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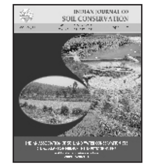

Hydrodynamic evaluation of irrigation efficiency through raingun sprinkling

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ABSTRACT

High pressure sprinkling in overlapping wetting circle geometry was attempted with rain-gun sprinklers. Discharges and radii of throw in tandem with frictional head losses along the pressurized flow grid were calibrated for different operating pressure heads. For a square grid overlapping of four wetting circles, the total depth of water received in the overlapped zone was mathematically modeled. The deviations of on-field observations using catch cans with a grid square of 5 x 5 m were analyzed and the water distribution uniformity was computed. For this impulse of water distribution uniformity, the responses in terms of the sub-soil moisture storage, application and distribution efficiencies were determined. Rain-gun sprinkling has been found to be relatively more efficient (CU >72%) than the conventional sprinkling for given soil, crop and field conditions. The performance evaluation of rain-gun system showed that the water was applied with moderate uniformity with a low pressure (1.5 kg cm^{-2}) pump. The results showed that the uniformity of application was increased by around 7.3% and 6.87% by giving 50% overlapping by another full-circle and half-circle rain-gun sprinkler, respectively. The soil moisture distribution efficiency was found to be around 81% within the effective root zone after irrigation. The study also suggested that in case the rain-gun irrigation system was operated with low HP pumping system, efficient water application and uniformity could be achieved only with sufficient overlapping network.

1. INTRODUCTION

The traditional field irrigation methods are susceptible to the inevitable losses of water by way of deep percolation beyond the effective root zone of a crop or by way of runoff. Due to these losses, the water application efficiency gets drastically reduced to the tune of 60-75% (Burton, 2016; Kumar *et al.*, 2012; Parhi, 2017 and Mohanty *et al.*, 2016). If the field topography is uneven or the source of irrigation is at a lower elevation than the fields, gravitational system becomes infeasible and impractical. Besides, the gravity system layouts warrant expensive land leveling and grading operations in forming water application bays such as check basins, furrows or borders. Such situations warrant the usage of pressurized irrigation systems. The basic premise of such pressure irrigation systems is to achieve high water application efficiencies. Micro irrigation systems offer many advantages over the traditional gravity systems of irrigation. Even as these systems are becoming more and more popular, certain constraints such as the initial high investments and certain operative and maintenance difficulties have made the farming community a bit reluctant to switch over from the traditional system. These systems are unquestionably the effective means in saving irrigation water by more than 40% (Ali, 2011).

However, the operational efficiencies of these systems depend on the hydraulic parameters such as the operating pressure heads, discharges and the frictional head losses along the flow throughout the system. Pressure and discharge compensation mechanisms have been frequently evolved on modifications and improvements, which are incorporated in the design (Panigrahi *et al.*, 2011 and Paul *et al.*, 2013).

Sprinkler systems aim at the coverage of a number of plants at a time, by way of simulating a sort of rainfall in the form of a fine, conical spray of water with its own circle in accordance with the operating pressure heads. But the sprinkler systems are relatively high pressure systems requiring a minimum of 2.5 kg cm^{-2} for operation (Hoffman, 2007). Rain-gun irrigation is an improvement over the traditional rotating head sprinkler system requiring still higher operating pressure heads to the tune of 4-8 kg cm^{-2}, such that the radius of throw will be greater and the aerial coverage is more compared to the standard sprinkling systems (Ahmad, 2000). However, many farmers are reluctant to switch over to rain-gun or any other high capacity system requirements. Moreover, these systems should also be evaluated for their performance efficiencies with particular reference to the irrigation application and water usage efficiencies for different soil and crop environments. In this context, the performance of a rain-gun sprinkler unit was tested in the experimental fields of Tamil Nadu Agricultural University, Coimbatore.

