ZIBELINE INTERNATIONAL™ PUBLISHING

Water Conservation & Management (WCM)

DOI: http://doi.org/10.26480/wcm.03.2025.446.454

ISSN: 2523-5664 (Print)
ISSN: 2523-5672 (Online)
CODEN: WCMABD

CrossMark

RESEARCH ARTICLE

SELECTING AN EFFECTIVE SPRINKLER IRRIGATION SYSTEM SPACING: BASED ON ISODENSITY CONTOUR MAPPING- VORONOI-LIKE CONNECTION- HOTSPOT CLUSTERING MODELS

Arifjanov Aybek, Samiev Luqmon*, Abduraimova Dilbar, Jalilova Khumora

Tashkent Institute of Irrigation and Agricultural Mechanization Engineers
****Corresponding Author Email: luqmonsamiev@mail.ru, xumora798911@gmail.com***

ARTICLE DETAILS

Article History:

Received 20 June 2025
Revised 05 June 2025
Accepted 03 July 2025
Available online 21 July 2025

ABSTRACT

The main objective of this study is to determine the optimal spacing of sprinkler irrigation systems in arid and water-scarce regions of Uzbekistan. The study used a combination of isodensity contour mapping, Voronoi-like connection, and hotspot overlap analysis methods. Sprinklers with 8 m, 10 m, and 12 m spacing were modeled in zigzag and linear patterns. The results showed that the 10-meter zigzag pattern was the most effective model, ensuring consistent water distribution. The model developed at the end of the study can serve to increase irrigation efficiency and ensure rational use of water resources.

KEYWORDS

Sprinkler space, irrigation clusters, hydraulic calculations, water distribution, overlap zone.

1. INTRODUCTION

Today, sprinkler irrigation is one of the most widely used and researched water-saving irrigation technologies worldwide. One of the main elements of sprinkler irrigation is its proper design, that is, in addition to the correct selection of the water consumption and nozzle of the sprinkler, it is also important to correctly calculate its spacing. The limited water resources in the region of Uzbekistan, especially against the backdrop of climate change, have made the introduction of water-saving technologies in agriculture an urgent issue. In recent years, sprinkler irrigation systems have begun to replace traditional open ditches. However, if factors such as location intervals, uniform water distribution, wind, pressure and relief are not taken into account when implementing these systems in practice, they may not give the expected results. While previous studies have selected the location of sprinklers mainly based on an empirical approach, in this article, zonal maps were created based on GIS and statistical methods and built based on a model. The goal is to determine the optimal sprinkler spacing that is appropriate for soil and vegetation conditions and that effectively uses water resources. It has been proven that the spacing of the sprinkler is important for the correct distribution of water (DeBoer, 2001). Although water consumption and pressure are important in a sprinkler irrigation system, sprinkler spacing is even more important, as these spacings offer the greatest potential for saving time, water, and money (Samiev, 2023). The sprinkler placement simulation was developed by taking into account several parameters through two-step interpolation and superimposition methods (Dwomoh, 2014). Netafim's company in America has also conducted several studies on sprinklers and calculated the sprinkler spacing for greenhouses and large irrigated areas according to their parameters (water consumption and discharge). Another source suggests that the sprinkler operates at a single fixed point in the center of a pivoting area or designated area - this is the case when sprinklers are 200 feet to 2,640 feet (half a mile) long, calculated by the length of the pipes attached to them (USA). They rotate in a full or semi-circle around the center point. The velocity of the water discharged from the sprinklers is specified to be 10 to 75 PSI, at pressures ranging from 100 to 3,000 GPM (Price, 2019). Ecourse online has developed several steps for calculating and placing sprinkler spacing, which are:

- The mains should be run up and down.
- Laterals should be laid along or almost along the contour.
- The lateral pipe sizes should not exceed two diameters for multiple lateral operations.
- If possible, the water supply should be selected as close to the center of the area as possible.
- The locations should facilitate minimal lateral movement during the season.
- The differences in the number of sprinklers operating for different settings should be minimal.
- Booster pumps should be considered where small sections of the field require high pump pressures.
- The scheme should be modified to accommodate different pressures and quantities of water where soils vary significantly within the design area.
- The main and sub-main schemes should be connected to the lateral layout.
- When laterals cross significant slopes, the main or sub-mains usually run up and down the slopes.
- Where it is necessary to pass the side sections up and down the hill, the main or sub-main sections should be located on the slopes to prevent uphill movement (Ecoursesonline).

