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Optimization of Irrigation Spray Distribution in the Term of its Uniformity

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Abstract

The production process of agricultural and livestock production is affected by climatic conditions, mostly including the amount and quality of rainfall. In High Tatras region is annual atmospheric rainfall between 500 and 2000 mm. During vegetation period the rainfall on the most agriculturally significant areas is even less and its value is between 300 and 250 mm. This amount is insufficient for the most of economic significant plants. From this point of view, the artificial irrigation represents one of the most important factors that improve the agricultural production.

Considering stochastic effects like wind or technical parameters of irrigation machines, slope of terrain, the distribution of spray is not equal over the whole irrigated area. For economic benefits in the process of irrigation and supplying water to the irrigation machines, this spray non-uniformity must attain smallest possible value. This can be achieved by proper mathematical modeling of economic and technological processes, the irrigation process includes.

Key words

Irrigation uniformity, overlaps, simulation model, sprinkler.

Introduction

The optimization of spray has been the subject of research of many authors. They used many different methods and practices. Palková, Okenka and Rodný (1998, 2012) used principles of the Queuing theory and heuristic algorithms in their thesis. Domínguez (2010) descripted the methodology for determining the most suitable irrigation schedule under regulated deficit irrigation conditions. Pereira dealt with the optimization of central pivot irrigation machines (2012). Based on analysis of meteorological parameters during the irrigation season, Yacoubi (2010) developed models simulating the effectiveness of the night irrigation of tomatoes.

This contribution deals with optimization modeling of the spray distribution in the term of its uniformity using reel hose irrigation machines with calculations of the optimal overlap width.

Materials and methods

Spray uniformity is an important factor of irrigation quality and according to some authors, spray non-uniformity leads to a reduction of yield per hectare by 2-10%.

The spray equality mainly depends on the curve $i - \overline{L_d}$ (intensity-range), on the spacing of the sprinklers works in and on the effect of wind. Center pivot irrigation machines are placed to the vertexes of a square, rectangle or a triangle. The circles sprayed by the water stream are more or less overlaps, so some areas are irrigated more than one times. The amount of water in the overlapped areas is summed. This leads to deviations from the average amount of water on each elementary area. In 70^{th} of the last century, many formulas determining the spray equality has been developed.

The coefficient of uniformity $\mathbf{C_u}$ according to Christiansen:

$$C_u = 100 \cdot \left(1 - \frac{|\sum h_i - h_m|}{n \cdot h_m}\right) \qquad (1)$$

where:

- $\mathbf{h_i}$ is the amount of rainfall at i^{th} area (mm),
- $\mathbf{h_m}$ is the average amount of rainfall over the whole area (mm)
- **n** is the number of elementary areas (pcs).

The degree of non-uniformity $\mathbf{E_f}$ (Hofmeister, Oroszlany-Szalai):

$$E_f = \frac{\frac{\sum e_i}{n}}{\frac{\sum h_i}{n}} \qquad (2)$$

where:

- $e_i = |h_i - \bar{h}|$
- $\sum_{i=1}^{n} h_i = n \cdot \bar{h}$
- $\bar{h}$-

After substituting:

$$E_f = \frac{\sum_{i=1}^{n} |h_i - \bar{h}|}{n \cdot \bar{h}} \qquad (3)$$

The coefficient of variation $\mathbf{C_v}$ (Stefanelli, Strong):

$$C_v = \frac{\sigma}{\bar{h}} \qquad (4)$$

Where standard deviation $\sigma = \sqrt{\frac{\sum_{i=1}^{n} |h_i - \bar{h}|^2}{n}}$.

The coefficient of uniformity $\mathbf{C_{ws}}$ (Wilcox-Swales):

$$C_{ws} = \left(1 - \sqrt{\frac{\sum_{c=1}^{n} |h_i - \bar{h}|^2}{n \cdot \bar{h}^2}}\right) \qquad (5)$$

The coefficient of uniformity β given as the ratio between the maximum and average amount of rainfall (Lipták):

$$\beta = \frac{h_{max}}{\bar{h}} \qquad (6)$$

Geometrical factor γ represents the ratio between effectively irrigated area $\mathbf{S_h}$ and the whole area **S**.

$$\gamma = \frac{S_h}{S} \qquad (7)$$

Effectively irrigated area is the area, where the amount of water has a deviation from average amount. Lipták (1971) have used 3 values of geometrical factor with deviation from average value - ±10%, ±20%, ±33%. Instead of the factors mentioned, lots of exact procedures are used. These factors can be divided into five groups like below:

1. $\mathbf{C_u}$ and $\mathbf{E_j}$
2. $\mathbf{C_v}$ and $\mathbf{C_{ws}}$
3. $\mathbf{E_{p1}}$ and $\mathbf{E_{ph}}$
4. β
5. γ_{10}, $\gamma_{20,}$ γ_{30}

Factors from 1 to 4 represent the uniformity of spray by one value determined by a statistic processing of rainfalls catch in rain gauge vessels. Using these formulas in a mathematic-analytic model, uniformity optimization of spray can be achieved.