The operating pressure heads and the head loss due to friction along the system govern the sprinkler discharge and the corresponding wetting circle radii. High degree of uniformity of application is possible only when the individual wetting circles are made to overlap in view of compensating for the water deficits at the extreme 1/3rd of the wetting circle. In a study conducted in Pakistan it was found that water used under rain-gun sprinkler was 26% less than the water used with border irrigation method (Waheed-uz *et al.*, 2000). Anwar *et al.* (2004) reported that the application efficiency of rain-gun sprinkler system varied from 88 to 78% during the whole season which is higher than the border irrigation. At the same time, the crop yield under rain-gun sprinkler was 31% higher than with border irrigation method. Shauq (2003) showed that the rain-gun is effective for irrigation when wind speed is not more than 7 km h^{-1}. Bhagyawant *et al.* (2007) observed that in rain-gun irrigation, uniformity coefficients were 73.36%, 76.52% and 79.54% at operating pressures of 2.0, 3.0 and 4.0 kg cm^{-2}, respectively.

Rana *et al*. (2006) found that the use of rain-gun sprinkler irrigation during early crop season helped in saving water as the soil infiltration rate at that time was very high and need of water in the root zone was less. It was observed that nitrate-nitrogen leaching was low with 50 mm depth of irrigation by rain-gun sprinkler irrigation as compared to 75 mm depth of irrigation by basin and furrow irrigation system. They also found that yield was about 5.64% and 1.71% more in rain-gun sprinkler irrigation system as compared to basin and furrow irrigation systems, respectively. However, Mostafa and Derbala (2013) reported the corn total yields obtained from different treatments as 25.76, 24.23 and 9.30 Mg ha^{-1} in drip, rain-gun and rainfed irrigated maize, respectively. Sasayama *et al*. (2007) evaluated the efficiency of sprinkler spray systems installed with rain-gun and found that the adjustment of spray area is easy in this method and thus irrigation in remote separate orchards is possible. They also observed that the time of spray could be reduced to a significant extent.

The hydrodynamics of rain-gun irrigation is the same as the traditional sprinkler system and the water distribution uniformity depends on the operating pressure head and the technical design dimensions of the sprinkling unit (Knox *et al*., 2007). Observations done by Dukes *et al*. (2006) showed that the individual spray cones of water applied had maximum depth of water at the centre with gradual reduction as the radial distance from the sprinkler increases. In order to achieve high levels of uniformity all over the field, the wetting circles need to be overlapped. With the help of advanced technology, automated irrigation control systems can be designed considering the theoretical aspects and mathematical model for water application and wetting pattern. Suresh *et al.* (2014) designed a GSM based automatic irrigation scheduling system for rain-gun irrigation. They also reported that the rain-gun irrigation system saved more than 50% of the water used by flood irrigation system and electricity. To improve upon the water distribution efficiency by rain-gun system and study the pressure impulse on discharge-wetting circle response under this system, this study was undertaken and salient results are described herein.

2. MATERIALS AND METHODS

The performance efficiency of a pressure system of irrigation, irrespective of whether it is a drip system or a sprinkler system, depends on the manipulation of the hydraulic gradients by suitable pressure compensating mechanisms. The methodology for evaluation normally comprises the development of a conceptual and mathematical model followed by the validation of the model to arrive at the condition specific or system specific parameters. Accordingly, a conceptual mathematical model for rain-gun sprinkler was developed which is compatible with the design requirements as given below:

If a sprinkler is rotated at a uniform speed in perfectly still air, the resulting pattern will be symmetrical about the centre. The depth of water at any point resulting from a set of sprinklers was calculated as given below:

If q is the average discharge from each sprinkler, then total volume of water, Q, delivered by each sprinkler within the time, t, is given by:

$$Q = qt \qquad ...(1)$$

The water spreads over the surface and sub-surface soil around the sprinkler in the form of a cone whose volume equals $1/3 \prod R^2 h$ where R is the radius of spray of the sprinkler and h is the maximum depth of water application likely to occur at the centre.

Let h_p = depth of water received at point p and r = radius of spray at point p.