In addition, another study used sprinklers for several crops and irrigated them at the same spacing, which resulted in water savings and increased yields. The results showed that the water consumption per sprinkler was

Quick Response Code	Access this article online	
	Website: www.watconman.org	**DOI:** 10.26480/wcm.03.2025.446.454

2.144 liters/sec and the sprinkler water velocity was 8.85 mm/h, the pump required to operate the system was approximately 2 hp and the pressure at the main pipe inlet was 13.44 bar (Zakari et al., 2017). Sprinkler irrigation system sales worldwide in 2019-2029 are shown. According to it, 1.35 billion dollars were observed in 2023 worldwide. The types of sprinkler irrigation systems in the world are divided into several parts according to the type of purchase, the type of use. According to it, the type of purchase in the countries is divided into 5 continents, namely, North America, Europe, Asia, Central and South America, the Middle East and Africa. Also, according to the movement, it is divided into stationary and fixed types, according to the purpose of use, into agricultural and non-agricultural areas, according to the type, into center pivot, movable lateral, Solid set and other types, according to the same area size, into the above types and scattering types. The types of use of sprinkler irrigation systems in the world are divided into different parts. According to it, 4 types of sprinklers are divided into types of use according to the size of the area, type of movement, type of spraying parts, purpose of use, type of crop, and use on a national scale (TechSci Research, 2023). Sprinkler irrigation system sales in North America from 2016 to the present and the revenue from it are forecasted to 2027. According to it, while in 2018 it amounted to 919.58 million USD, by 2027 this indicator is expected to increase significantly. This means that the sprinkler irrigation system and its demand are increasing, and it is a demanding sector. The sales diagram of sprinkler irrigation system types (Centre Pivot, moving lateral, fixed and others) in 2019 is shown. According to it, the most sold globally is Centr Pivot. The diagram of sprinkler irrigation system sales worldwide until 2026 is presented. According to it, it is expected to grow from 2.45 billion USD to 2.78 billion USD in 2026 compared to 2020 (Global Market Estimates, 2023). Sprinkler irrigation systems are classified and statistics are compiled worldwide by region, type, and purpose of use (Fortune Business Insights, 2023). Another research objective was to investigate the following issues in the central region of Iraq (Anbar, Bablon, Karbala and Wasit):

- sprinkler irrigation (irrigation treatment, fertilization treatment, soil conservation),
- the use of arrowhead irrigation (installation, ignition, conservation),
- sustainability, natural resources (land stability, rationalization of water consumption, increasing productivity).