Simulation model for optimizing the spray uniformity with optimal overlaps using reel hose irrigation machines

During the irrigation with hose reel irrigation machine, the irrigation truck continuously moves down the proper line. Practical measurement of water volumes dropped in all elementary areas the whole irrigated area is divided into is not possible (Látečka, 2000). One of the most widespread methods is the method of evaluating the transverse uniformity of spray.

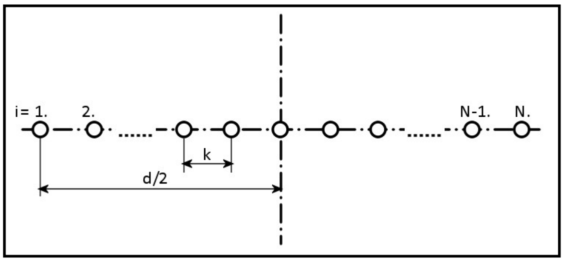


Figure 1: Method of evaluating the transverse uniformity of spray.

Rain gauge vessels are set along the irrigation width perpendicular to the direction of the irrigation truck. The input file for the simulation model contains water volumes measured in all rain gauge vessels for two tested nozzles. We have used Bauer Rainstar 90/300 reel hose irrigation machine.

Technical parameters of Bauer Rainstar 90/300 are as follows (Jobbágy, 2011):

Diameter and length of the hose	90 mm / 300 m
The maximum length of the belt	340 m
Flow rate	17 – 65 $m^3.h^{-1}$
Connecting pressure	0,35 – 1 MPa
Nozzle diameter	16 – 30 mm
Weight with a hose with water	3270 kg
Weight with a hose without water	1850 kg
Total length including the tripod	5350 mm

We have used SR 101 sprinkler with two different nozzles of the same diameter of 20 mm. During the measurements, the wind speed did not exceed 1 $m.s^{-1}$ and the terrain was flat, the slope was up to 1°. The speed of spooling of the hose was set to

15,1 m.h^{-1}. Number of plastic rain gauge vessels was 61 and they were placed according to Christiansen perpendicular to the direction of move. The distance between two adjacent vessels was 1 meter (Jobbágy, 2011).

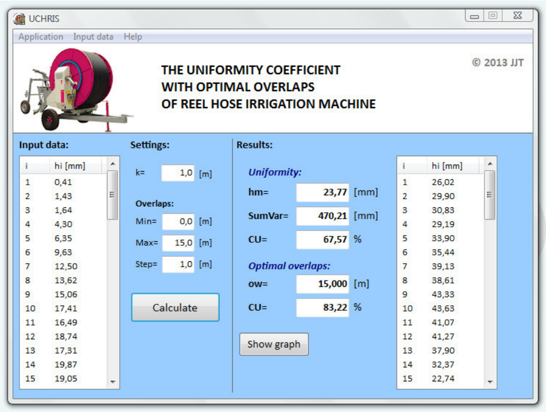
By measuring the transverse uniformity in one irrigated line, we measured the following water volumes in all vessels:

Index of rain gauge vessel	Nozzle #1 Volume [mm]	Nozzle #2 Volume [mm]
1	0.41	1.17
2	1.43	2.4
3	1.64	2.53
4	4.30	2.61
5	6.35	3.87
6	9.63	6.42
...	...	
56	26.22	6.49
57	24.58	7.03
58	22.53	3.61
59	20.59	2.04
60	12.50	0.57
61	3.69	0.2

Source: own measurement

Table 1: Measured water volumes

We designed a Win32 application that calculates the coefficient of uniformity according to Christiansen out of the input data shown in the table above. The application was designed in Embarcadero Delphi 2010 Architect programming environment. Its executable is fully compatible with all Windows versions from Windows NT to Windows 7.



THE UNIFORMITY COEFFICIENT
WITH OPTIMAL OVERLAPS
OF REEL HOSE IRRIGATION MACHINE

Input data:

i	hi [mm]
1	0,41
2	1,43
3	1,64
4	4,30
5	6,35
6	9,63
7	12,50
8	13,62
9	15,06
10	17,41
11	16,49
12	18,74
13	17,31
14	19,87
15	19,05

Settings:

k= 1,0 [m]

Overlaps:

Min= 0,0 [m]
Max= 15,0 [m]
Step= 1,0 [m]

Results:

Uniformity:

hm= 23,77 [mm]
SumVar= 470,21 [mm]
CU= 67,57 %

Optimal overlaps:

ow= 15,000 [m]
CU= 83,22 %

i	hi [mm]
1	26,02
2	29,90
3	30,83
4	29,19
5	33,90
6	35,44
7	39,13
8	38,61
9	43,33
10	43,63
11	41,07
12	41,27
13	37,90
14	32,37
15	22,74

Source: own processing

Figure 2: The front page of application of modeling optimal overlap of hose reel irrigation machines.

