Evaluation of a gravity-fed drip irrigation system under varying hydraulic head and land slope for hilly terrain

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Abstract: This study examined the performance of gravity-fed drip irrigation system under the varying hydraulic head and sub main line placed on varying field slope for hilly terrain of Sikkim, India. The coefficient of uniformity (CU) and emission uniformity (EU) of gravity fed drip irrigation system were evaluated for different combinations of hydraulic head and field slope. From the findings of the study, EU found to be 91.03%, 84.50%, 75.20% and 70.84% at 3.0 m hydraulic head for 0%, 5%, 10% and 15% land slope respectively. The CU and the EU decreased with lowering the hydraulic head (tank height and increasing the sub main line slope. The CU and the EU decreased significantly at sub main slope steeper than 10%. The CU and EU follows a linear relationship with either hydraulic head or slope. At the 3.0 m head at all slopes, the performance of the gravity system was optimum as compared to less than 3.0 m head. Developed regression models for the CU at varying head and slope may be used for predicting water distribution uniformity and standardization of gravity drip irrigation system in the region.

Key words: coefficient of uniformity, emission uniformity, hydraulic head, gravity drip, field slope

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1 Introduction

Agriculture uses more than 70% of all freshwater withdrawals globally, with irrigation accounting for the vast majority of this demand. In developing countries, crop production is very dependent on the availability and quality of water resources. Therefore, for the agro-food business to be sustainable and productive, better agricultural water management is crucial. Irrigated land is two to three times more productive than rained land. Irrigated farmland has helped India produce more food in recent years. Irrigation also improves the efficacy of other agricultural inputs including fertilizers, better seeds, and agrochemicals.

Surface irrigation techniques including border, check basin, and furrow irrigation have been employed by Indian farmers for a long time. Due to the inefficiency of these methods, long-term environmental problems such salinity, runoff, and water body contamination ensue (Tripathi et al., 2011). Due to limited water resources and the negative environmental effects of conventional irrigation techniques, drip irrigation technology is becoming more and more popular. Drip irrigation has been found to be an excellent way for lowering water application and boosting water use efficiency by supplying consistent water directly to each plant's root zones, particularly in locations where rainfall is uneven and scanty (Champaneri et al., 2023).

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Narayanamoorthy (2003) argued water utilization efficiency of up to 90% in drip irrigation compared to 30%-40% in furrow irrigation. Although the drip irrigation system is considered to be the most successful irrigation system, but its performance is significantly affected due to water quality issues, improper design and layout, mismanagement, and system maintenance issues (Dağdelen et al., 2009; Champaneri et al., 2023). The emission uniformity (EU) and coefficient of uniformity (CU) of a drip irrigation system indicates how uniformly it distributes water over a field. It is regarded as one of the most significant factors in the selection, design, and management of drip irrigation system (Tagar et al., 2010). Drip irrigation systems that are properly designed and operated save a large amount of water and energy. Poor drip irrigation system design may result in under watering and overwatering in the field (Sinha and Shasikant, 2021). When compared to traditional irrigation, drip irrigation increases water use efficiency saves water (20% to 60%), reduces fertilizer requirements (20% to 33%) through fertigation and increase yield and quality of produce (Mane et al., 2008). Water distribution uniformity (WDU) is an important element to consider while characterizing drip emitters and designing a drip irrigation system. In general, the CU and distribution uniformity (DU) increase with increasing heads and decrease with increasing slope. Saxena and Gupta (2006) evaluated the hydraulic performance of drip irrigation under Litchi plantations through Christiansen's CU and reported that the system performed well although its performance improved after change of drippers. Ella et al. (2009) discovered that the homogeneity of water distribution reduced as the slopes increased in a low-cost drip irrigation system with varying slopes and hydraulic loads. They reported that the WDU influenced by the hydraulic head and the slope. Tagar et al. (2010) evaluated the hydraulic performance of different emitters under varying lateral lengths in Karachi, Pakistan. They found 91.2% and 88.2% of emission uniformity with pressure compensated type emitters and 82.8% and 79.4% emission uniformity using micro tube type emitters. Valiahary et al. (2014) evaluated the emission uniformity for trickle irrigation systems in Iran. They found that emission uniformity (EU) of the systems varied within the range of 48.13% to 82.8% and reported that reduction in the crop yield due to the non-uniform distribution of water. Çolak et al. (2018) evaluated effect of surface and subsurface drip irrigation regimes on the yield and quality of eggplant in the Mediterranean Region of Turkey. Chamba et al. (2019) studied the hydraulic characteristics of drip irrigation system performing the laboratory experiment under a various range of pressure heads. Mostafa and Sultan (2018) performed the hydraulic evaluation of locally modified emitter under laboratory conditions under different operating pressures (0.50 to 1.25 bar) to determine emitter flow rates and emitter EU and manufacturing coefficient of variation (CV) and reported 98.5%, EU and 93.8% EU for the original emitter and the modified emitter, respectively. Mohammed et al. (2021) studied the effects of land slope on hydraulic performance and water productivity of cucumber under drip irrigation system in greenhouse and reported that there was a significant difference ($p \le 0.05$) on all the hydraulic performance parameters due to variation in land slopes. Nogueira et al. (2021) studied the variation in the flow rate of drip emitters in a subsurface irrigation system for different soil types using a pressure-compensating drip emitter (PC) and a non-pressure-compensating emitters (NPC). They reported that the flow rate varied even at shallow depths for some soils, and the soil type and emitter flow rate affected this variation.