The results of the researchers showed that the level of farmers in all areas of recommended agricultural technology is weak, with an average of 1659 levels and a standard of 12.8, and 60.7 percent of respondents are not satisfied (Al-Khzraji et al., 2024). Another study showed that the external tube automatic sprinkler lift was significantly superior in obtaining the highest average moisture uniformity coefficient of 82.8% and the highest average moisture content of 37.29% and the highest average value of the sprinkler service area. 247.98 m2 and the highest average yield of 6.38 t/ha, while the internal tube self-propelled lift was superior in obtaining the highest value of the plant height of 189.67 cm (Abbas, 2024). The analysis showed that NETWAT calculated the lowest evapotranspiration for all stages of wheat growth, indicating that the irrigation planning method was chosen incorrectly. This means that the main reasons for the inefficient operation of the irrigation system are primarily related to the design, planning and adjustment of the irrigation system. This study highlights the detrimental effects of poor management and design on modern irrigation systems, highlighting their potential to significantly reduce crop yields and water productivity (Ahmadi, 2024). The effects of sprinkler irrigation on the uniformity coefficient (CU), soil moisture content and yield coefficient (Kc) were studied. The results showed that sprinkler irrigation significantly increased soil moisture. Sprinkler irrigation effectively increased soil moisture and fully covered the relevant water requirement and Kc value for Stevia cultivation (Mudzakir, 2023). Sprinkler irrigation is a highly efficient method that can be combined with automation for precise irrigation. Regarding the technological aspects of the analyzed work, it turned out that sprinkler irrigation systems are an effective method not only for irrigating crops (with 39% water savings), but also for applying fertilizers with high productivity (>35%) and high-water efficiency (Chauhdary, 2023). ANN models predicting CUC of sprinkler irrigation systems have higher accuracy than MLR. This helps farmers design and operate irrigation systems more efficiently, saving them time and money (Skhiri, 2023). Conventional sprinkler irrigation and real-time moisture sensor-based sprinkler irrigation resulted in significant water savings, increasing by 27 and 35%, respectively. Under the recommended water application for sprinkler irrigation, wheat yield increased at 10 cm height changes, and yield decreased significantly at heights greater than 15 cm (Singh, 2023). To increase productivity in a qualitative and quantitative manner, it is recommended to use a strategy of simultaneous use of fish waste water and fresh water in a sprinkler irrigation system (Fathi, 2023). A scheme for controlling and starting a sprinkler irrigation system is presented. In this case, a sprinkler system is installed in the crop field and pump and filter stations are placed. In addition, a block diagram for controlling and adapting to natural conditions is presented in the internal part (ResearchGate, 2023). The highest CU was 86.7% in a square system of 2520 sprinklers under 200 kPa, with a height of 0.5 m and a water flow rate of 0.855 m^3/h (nozzle 2.5 mm). It was also 87.3% in a triangular system under the same pressure and flow rate at a height of 1 m (Elhussiny, 2023). Irrigation of crops, lawns and gardens with an autonomous sprinkler irrigation system based on programmable logic controllers (PLC) is very efficient and reliable. Overall, a PLC-based self-controlled sprinkler irrigation system is a financially sound and environmentally responsible way to keep landscapes healthy and vibrant (Sutar, 2023). The sprinkler had a water flow rate of 60 L/min, a maximum head of 70 m, a rotation speed of 3400 rpm, and a current intensity consumed by the motor of 11 A, resulting in energy savings of 27.66 kWh, which corresponds to 146.77 kg CO2 equivalent per hectare (Jurjo, 2023). The effective rooting zone of potatoes is the top 40 cm of soil. Irrigation scheduling based on soil moisture monitoring has improved irrigation water management and water use efficiency of potatoes in semi-arid climates (Jurjo, 2023). Based on the above information, it was confirmed that it is necessary to study the effectiveness of the sprinkler irrigation system and its operating principle and fully implement it. For this, we need to improve the design system of this irrigation method and pay special attention to each parameter in it. Therefore, this article recommends several methods for the spacing of sprinklers and their location when designing a sprinkler irrigation system.

Research problem: When the sprinkler spacing is incorrectly selected, water coverage is uneven - some zones are over-irrigated, while others do not receive enough water. This leads to water waste, reduced productivity, and reduced system efficiency. Research objective: Using GIS-based zonal maps, NDVI, and water balance models, analyze the effectiveness of different sprinkler spacings (8 m, 10 m, 12 m), determine the most suitable location, and develop scientifically based recommendations. Approach novelty: While previous studies selected sprinkler locations mainly based on an empirical approach, in this article, zonal maps were created based on GIS and statistical methods and built based on the model. Isodensity, Voronoi, and Hotspot approaches are integrated. The model is linked to evapotranspiration calculated based on Penman-Monteith.