To do any further calculation, a user must load the input values representing the water volumes in all rain gauge vessels. The application expects the raw ANSI text file with CRLF line separator to be selected containing these values. There is no need of special extension for this file. The structure of this file is simple, where every line of the file represents the water volume. The proper structure of this file looks like this:

```
0.41
1.43
1.64
4.30
6.35
9.63
12.50
13.62
15.06
```

…

Because every line represents one vessel, the count of vessels must equal to the number of rows. If there are more rows in the file, extra lines are ignored. In the application, a user can enter the value representing the distance between two adjacent ran gauge vessels as they were placed during the test in real conditions. For the calculation of optimal overlap values representing the minimum and maximum width of overlaps on both sides of irrigation belt are also entered, even we can set the step in which the width of overlaps increases. The default value for the maximum overlap width is 15 meters – a quarter of the watering range of the sprinkler we used. Values higher than a quarter are not considered of having an economical benefit due to ineffective water consumption. We set the step 1 meter that equals the distance between two adjacent vessels.

For the calculation of optimal overlaps we used modified formula for the coefficient of uniformity according to Christiansen (form. 1). Modeling of overlapping is realized by the sum of water volumes in a pair of vessels according to the following formula:

$$h_i = h_{n-i+1} = h_i + h_{n-i+1} \tag{8}$$

where:

h$_i$ – water volume in the ith rain gauge vessel,

n – total number of vessels.

The formula shown above is valid in case of indexing vessels from 1. In computer programming we tend to start indexing from 0 due to natural organization of data stored in the operation memory. In that case, the proper right vessel is determined with the index of h_{n-i}. The highest vessel index is determined according to the known total number of used vessel during the spray measuring test. This is the last vessel in the row that receives the water drops. Using the following formula, we calculated the last vessel in the overlap area:

$$i = trunc(ow/k) \tag{9}$$

where:

ow – actual modeling width of overlap,

k – distance between two adjacent vessels.

Optimal overlap width is determined by the highest possible value of the coefficient of uniformity over the whole irrigated belt. Application simulates all possible widths of overlap by increasing its value by an entered step. Direct calculation of the coefficient of uniformity would be slow and less effective. Sufficient calculation might be realized by the following formula:

$$c_f = \frac{\sum_i^n |h_i - h_m|}{h_m} \tag{10}$$

In the denominator of the formula above, value n representing the total number of used vessels is omitted. This value is constant during the whole process of calculation. We are looking for the value of $c_{f,}$ that represents the minimum calculated of all simulated overlap widths. In the formula, sharp inequality is used. In case of testing with even possible equality, if the application finds two or more equal minimum calculated values, the result would be the last value which means higher overlap width. We need to know the smallest overlap width possible.

After determining the minimum calculated value of c_f, application transforms this value into the coefficient of uniformity using the following formula:

$$CU = 100 * (1 - \frac{cf}{n}) \tag{11}$$

Results

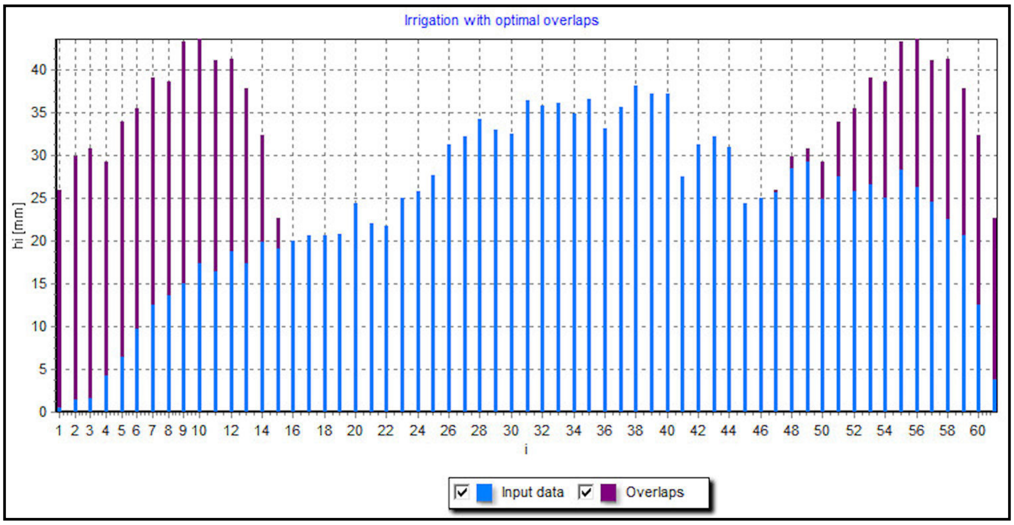
According to measured water volumes using two different nozzles, we simulated the optimal overlap width with calculation of the coefficient of uniformity.