Martinez et al. (2022) evaluated the hydraulic performance of two locally available low-cost drip irrigation kits under constant head conditions having 10 m submain and 20 m lateral length. Results showed that emitter discharge rate increased with increasing operating hydraulic head of gravity drip system. They also reported that the Christiansen's CU in the range of 97.5% to 98.5% and EU ranged from 95.9% to 97.7%.

In the state of Sikkim, people usually adopt the conventional surface irrigation methods to irrigate the crop. The main drawback of surface irrigation is the loss of water by evaporation, percolation losses, low application efficiency and high conveyance losses. Moreover, there is a tendency of farmers to apply excess water when it is available and under limited water supply condition they tend to increase irrigation interval without considering the critical stages, this results in low yield and poor quality produce. Drip irrigation provides small and frequent water drop by drop directly in the area of plant root zone using less amount of water. Drip irrigation is preferable for the cultivation of organic vegetable and fruits crops due to its high economic return. A gravity fed irrigation system is a cheap effective way to provide water for a smaller sized crop area. The North Eastern Region (NER) of India including the area under study consists of hilly topography, cropping areas are characterized by small plots. Due to topographical advantages, drip irrigation systems in hilly areas can be pressurized by elevation change without the need for pumping (Patle et. al., 2018). The use of low cost gravity drip irrigation system may pave the way to find solutions to these problems. Non-uniform distribution of water severely affects the crop performance and the yield. In gravity fed drip irrigation, proper operating head is very essential as it governs the flow performance namely WDU. WDU is one of the important criteria and is influenced by the operating head of the drip system and ground slope (Raphael et al., 2018). Considering above points, this study was undertaken for evaluating the effect of varying hydraulic head and land slope on WDU and to develop the regression models between WDU and hydraulic head or slope for adjudging the performance of low cost gravity fed drip irrigation system.

2 Material and methods

2.1 Description of study area

The experiment was carried out at College of Agricultural Engineering and Post Harvest Technology (CAEPHT), Ranipool Gangtok, Sikkim. The experiment site is situated near the New Girl’s Hostel of CAEPHT having latitude 27 ˚17’23” N to longitude 88 ˚35’26” E (Figure 1). The climate in the area is semi-humid, with annual rainfall of 2045 mm and most of which received in June to September month. The winter season in the region is mostly dry with almost no rainfall. The average wind speed of the area is 1.2 km h^{-1}. Soil analysis was carried out for determining texture, bulk density, infiltration rate etc.