So by the principle of similarity:

$$h/R = h_p/R\text{-}r$$

$$h_p = h(R-r)/R \qquad ...(2)$$

Considering the spray cone realized over the given duration of irrigation, the volume of the spray cone yields the volume of water delivered.

$$v = 1/3 \prod R^2 h \qquad ...(3)$$

Then by volume balance, equation (1) and (3) can be equated:

$$qt = 1/3 \prod R^2 h$$

$$h = 3qt/\prod R^2 \qquad ...(4)$$

Substitute the same in eq. (2):

$$h_p = 3qt(R-r)/\prod R^3 \qquad ...(5)$$

If the value of q bears a relationship with the operating pressure head H, then $q = f(H) = \alpha H^{\beta}$, where α and $^{\beta}$ are coefficients *i.e.* from the operating pressure head, the discharge can be derived.

The theoretical value of β is 0.5 since $q \, \alpha \sqrt{H}$ or $v = \sqrt{2gH}$, where, v = velocity head.

In case two overlapping sprinklers, the spray pattern and water distribution varies. Considering a point 'p' in overlapped area:

Let Δh_1 is the depth of water contributed by the first sprinkler and Δh_2 by the second sprinkler, so that the depth of water delivered at point p is given by:

$$h_p = \Delta h_1 + \Delta h_2 \qquad ...(6)$$

From eq. (5), we have:

$$h_p = 3qt[(R-r_1)+(R-r_2)]/\prod R^3 = 3qt[(2R-(r_1+r_2)]/\prod R \qquad ...(7)$$

Where, r_1 and r_2 are radii of first and second sprinkler, respectively.

If more numbers of sprinklers are made to overlap for contributing water at a point p, then this equation can be generalized as:

$$h_p = 3qt[(nR-\Sigma r_i)]/\prod R^3 (i=1,n) \qquad ...(8)$$

Subsequently, a conceptual model for a segmental layout with overlapping of four sprinkler guns was also evolved, as depicted below:

Let L be the spacing between the laterals and S be the spacing between sprinklers along the laterals. Consider a point p in the completely overlapped zone by the four wetting circles. For the scale of convenience, express the dimensional characteristics of other sprinkler with respect to the first sprinkler S_1. Let r_1 be the radial distance of p from sprinkler 1 at an angle of orientation θ.

Let r_2, r_3 and r_4 be the respective radial distance from the sprinklers.

$$r_2^2 = r_1^2 \sin^2\theta + (s - r_1 \cos\theta)^2$$

$$r_2 = [(s^2 + r_1^2(\sin^2\theta + \cos^2\theta) - 2 s r_1 \cos\theta)]^{1/2} = [(s^2 + r_1^2 - 2 s r_1 \cos\theta)]^{1/2} \qquad ...(9)$$

Similarly, $r_3 = [(L - r_1 \sin\theta)^2 + (s - r_1 \cos\theta)^2]^{1/2}$

$$= [L^2 + s^2 + r_1^2 - 2r_1(L \sin\theta + S \cos\theta)]^{1/2} \qquad ...(10)$$

$$r_4=[L^2+r_1^2-2L\,r_1\sin\theta]^{½} \qquad ...(11)$$

Hence, the values of r_2, r_3 and r_4 can be reckoned in terms of the reference radial distance r_1, the reference angle of orientation θ and the given spacing L and S. These values can be substituted in equation (8) to calculate the total depth of water delivered at p by all four sprinklers.

A rain-gun irrigation system was installed at the experimental field of Agricultural Engineering College and Research Institute, TNAU, Coimbatore having an area of area 1600 m^2 (Fig. 1). The size of the plot was 40 x 40 m and 64 grids of size 5 x 5 m were demarcated using pegs and nylon ropes. Catch cans of diameter 0.12 cm and volume 1 litre were placed on all the four corners of each grid. The rain-gun sprinkler was operated for 10 minutes for each of the experiment and the water collected in each catch can was measured at the end of each run of experiment using a measuring cylinder. Five minutes after the stoppage of the sprinkler operation, soil samples were collected using auger from depths of 15, 30, 45 and 60 cm apart from surface soil samples.

The experiment was repeated for three times and also with two full circle and half circle rain-gun sprinklers with 50% overlapping. For obtaining 50% overlapping, the rain-gun sprinklers were kept at a distance of 20 m from each other.