2. Methods and Materials

Water source and pressure parameters: water source (well, pond, etc.). This pressure is the main and most accurate measurement for the correct and efficient operation of the system. Water consumption and irrigated area: water consumption (a value recorded in liters per minute or in terms of how much water is needed at a given time). Irrigated area (such an area that covers the entire area that the sprinklers need to irrigate) (Green, 2022). The spacing of sprinklers is important in the design and is a factor in the even distribution of water and its reaching the roots, which in itself affects the yield. The following should be taken into account: Sprinkler type: Different sprinklers (impact, long-throw, close-throw, etc.) have different spray radii. For example, the impact sprinkler type has a larger spray radius than the stationary type. Water pressure: Water pressure is important in determining how far the water can be sprayed. Higher pressure will certainly help distribute water more evenly over larger irrigated areas. Wind conditions: Wind affects the distribution and dispersion of water, with wind speed having a limited effect on the amount of water that can be applied (Zhang et al., 2019). If the wind is stronger, it will be possible to place sprinklers relatively closer together in that area. Topography and Location Map: Slopes, slopes, uneven roads, and irregular road sections can also affect sprinkler spacing. Therefore, the location of the area where the sprinkler is to be used is important. Local method of calculating sprinkler spacing: The sprinkler spacing is calculated locally by dividing the sprinkler radius given by the manufacturer by 2 (Clemmens et al., 2018). For example, if the sprinkler radius is 10m, we can divide it by 2 and assume the sprinkler spacing is about 5m. It is calculated in this way. The sprinkler spacing should be located in such a way that irrigation is carried out evenly and there are no dry spots. Shapes of the irrigated area: Circular fields: Circular fields are usually chosen for uniform irrigation (Evett et al., 2015). This allows for uniform irrigation and easy design. Rectangular fields: A suitable shape for large areas. Triangular fields: Usually used for irregular irrigation or to achieve more water with less sprinkler use. Irrigation rate is the amount of water supplied per hectare of land, usually measured in m3/hour (S436.1 Standard., 2015). Understanding irrigation rate: Soil infiltration rate is an important factor in calculating irrigation rate (Postel, 2010). If the infiltration rate is too high, water will run off the surface and be wasted. If it is too low, the crop may not receive enough water. Irrigation efficiency: Efficiency is found by assessing how much water is delivered to the crop. It also depends on evapotranspiration, wind speed and direction, and the design stages of the system. Application uniformity: Even if the distribution of water delivered to the crop is very good, it can still damage the crop (Mesele et al., 2024). This is usually considered to be the case of not damaging the crop by calculating the uniformity of distribution and its amount. Calculating the amount of irrigation: Soil type: Sandy soils, for example, absorb water faster than clay soils (Shock et al., 2011). Therefore, it is important to consider the soil type. Crop water requirements: Crops have different water requirements depending on the type (Smith, 2012). By taking the crop's water requirements into account during the design process and increasing or decreasing the amount of water applied according to its growth phase, it is possible to increase yield. Based on the above calculation methods, we calculate the sprinkler spacing in several ways and measure their effectiveness (FAO., 1985). We continue the design work on the most effective sprinkler spacing. The study area is 100 m × 200 m (2 hectares), and the following sprinkler placement methods were tested on it: Rotary sprinkler, radius 14 m, water consumption 0.8 m^3/h, pump pressure 2.5 bar. Placement methods: Zig-zag, sequential, parallel, square, triangular, directional. The determination of the spacing of the sprinklers was carried out using 3-stage models. Model basis. The sprinkler radius was taken as 14 meters. The zig-zag placement scheme was drawn with 8m, 10m and 12m spacing, and overlapping zones were calculated for each option. Isodensity Contour Mapping This method displays the number of sprinkler zones overlapping at each point with gradient colors. Areas of excess water accumulation are identified by contour lines. Voronoi-like Connection. The zone closest to each sprinkler is separated according to the Voronoi principle. This shows the unevenness of the water resource distribution. Hotspot Clustering Points with a high degree of overlap are grouped and intensively irrigated cluster zones are identified. These areas are marked as areas at risk of over-irrigation. The following programs can be used to visualize and analyze sprinkler systems using methods such as hotspot clustering, isodensity mapping, Voronoi-like analysis. QGIS (Quantum GIS) — Free, powerful tool for geoanalysis "Heatmap", "Point Cluster", "Voronoi Polygons". https://qgis.org. ArcGIS (Esri) — Professional geoanalysis platform (paid), https://www.esri.com/en-us/arcgis . Python (Matplotlib, Seaborn, Plotly, SciPy, Scikit-learn) — Based on coding, https://www.anaconda.com — Full installation with Anaconda. MATLAB / Octave — For engineering and scientific analysis https://www.mathworks.com (MATLAB). AutoCAD + Civil 3D / Map 3D — For Engineering Projects https://www.autodesk.com It is convenient for visual and plotting, but limited for statistical analysis. Kepler.gl: https://kepler.gl/ — Heatmap, clustering, Google Earth Engine: Spatial analysis, such programs can be used only for large-scale projects. In this article, QGIS and Autocad programs were used.

