finally, we must choose one of all the solutions that satisfy the selection criteria.

The final solutions for the different machine speeds show that our proposed algorithm has reduced the runoff amount for at least 91.76% for Loamy sand, 90.7% for Sandy Loam, and 97.79% for Loam soils as compared to the non-pulsed continuous application rate. Moreover, it completely eliminates the runoff resulted of some machine speeds and for the different soil type. The final tables that contain the best solutions for the speed ranges and every soil type will be considered as look-up tables (i.e. for every machine speed the computer can directly pick the solution that gives the best results from these tables).

Figure 9 shows a comparison between the average infiltration depth before pulsing (*Ib*) and after pulsing (*Ia*) for different irrigation machine speeds and all the soil types. Although the delivered average irrigation depth using the VPIA is slightly decreased compared with the normal continuous application rate, the VPIA achieved the delivery of an acceptable high irrigation depth with very low runoff losses. Figure 10 shows a comparison between the runoff before pulsing (*ROb*) and after pulsing (*RO*a) for different irrigation machine speeds and all the soil types. The results also show that the proposed VPIA maintain a high uniform distribution of water in the direction of movement. The uniformity of water distribution and the runoff have a direct impact on crop growth, crop yield, soil and water resources sustainability. Therefore, the VPIA allows the irrigator or the farmer to specify the threshold for the accepted runoff and the level of uniformity according to their experiences about the impact of these factors on the crop growth and resources sustainability.

6. Conclusion

The proposed VPIA to reduce runoff losses under low-pressure lateral-move sprinkler irrigation machine was evaluated using a MATLAB simulation code. The simulation results demonstrated that the VPIA is efficient in reducing the runoff losses while delivering a high irrigation depth with a high level of distribution uniformity with lowest pulse numbers for different soil types. The results show a runoff reduction of at least 91.76% for Loamy sand, 90.7% for Sandy Loam, and 97.79% for Loam soils as compared with the continuous application rate. From the runoff potential table (RPT), it is shown that the runoff losses under the low-pressure linear move system can reach more than 50% of the applied water for the soils with low infiltration rate such as the Loam soil. Therefore, reducing runoff losses will have a significant impact on the conservation of irrigation water, and minimizing the negative impacts of runoff on crops, soil and the environment. Also, the results revealed that the number and width of the OFF pulses and their location within the total time (*T*) of the application rate, have a significant impact on the amount of runoff and the uniformity of water distribution in the direction of movement. Thus, the selection of the number and width of the OFF pulses and their distribution within the total time (*T*) according to the proposed algorithm, rather than assigning the OFF pulses with a specific percentage from a fixed cycle time (as other researchers have done), has led to reducing the runoff to a low values and obtaining a high level of distribution uniformity.

The results proved that VPIA can be applied to different types of soil and can reduce surface runoff losses regardless of their size while delivering an acceptable irrigation depth with high distribution uniformity. Also, the results show that for the soils with low infiltration rate, the application rate should be pulsed with a high number and large width of OFF pulses to reduce the runoff loses compared with the soils with high infiltration rate. Overall, the evaluation proved the VPIA had provided a consistent manner in selecting the pulse numbers and widths to achieve the desired irrigation depth with very low runoff losses under the low- pressure linear move irrigation machine. Thus, this method can be considered as a new method in terms of selecting the width and number of pulses compared to the rest of the research and studies in this field. This paper represents the basic step in our research, and the work is proceeding in testing the proposed algorithm to apply variable rate irrigation and investigate its impact on delivering low irrigation depth while achieving a high distribution uniformity.