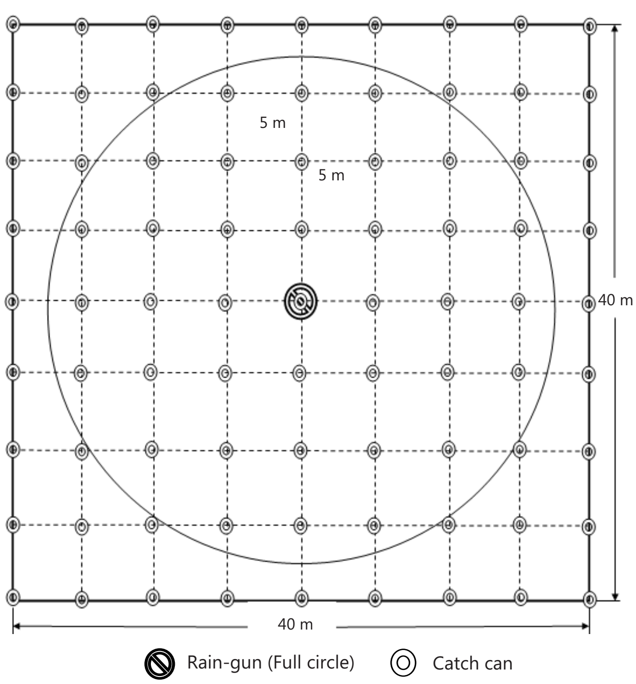


Fig. 1. Layout of the system

The system was evaluated for its performance on pressure discharge relationship and uniformity co-efficient. The detail specifications of the rain-gun used in the present study are shown in Table 1. The performance indicators, CV, the coefficient of variation and Christiansen (1942) coefficient of uniformity (CU) were determined (Knox *et al.*, 2007). While coefficient of variation, CV is defined as the ratio between the standard deviation of the sample and the average of the sample, the CU is given as follows:

$$CU = 100\%(1-\Sigma x/mn) \qquad ...(12)$$

Where, Σx is the sum of the absolute deviations from the mean (mm or ml) of all the observations, m is the mean application depth measured (mm or ml), and n is the number of observations (catch-cans).

3. RESULTS AND DISCUSSION

The maximum operating pressure head that could be generated with the available centrifugal pump of 1.5 HP was only 2 kg cm^{-2} with an effective radius of throw 17.5 m for one rain-gun. The water distribution pattern from an individual rain-gun sprinkler was studied and it was observed that a fine conical spray of water was delivered by the rain-gun sprinkler head, delivering the maximum depth of water at the centre of the cone with gradual decrease in the depth of water from the centre to the circumferences. The theoretical analysis pertaining to water distribution pattern from an individual rain-gun sprinkler also implied the same pattern.

Every sprinkler had its own wetting circle within which a fine spray cone of water was delivered, when the sprinkler is in operation. The accuracy of water application was verified by comparing the uniformity coefficients. Even if these sprinklers were positioned with designed row to row as well as sprinkler to sprinkler

Table: 1
Specifications of rain-gun sprinkler

S.No.	Particulars	Specifications
1	Model	Jain Komet 162
2	Nozzle size	10 mm
3	Rotating angle	3600
4	Trajectory angle	240
5	Maximum pressure	5 kg cm^{-2}
6	Maximum discharge	2.98 L s^{-1}
7	Maximum Radius of throw	28.5 m
8	Maximum application rate	0.43 cm h^{-1}

spacing, uniform wetting circles could never be created. The reason was that the operating pressure head established at the inlet of the system during pumping gets gradually reduced owing to flow turbulence associated with frictional head losses. Since the discharge delivered by a sprinkler was proportional to the square root of the operating pressure head, the hydraulic gradient created along the flow path tends to reduce the corresponding discharges from individual sprinklers in accordance with their distance and locations from the pumping unit.

The entire filed was divided into grids and catch cans were placed on square grid of 5 x 5 m. The depths of water collected in the catch cans were measured and contours for different depths of water collected were obtained using *Surfer* software package. From Fig. 2, it could be seen that the maximum depth of water got precipitated within an effective radius of 10 m. For the rest of the portion, non-uniformity in distribution could be observed and the distortion in the concentric contours was naturally due to the wind conditions prevailing at the time of observation. The water distribution contours of half circle rain-gun sprinkler are depicted in Fig. 3, which also shows similar results within its wetting half circle.