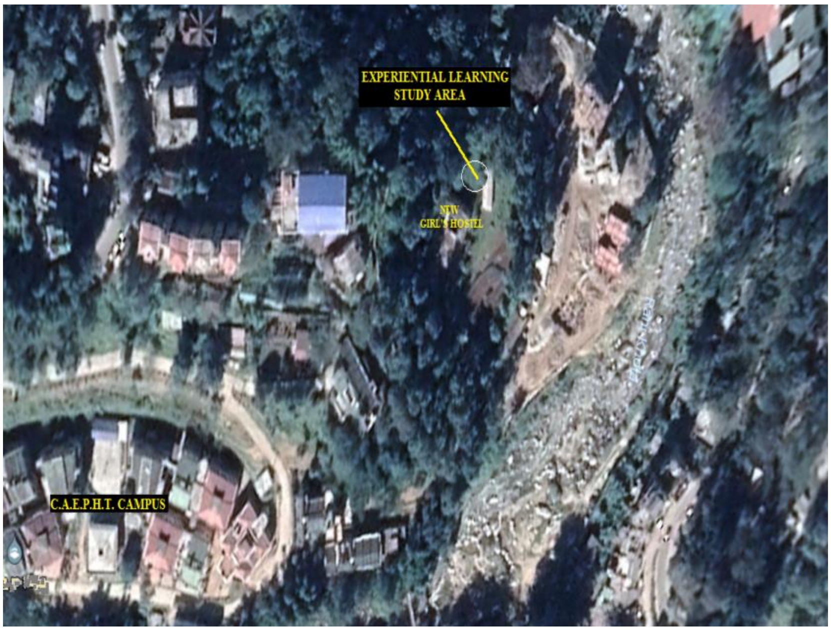

Figure 1 Aerial view of site location

An experimental setup for the evaluating the effect of hydraulic head and slope on WDU consists of fabrication of angle iron stand, development of gravity fed drip irrigation system for the 80 m^2 area and its installation and evaluation of the gravity drip system with respect to changing tank height and land slope. Angle iron stand of 3.5 m height was fabricated and fixed in the ground for keeping the water storage plastic tank of 500 liter capacity. Provision for lowering and rising of water storage tank height was made. Installation was done by erecting four legs of the stand at about 50 cm depth and cement grouting was done for more stability of sand.

2.2 Development and installation of gravity fed drip irrigation system

In the hilly state of north east region and particularly in Sikkim state, farmers cultivate vegetables and flowers inside the polyhouse of about sizes ranging from 50 to 100 m^2 or in the open field area available near the house. Fields are mostly undulating and sloppy which are available for the cultivation of the crops. In view of above gravity fed drip irrigation system was developed and installed for an area of 80 m^2 (10 m × 8 m). Following steps were considered for the design of gravity drip irrigation system namely selection of dripper (emitter), selection and design of lateral, selection and design of sub-main and selection of design of main line. Patle et al. (2018) has reported the water requirement of vegetables (broccolli, cauliflower, cabbage etc.) is less than 2 liters per day for Sikkim condition. Therefore, gravity drip system was installed using 2 LPH pressure compensating (PC) drippers. Performing the standard calculations, 50 mm PVC mainline and 40 mm submain line was selected with the 12 mm linear low density polyethylene (LLDPE) lateral pipe. Gravity drip was installed on the 80 m^2 area. Table 1. Shows the detail information for the installed gravity drip irrigation system.

Table 1 Detail information about installed gravity drip irrigation system

Particulars	Specifications
Experimental plot size	80 m^2 (i.e. 10m × 8m)
Storage Tank	500 liters
Mainline/sub-main	50/40 mm diameter
Laterals	12 mm diameter, 10 m length
Emitter type	2 lph online PC emitters
Spacing between lateral and emitters	cm × 50 cm

2.3 Evaluation of the gravity drip system

The gravity fed drip irrigation system was tested at different levels of operating heads 1 m, 2 m, 2.5 m and 3m etc. with respect to the junction of the first lateral on the upstream side, at varying sub-main slope (i.e. 0%, 5%, 10% and 15%). The slope of the lateral was kept at zero per cent. For each setting, emitter discharge was measured through direct volumetric measurement from the selected emitters from each lateral. Emitter discharge was measured for the different tank height and slope treatments. Three observations were taken and average of three was used for the calculation of different hydraulic parameters and evaluation of the system.

2.4 Determination of water distribution uniformity (WDU)

Direct measurement of emitter discharge data was used to calculate the water distribution uniformity. Following indices were used for the determination of water distribution uniformity (WDU).