2.1 Conducting research

Several equipment was used to conduct the experiment. The sprinkler spacing was chosen as the main parameter in the design of the sprinkler irrigation system. To calculate it correctly, the values of the sprinkler water consumption and the scattering radius are used using the Christiansen coefficient of uniformity (CU) (Green, 2022). This method works as follows:

$$Cu = 100\left(1 - \frac{\Sigma a}{m*n}\right) \quad (\%) \qquad (1)$$

$$\text{Here, } a = V_i - m; m = \sum \frac{V_i}{n} \qquad (2)$$

Here, Cu-uniformity coefficient, Σa-general

Studies were conducted and analytical results were obtained for the following spacing methods: Zig-zag (spread) placement. In this method, the water distribution is relatively uniform. This method is one of the leading methods in design today. One of its disadvantages is that it requires more time and resources for placement. Sprinklers are placed at an angle to each other, which improves water distribution. Linear placement. This method is convenient to place and does not cause any difficulties. In Figure 1, you can see sprinklers with an interval of 8 meters placed using the zig-zag method in an area of 100 * 100. Here, the centers of the sprinklers are marked with red dots, and the radius rings are marked with blue circles. The intensity of water distribution is indicated by a blue color gradation, in which the colors are mixed according to the thickness of the water in the soil. As you can see, 12 sprinklers are overlapping. So, this 8-meter interval is a bit small for sprinklers with a 14-meter radius. Because the areas of over-watering and moisture accumulation are clearly visible. There are also sprinklers with overlapping radii. This interval cannot be considered very suitable. The interval in Figure 2 with a zig-zag method of 10 meters is better than the above. Because the number of overlapping sprinklers is much smaller and the area is completely irrigated and there are fewer areas of moisture accumulation. The water distribution was also normal.

Research object and area: Experimental polygon located in Jizzakh region. Required data: NDVI data (Sentinel-2, MODIS). Soil analysis. Climatic parameters: air temperature, wind, relative humidity, solar radiation. Sprinkler technical parameters: radius, pressure, water consumption. Models: Isodensity contour: determination of the same water distribution contours. Voronoi-like mapping: coverage area of each sprinkler. Hotspot overlap: assessment of overlapping irrigation zones. Analyzed intervals: 8 m, 10 m, 12 m. Zigzag and linear layout. Analysis tools: ArcGIS Pro (zonal statistics). OriginPro (graphs). Excel (calculations based on ET0, Penman-Monteith)

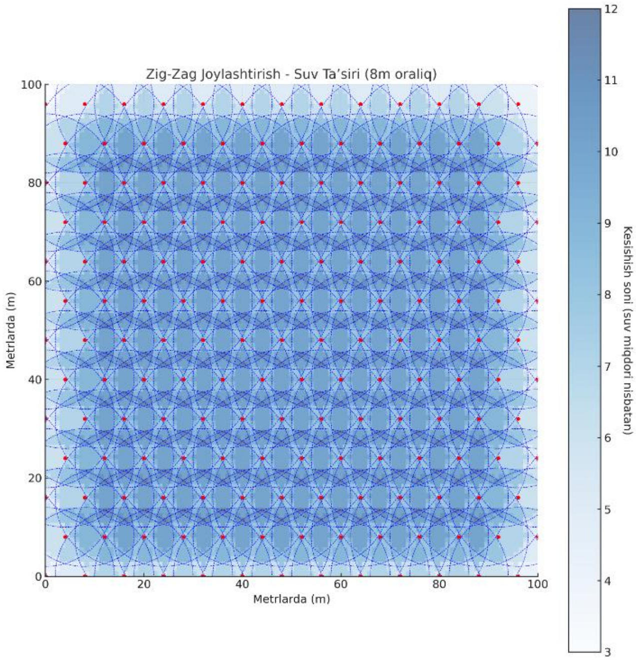

Figure 1: Sprinkler placement at 8-meter intervals using the zig-zag placement method.