The 3- Dimensional depiction of the depths of precipitation clearly indicates more concentration of precipitation in the vicinity of the sprinkler. As the radial distance increases, the depths of water delivered tends to be zero. In order to compensate the water deficits within the wetting circles, the

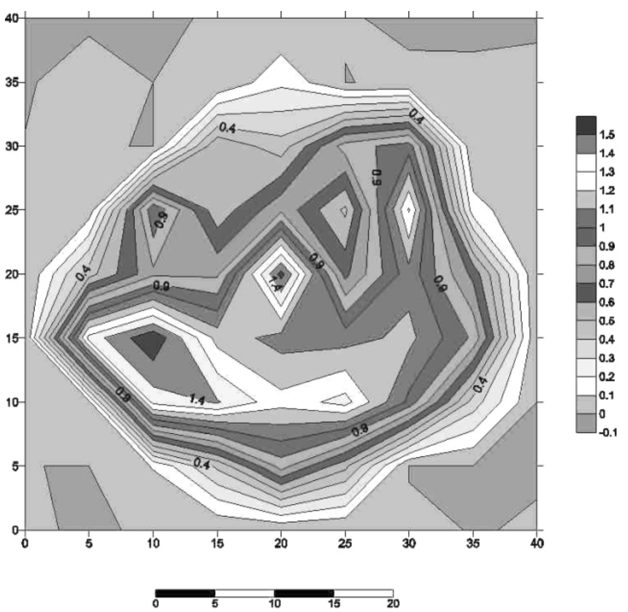
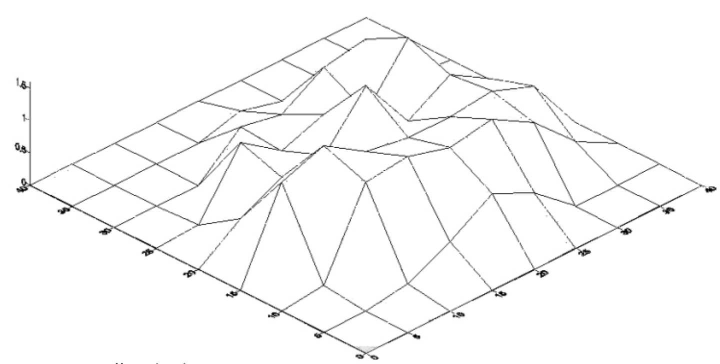