In the table below, the results calculated for the first nozzle are shown. The CU without overlaps is very low and insufficient. The optimal overlap width was calculated to 15 meters that equals to the quarter of the whole irrigation width (60 meters). The CU after simulating overlaps was calculated to 83.22%.

Nozzle #1	
x	1.0 m
hm	23.77
CU without overlaps	67.57 %
ow (optimal overlap width)	**15.0 m**
CU with overlaps	**83.22 %**

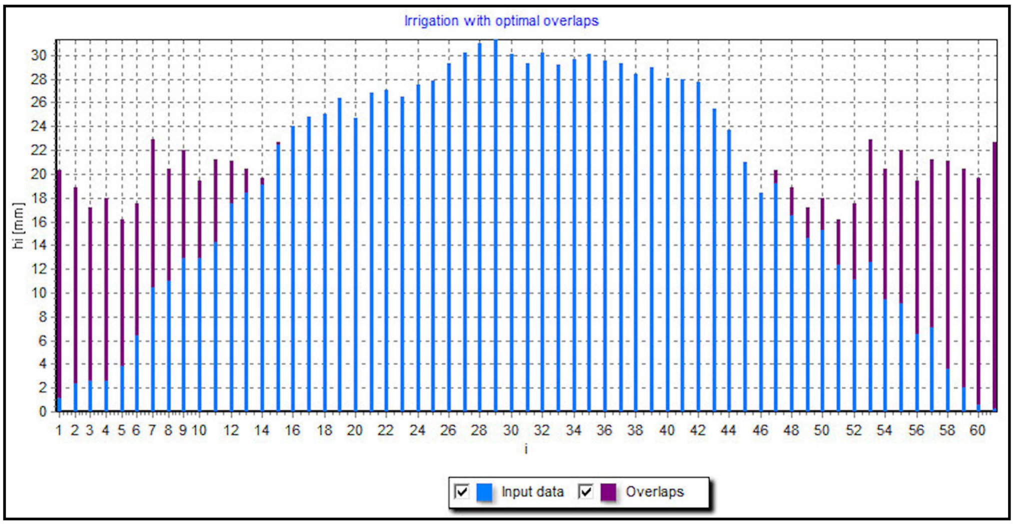
Source: own measurement

Table 2: CU using the first nozzle.



Source: own procesing

Figure 3: Measured and calculated water volumes using nozzle #1.



Source: own procesing

Figure 4: Measured and calculated water volumes using nozzle #2.

In the figures above, the water volumes with overlaps are presented.

The horizontal axis represents the index of rain gauge vessel. The distance between two vessels was set to 1 meter. Even the whole irrigation width was 60 meters we used 61 vessels to also catch the drops falling on both edges. Light blue bars represent measured water volumes in each vessel. Magenta bars represent the calculated optimal overlap width. The waters volumes on left and right sides sum to the final volumes. The vertical axis represents the water volume in ml.

The next table shows the calculated results for the second nozzle.

Nozzle #2	
x	1.0 m
hm	18.82
CU without overlaps	52.74 %
ow (optimal overlap width)	**15.0 m**
CU with overlaps	**82.98 %**

Source: own measurement

Table 3: CU using the second nozzle.

As shown in the table, the CU without overlaps is a lot worse than that when using the first nozzle. Instead, the final CU with overlaps is similar.

Conclusion

In the presented paper, we focused on optimization of the amount of spray during irrigation. Since the quality of work of reel hose irrigation machines is evaluated by the coefficient of uniformity on one side, we developed an application to ease its calculation. One of the results is the design of optimal overlap width to achieve the maximum value of the Christiansen's coefficient of uniformity. The optimal overlap width is calculated depending on minimum and maximum width of overlaps. The user of this application can set this interval. The value of the coefficient of uniformity is influenced by many external factors, including the terrain of irrigated area, effect of wind and the slope of the irrigated area. The results obtained after measurement in 2011 were successfully evaluated by the UCHRIS (JJT, 2013) application. The results shows, that according to some authors, the quality of work of tested reel hose irrigation machine was sufficient, but according to the ISO norm was not. Our program calculated the optimal overlap width to 15 m, getting the higher value of the coefficient of uniformity (83.22 % and 82.98 %). The increment of the quality of work generally leads to higher values of uniformity in irrigation of crops, providing higher agricultural and livestock production. On the other hand, the overlaps decrease the effective scope of irrigation machines and increase the irrigation costs.

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