2.4.1 Christiansen's uniformity coefficient (CUC):

Christiansen (1942) described the CU is a measure of absolute difference from the mean divided by the mean. The Christiansen's uniformity coefficient (*CUC*) can be expressed as Equation 1.

$$CUC = \left[1 - \frac{\frac{1}{n}\sum_{i=1}^{n}\left|q_i - \bar{q}\right|}{\bar{q}}\right] \times 100\% \quad (1)$$

Where, CUC is the Christiansen uniformity coefficient, %;

$\bar{q} = mean\ emitter\ flow\ discharge, litres/hr$

$q_i = emitter\ flow\ discharge, litres/hr$

$n = total\ number\ of\ observations/emitters$

2.4.2 Merriam and Keller's emission uniformity

The emission uniformity of Merriam and Keller (1978) can be expressed as Equation 2.

$$EU_f = \left(\frac{q_n}{q_a}\right) \times 100\% \quad (2)$$

Where, EU_f is field emission uniformity, %; q_n is the average of lowest 1/4 of the emitter flow rate, liters/hr; and q_a is the average of all emitter flow rates, liters/hr.

Coefficient of variation (C_v): It was calculated by using the expression Equation 3.

$$C_v = S/q \quad (3)$$

Where, C_v is the coefficient of variation of emitter flow and S is the standard deviation of the emitter flow.

2.5 Development of the regression models

Mathematical relations were developed to relate the uniformity coefficient with varying operating heads at different slopes.

3 Results and discussion

3.1 Development of gravity drip irrigation system

Gravity drip irrigation system was developed and installed at the experimental site for evaluating the effect of tank height and slope on the water distribution efficiency. The Schematic layout of the developed gravity system with the specifications is shown in Figure 2. The components of developed gravity drip irrigation system are shown in the figure. Experimental field view of gravity drip system at 0% slope and 3.0 m tank height and at 10% slope and 3.0 m tank height is shown in Figure 3.

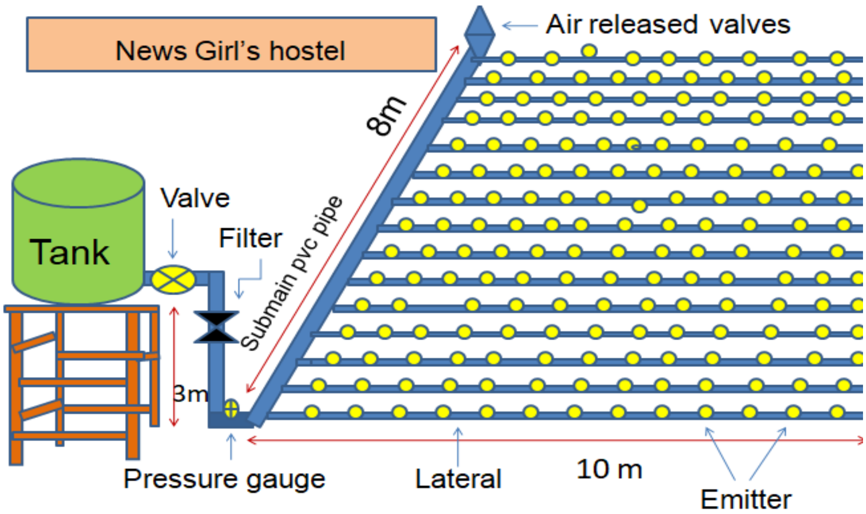

Figure 2 Schematic layout of the experimental field

Figure 3 Experimental field view of gravity drip system at 0% slope and 3.0 m tank height and at 10% slope and 3 m tank height

3.2 The performance evaluation of gravity drip system

The performance of the gravity drip irrigation was tested at the different hydraulic head and land slope and is shown in terms of the WDU which also known as CU. Results are presented in Table 2 and Figure 4.

CU was found to be 92.08%, 84.51%, 81.35% and 77.55% at 3.0 m hydraulic head for 0%, 5%, 10% and 15% slope respectively. Similarly, CU was 90.37%, 81.21%, 78.00% and 72.61% at 2.5 m head. In case of 2.0 m head, coefficient of uniformity found to be 88.24%, 80.54%, 71.57% and 63.55% at 0%, 5%, 10% and 15% slope, respectively. In case of 1.5 m hydraulic head, CU ranges from 85.13% to 61.66% for the 0 to 15% slope, whereas, the CU was 80.25% at 0% slope and 69.01% at 5% land slope. From the results, it was observed that as the tank height increases, the coefficient of uniformity of the gravity fed drip irrigation system is also increased. Whereas, as the land slope increases, the coefficient of uniformity also decreased significantly. This was mainly due to the variation in the system pressure and the emitter discharge. Gravity drip irrigation showed the good performance up to 10% land slope for tank height of 1.5m to 3.0 m. This performance is also attributed to the use of pressure compensating emitters for the sloppy terrain.