Fig. 2. Water distribution contours of rain-gun komet sprinkler-full circle

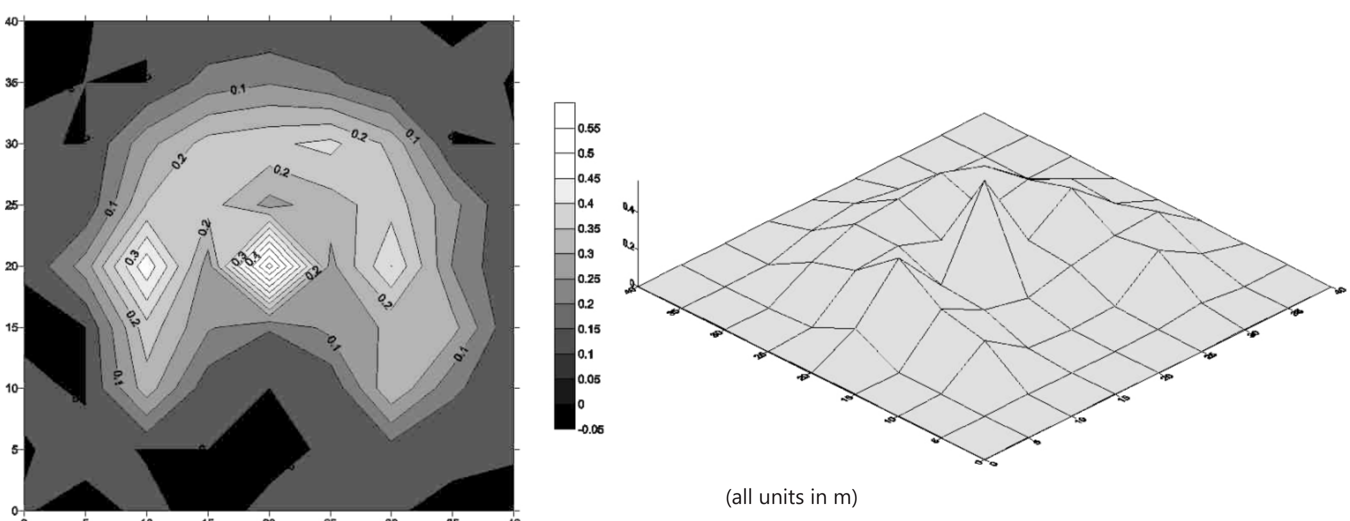


Fig. 3. Water distribution contours of rain-gun komet sprinkler-half circle

sprinklers need to be spaced in such a way that the wetting circles intersect with each other thereby compensating the deficits of water related to the surrounding sprinklers.

From Table 2, it could be seen that the coefficient of uniformity is approximately 65% for both half and full cycle sprinklers with a standard deviation of nearly 0.5. Similarly, coefficient of variation is also found to be very high, which is due to uneven distribution of water droplets. It is more obvious (82.61%) in half-circle sprinklers without overlapping, where water droplets had not reached to the farthest ends. However, the CV value drops to 69.31% with 50% overlapping. This clearly suggests that the uniformity of application can be improved only by way of providing overlapping of the wetting circles of the surrounding sprinklers. The overlapping rain-guns in turn contributes to the deficit areas of the given sprinkler. Repositioning the same sprinkler at the desired overlapping (suitably adjusting the spacing between the sprinklers at a distance equal to the radius of throw itself), it was possible to improve upon this uniformity up to 72%, both in the cases of full and half-circle rain-gun sprinklers. Maroufpoor *et al.* (2010) estimated Christiansen Uniformity coefficient of only 66.5% for sprinkler irrigation systems under different field conditions in Kurdistan Province of Northwest of Iran. He also suggested an overlapping network of four sprinklers would increase the CU by 10-15%. The results of the present study also showed matching results with almost 7% increase in the CU with an overlapping network of two rain-gun sprinklers. The water distribution pattern of two overlapped sprinklers is depicted in Fig. 4. Similar results were obtained in case of half circle rain-gun irrigation system too, as shown in Table 2.

However, it was observed that the extreme boundary portions of the field still suffer from water deficit. The percentage of such water deficit areas within rain-gun sprinkled field has been reckoned in the range of 5-15%. It was inferred that an efficient wetting of the entire area can be achieved with an overlapping network of three or more rain-gun sprinklers.

Though the rain-gun sprinkler is tested against the available pump set of 1.5 HP with low pressure head, it yielded moderate value of the CU. The decrease in uniformity was observed to be due to