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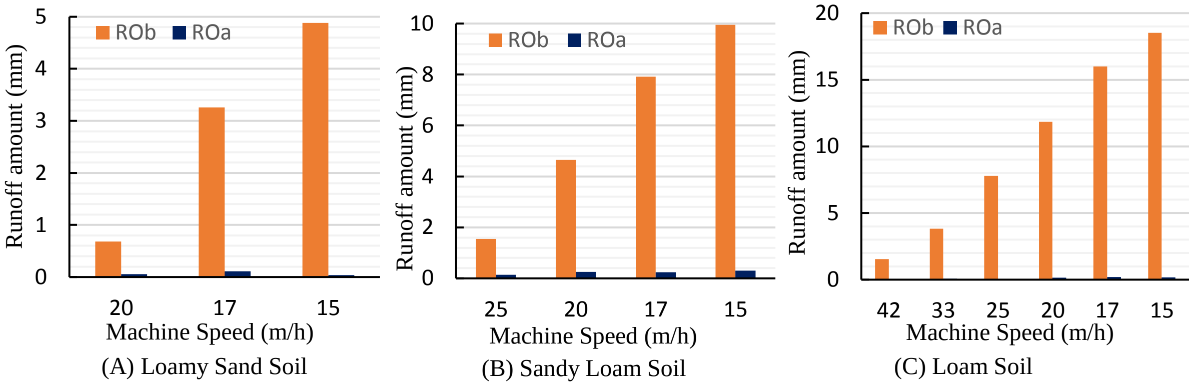

Figure 8. Runoff before pulsing (*ROb*) versus runoff after pulsing (*ROa*) for different soil types.

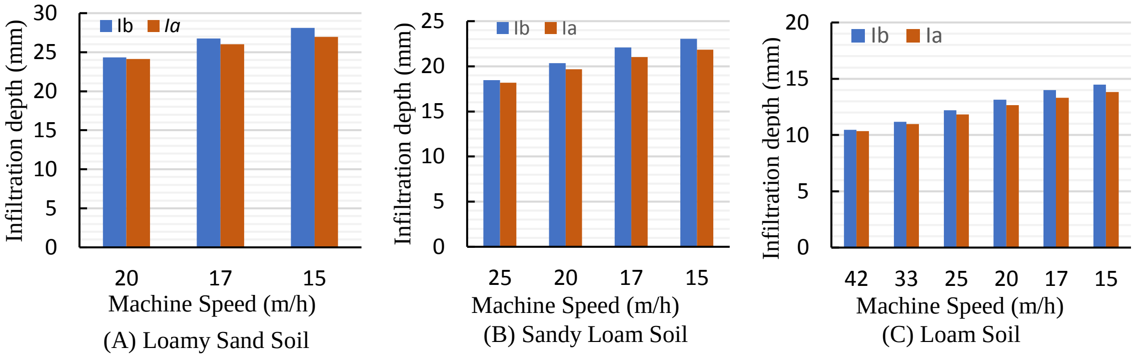

Figure 9. Infiltration depth before pulsing (*Ib*) versus Infiltration depth after pulsing (*Ia*) for different soil types.

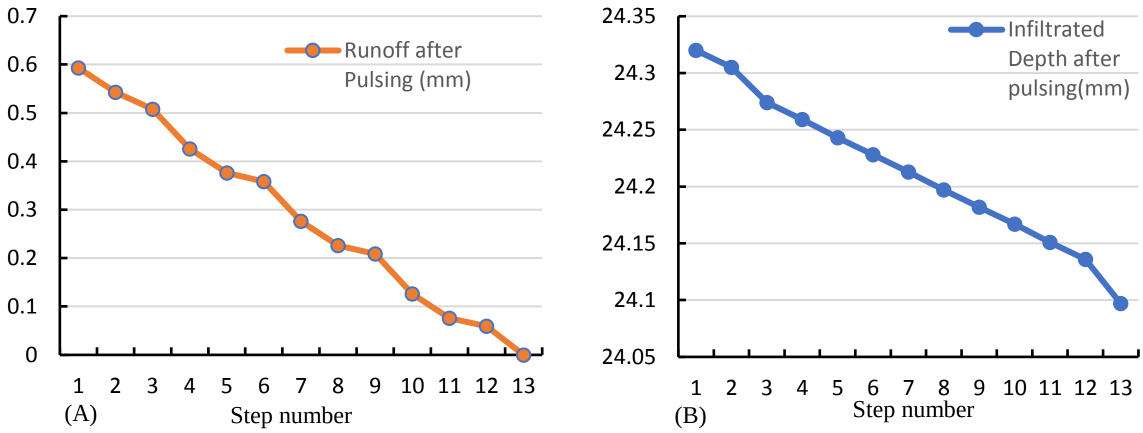

Figure 10. Infiltration depths and Runoffs values after applying case1 solution to the sucessive test points.

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