Table 2 Coefficient of uniformity at different slope percent

Tank height/Head	Coefficient of Uniformity at different slope percent			
	0	5	10	15
3.0	92.08	84.51	81.35	77.55
2.5	90.37	81.21	78.00	72.61
2.0	88.24	80.54	71.57	63.55
1.5	85.13	78.17	70.67	61.66
1.0	80.25	69.01	-	-

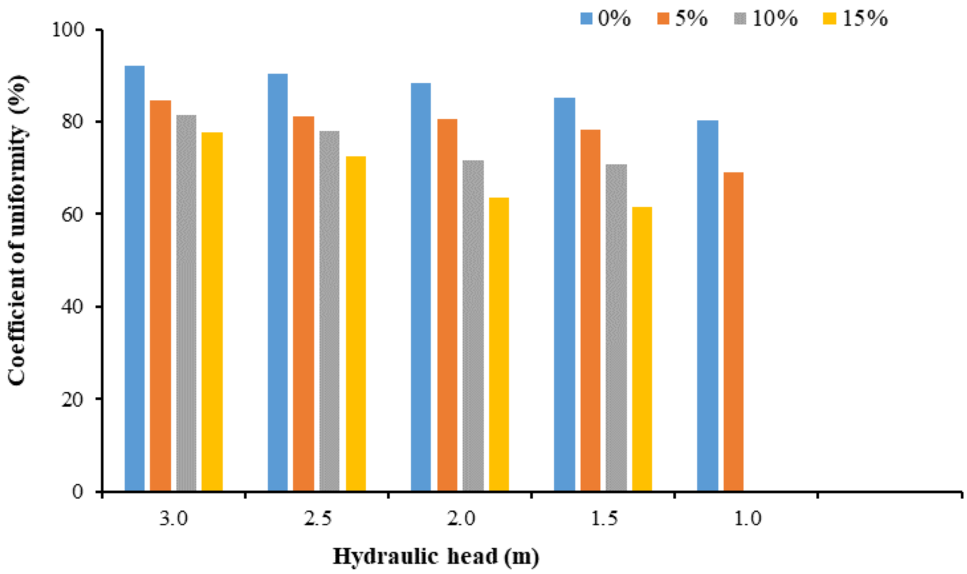

Figure 4 Effect of coefficient of uniformity at different land slope

3.3 Emission Uniformity (EU) vs. slope

Results of emission uniformity (EU) are presented in Table 3 and graphical presentation are shown in Figure 5. Emission uniformity found to be 91.03%, 84.50%, 75.20% and 70.84% at 3.0 m hydraulic head for 0%, 5%, 10% and 15% slope respectively. Similarly, emission uniformity (EU) was 90.00%, 80.80%, 70.27% and 64.65% at 2.5 m head. In case of 2.0 m head, emission uniformity found to be 85.00%, 73.03%, 67.58% and 60.77% at 0%, 5%, 10% and 15% slope, respectively. In case of 1.5 m hydraulic head, EU ranges from 82.11 to 57.66% for the 0 to 15% slope whereas, the emission uniformity was 80.21% at 0% slope and 67.50% at 5% land slope. From the results, it was observed that as the tank height increases, the emission uniformity of the gravity fed drip irrigation system is also increased. Whereas, as the land slope increases, the emission uniformity also decreased significantly. This was mainly due to the variation in the system pressure and the emitter discharge. Gravity drip irrigation showed the good performance up to 10% land slope for tank height of 1.5 m to 3.0 m. This performance is also attributed to the use of pressure compensating emitters for the sloppy terrain.

A criterion for the drip irrigation system uniformity classification is based on uniformity coefficient and is shown in Table 4.