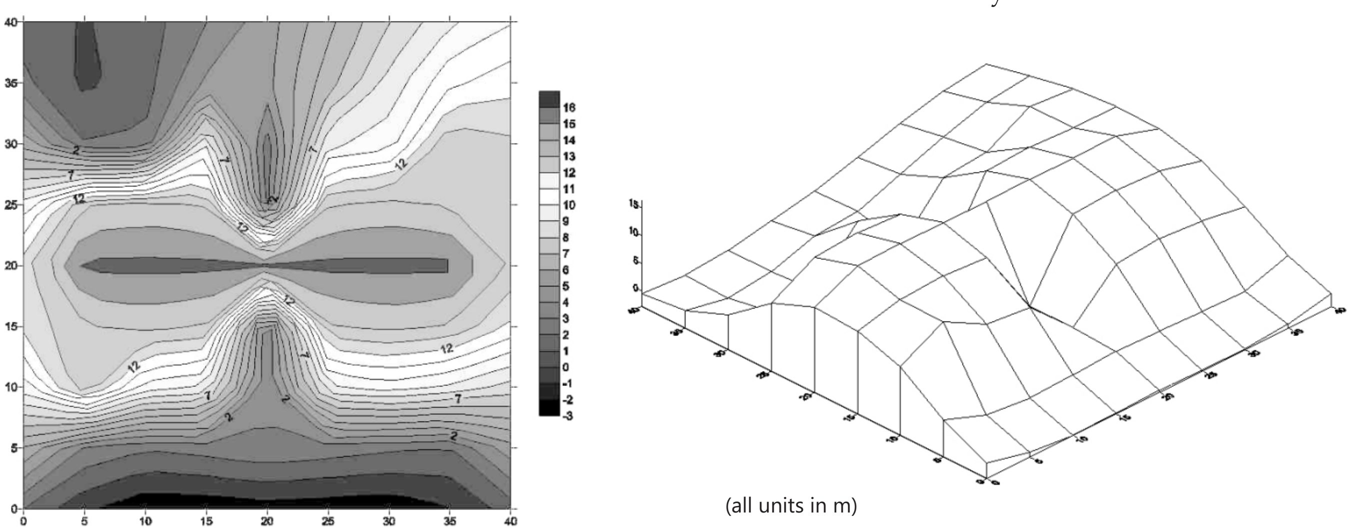


Fig. 4. Overlapped water distribution pattern of two sprinklers (full circle) at 50% overlapping

Table: 2
Summary of derived performance indicators for full and half circle rain-gun sprinkler

Performance indicator	Full circle sprinkler	2 Full circle sprinklers -Overlapped	Half circle sprinkler	Half circle sprinklers -Overlapped
Coefficient of variation (*cv* %)	67.27	69.31	82.61	69.31
Christiansen coefficient uniformity (CU %)	64.97	72.3	64.85	71.72

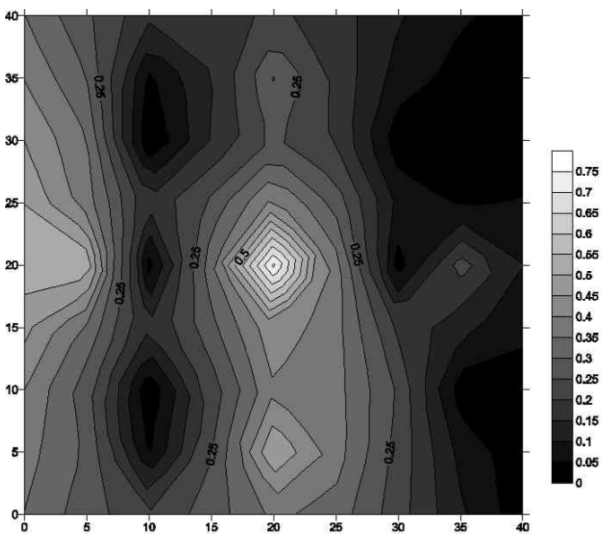
non-reach of water droplets to the corner grids due to insufficient throw of water, which in turn is due to low pressure. This implies that farmers can take up rain-gun irrigation with their existing pumping system of low HP provided that the distribution and application efficiencies are comparatively low. It was inferred that increasing the pressure or overlapping network would increase the water distribution uniformity.

The soil moisture distribution efficiency was found to be around 81% based on thermo-gravimetric soil sampling within the effective rootzone after irrigation. The observed increase in soil moisture was attributed to the lateral movement or seepage of water.

The sub soil moisture distribution pattern in the root zone area before and after irrigation is depicted in Fig. 5(a) and 5(b). The figure shows that the moisture distribution within rizosphere is more or less evenly distributed after irrigating with a full circle rain-gun sprinkler.

4. CONCLUSIONS

The performance evaluation of rain-gun system showed that the water is applied with moderate uniformity with a low pressure (1.5 kg cm^{-2}) pump. The results showed that the uniformity of application was increased by around 7.3% and 6.87% by giving 50% overlapping by another full-circle and half-circle rain-gun sprinkler, respectively. By providing a network of more overlapping sprinklers, the coefficient of uniformity can be further raised to optimum value. Under overlapped wetting pattern the distribution uniformity stood at around 72%, providing further scope for improvement with escalated pressure-discharge combinations. The soil moisture distribution efficiency for over lapped application was found to be around 81% based on



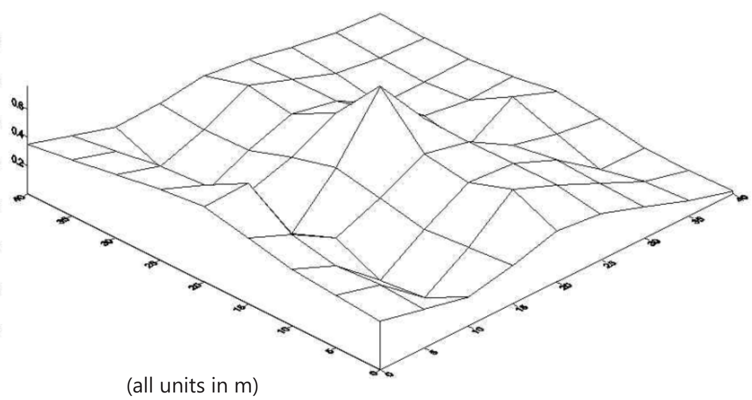


Fig. 5(a). Subsoil moisture distribution pattern within the rizosphere before irrigation

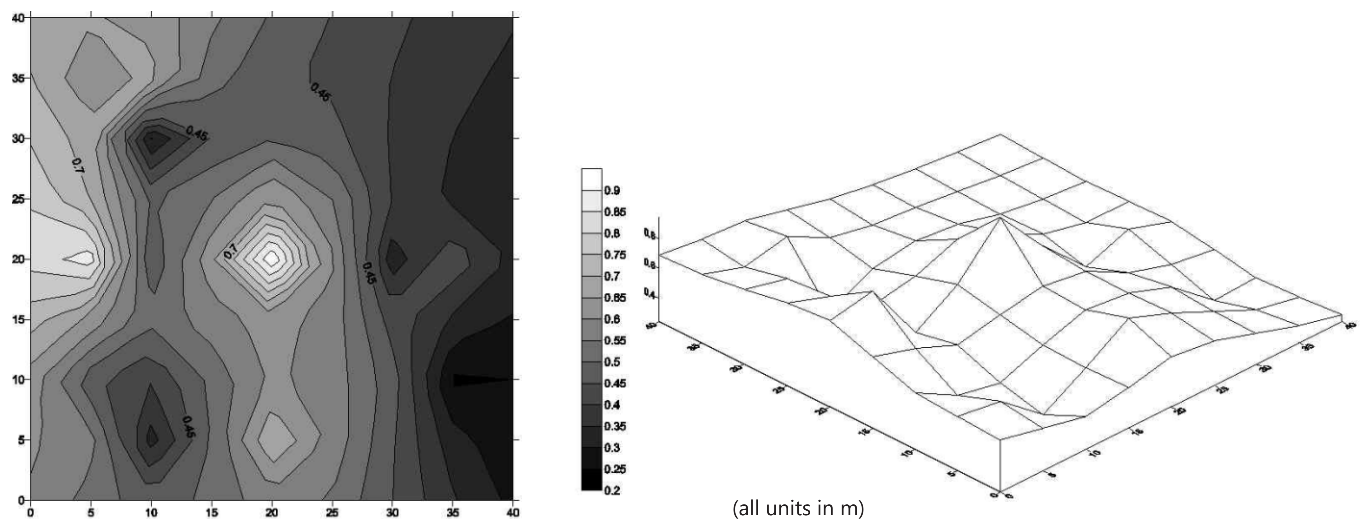


Fig. 5(b). Subsoil moisture distribution pattern within the rizosphere after irrigating with rain-gun komet full circle sprinkler thermo-gravimetric soil sampling within the effective rootzone after irrigation. The study also suggested that in case the rain-gun irrigation system was operated with low HP pumping system, efficient water application and uniformity can be achieved only with sufficient overlapping network.

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