Table 3 Emission uniformity w.r.t. slope and head

Head/slope	0%	5%	10%	15%
3.0	91.03	84.50	75.20	70.84
2.5	90.00	80.80	70.27	64.65
2.0	85.00	73.03	67.58	60.77
1.5	82.11	70.17	64.67	57.66
1.0	80.21	67.50		

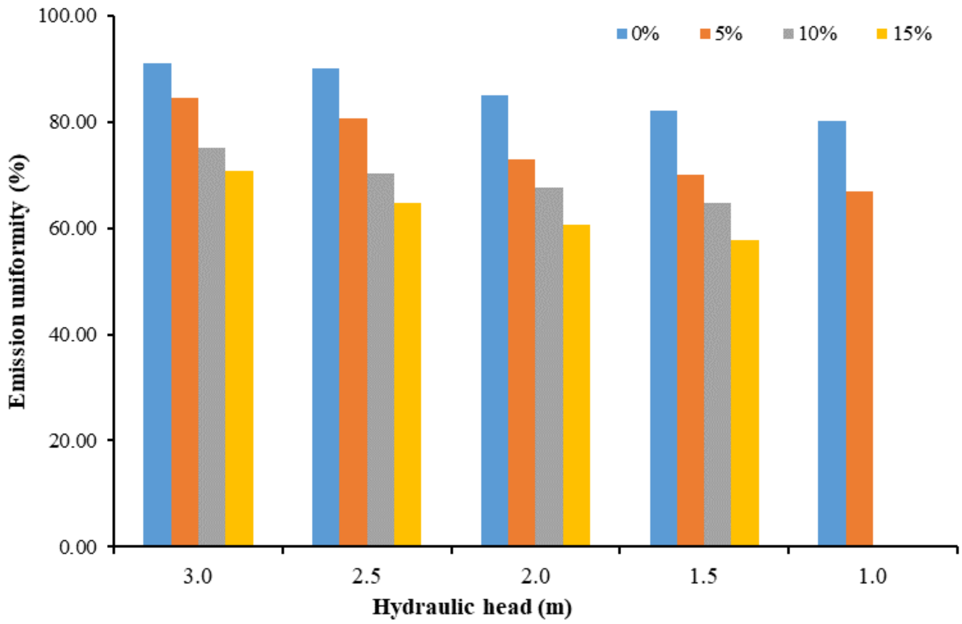

Figure 5 Effect of emission uniformity at varying hydraulic head and slope (%)

Table 4 Coefficient of uniformity classification for drip irrigation system

Coefficient of Uniformity, CU (%)	Classification
Above 90 %	Excellent
90%-80%	Good
80%-70%	Fair
70%-60%	Poor
Below 60%	Unacceptable

Table 5 Linear regression models between CU and head at various slopes

Slope (%)	Linear regression model	R^2
0	$Y= -2.89x + 95.884$	0.95
5	$Y= -3.404x + 88.9$	0.84
10	$Y= -3.847x + 85.015$	0.93
15	$Y= -5.673x + 83.025$	0.95

Note: Y = coefficient of uniformity, CU (%); x = head (m).

3.4 Development of regression models

Mathematical relationships/models between WDU or CU and head or slope was established through linear regression analysis. Here CU was considered as a function of either head or slope. Linear trends were observed with the R^2. In this study, Christiansen's coefficient of uniformity was considered instead of Merriam and Keller's emission uniformity owing to a better linear trend in the results of CU as compared to EU.

Table 5 and Figure 5 shows the results of the linear regression analysis between CU and slopes at varying head. All linear regression models exhibited relatively high R^2 value ranging from 0.84 to 0.95.

While most of the models are able to explain the variation substantially. Derived models for the 0 to 15% slope may be useful for predicting the coefficient of uniformity of the gravity fed drip irrigation system when the operating head with respect to the junction of the most upstream lateral is set between 1.0 m and 3.0 m.

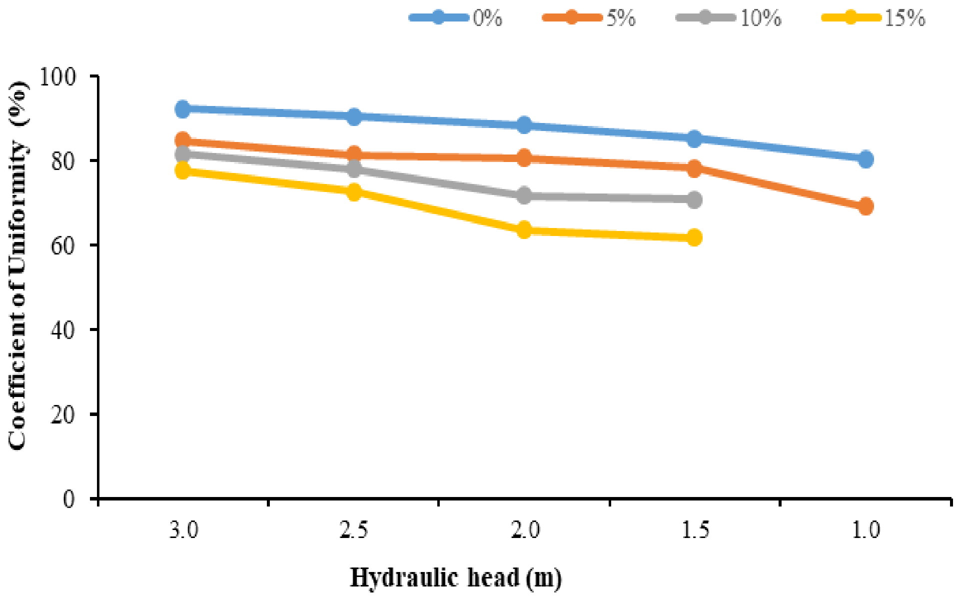

Figure 6 Effect of head on coefficient of uniformity at various slopes

Note: *Y* = coefficient of uniformity, CU (%); *x* = submain slope (%).

Table 6 and Figure 7 shows effect of head on uniformity coefficient at varying slope for the gravity drip irrigation system. Results show that R^2 value vary between 0.96 to 1 for the different head ranging from 3.0 m to 1.5 m, respectively. It was also observed that as the slope increases the coefficient of uniformity also decreased. This is mainly due to the more variation in the emitter discharges. Moreover, as far as design is concerned, the choice of water distribution parameter is not critical. In fact, any of the measures of water distribution uniformity may be used for design purposes as suggested by Barragan et al. (2005). In their study, it was demonstrated that EU, CU and other measures of water distribution uniformity are highly correlated with each other, making any of them eligible as a design criterion. Ella et al. (2009) and Barragan et al. (2005) reported that emission uniformity and the CU is highly correlated to the head or slope, any of both the parameter can be used as the design criteria for the drip irrigation system. Hence, for purposes of developing mathematical relationships for drip irrigation system design, the use of CU over EU should not create any problem.

Regression models were developed studying the effect of head on emission uniformity at varying slopes as shown in Table 7. R^2 value ranging from 0.84 to 0.99 in case of emission uniformity Derived models for the 0 to 15% slope may be useful for predicting the emission uniformity of the gravity fed drip irrigation system when the operating head with respect to the junction of the most upstream lateral is set between 1.0 m and 3.0 m.

Table 6 Effect of head on coefficient of uniformity at varying slope

Head (m)	Linear regression model	R^2
3	$Y= -4.675x + 95.56$	0.96
2.5	$Y= -5.649x + 94.67$	0.96
2.0	$Y= -8.304x + 96.735$	0.99
1.5	$Y= -7.791x + 93.385$	0.99
1.0	$Y = -11.24x + 91.49$	1

Note: *Y* = coefficient of uniformity, CU (%); *x* = submain slope (%)

Table 7 EU effect on head at various slope

Slope (%)	Linear regression model	R^2
0	*Y= = -1.686x + 93.166*	0.82
5	*Y= = -3.004x + 89.5*	0.84
10	*Y= = -2.847x + 84.015*	0.99
15	*Y= -4.173x + 81.525*	0.99

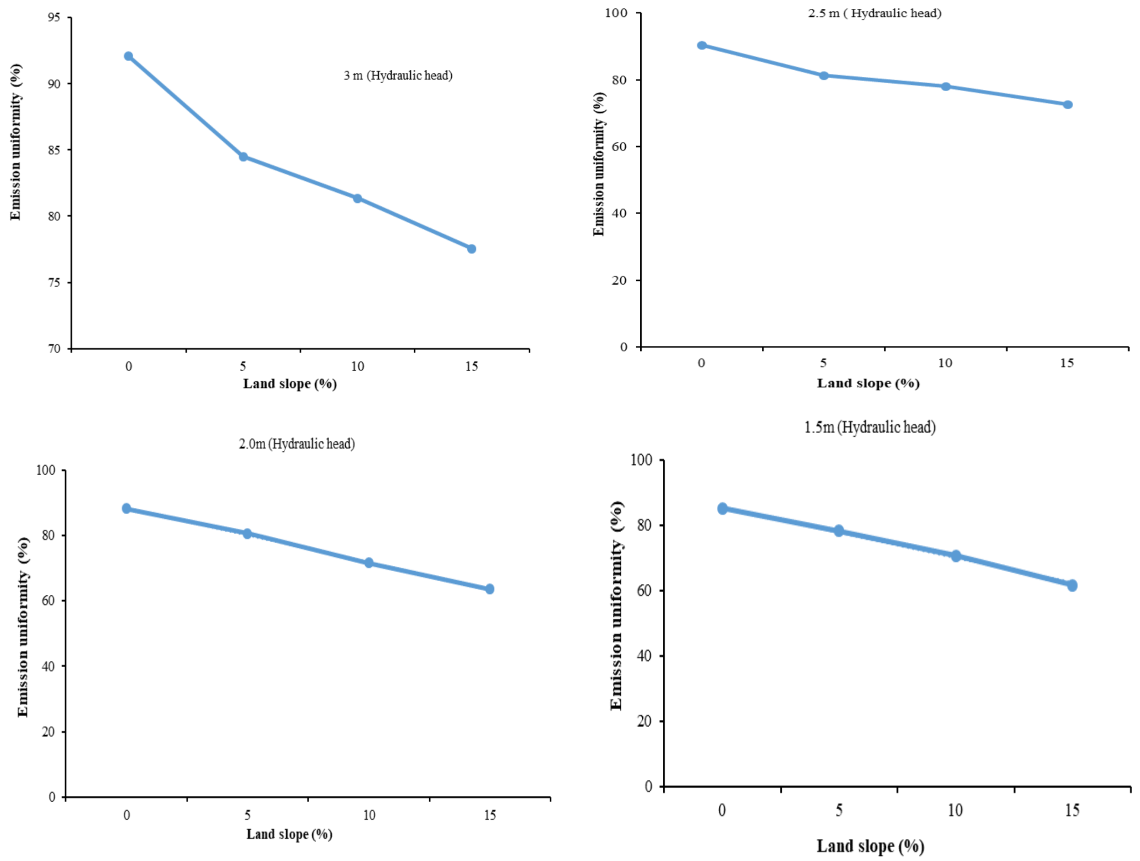

Figure 7 Effect of head on varying slope

Land and water are two vital resources and play a key role in the sustainable crop production in the hilly regions of India. Nowadays availability of productive land and fresh water becoming scarce and also threatening the agriculture production system. Sikkim has 7096 Sq. km. area of which only 15% area is under agriculture at varying altitude. Though the state receives more rainfall but observes water shortage mainly due to less water holding capacity of soil, insufficient storage facilities and inherent topographic limitations etc. Production of the horticultural crops can be increased in Sikkim through water management especially by adopting the low cost gravity drip irrigation system. Such interventions are suitable for the small farmers and may be adopted at large scale in the hilly landscape of the state if proper guidance/technical knowledge provided to the farmers.

4 Conclusions

Gravity drip irrigation system was designed for the small area of 80 m^2 at the experimental field of the college of Agricultural Engineering and Post Harvest Technology, Ranipool, Sikkim and was evaluated for the effect of varying head and slope on the WDU as represented by CU. Following conclusions were drawn from the study: Emission uniformity found to be 91.03%, 84.50%, 75.20% and 70.84% at 3.0 m hydraulic head for 0%, 5%, 10% and 15% slope respectively. The CU and the EU generally follow a linear relationship with either hydraulic head or slope. The CU and the EU decreased significantly at head at all slopes, the performance of the gravity submain slopes steeper than 10%. At the 3.0 m system was optimum as compared to less than 3.0 m head. Developed simple regression models for the coefficient of uniformity at varying head or slope may be used for predicting water distribution uniformity.

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