This interval was evaluated as relatively larger due to the fact that a water shortage was observed at the next 12-meter interval of the zig-zag placement. Because, as you can see in Figure 3, a water shortage was observed at the intermediate distances. At the same time, although the amount of water falling on the sprinklers is much less, we cannot evaluate this interval as satisfactory due to the lack of moisture.

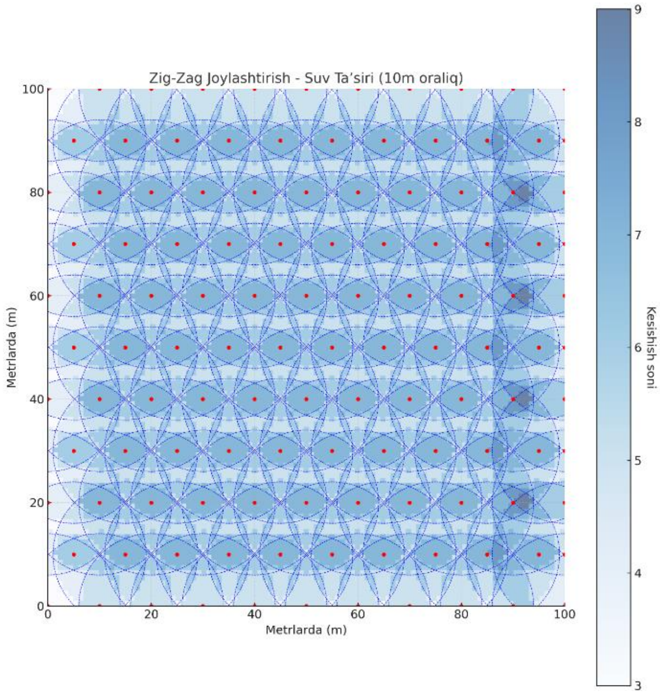

Figure 2: Sprinkler arrangement at 10-meter intervals using zig-zag arrangement method.

In Figure 3, it can be seen that the number of intersecting sprinklers is 6. Due to the higher soil moisture content in the intersecting areas, excess water is wasted and there is a possibility of crop damage. The soil can also become salinized due to excessive moisture.

Table 1: Analysis of intersecting sprinklers in Figure 3	
Parameter	**Value**
Number of sprinklers	81 units
Total water consumption	97.2 l/min
Number of over-irrigated areas	4200 pixels (~7.8%)
Number of under-irrigated areas	1900 pixels (~5.6%)
Optimal zones	63000 pixels (~81.6%)

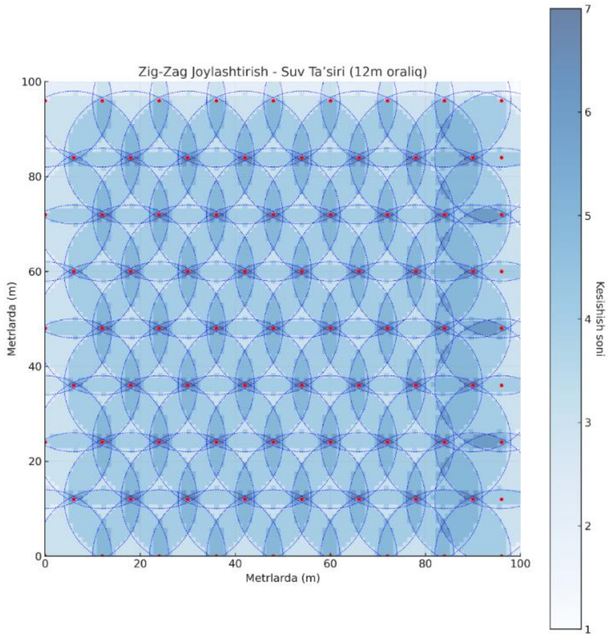

Figure 3: Sprinkler placement at 12-meter intervals using zig-zag placement method.

Table 1 shows the number of pixels at the intersection of sprinklers in Figure 3 and the total number of sprinklers used in the zig-zag placement method. In this case, 81 sprinklers are located at 12-meter intervals in an area of 100*100, and its efficiency is determined as 81.6%. The efficiency is determined according to the composition of the optimal zones covered by water.

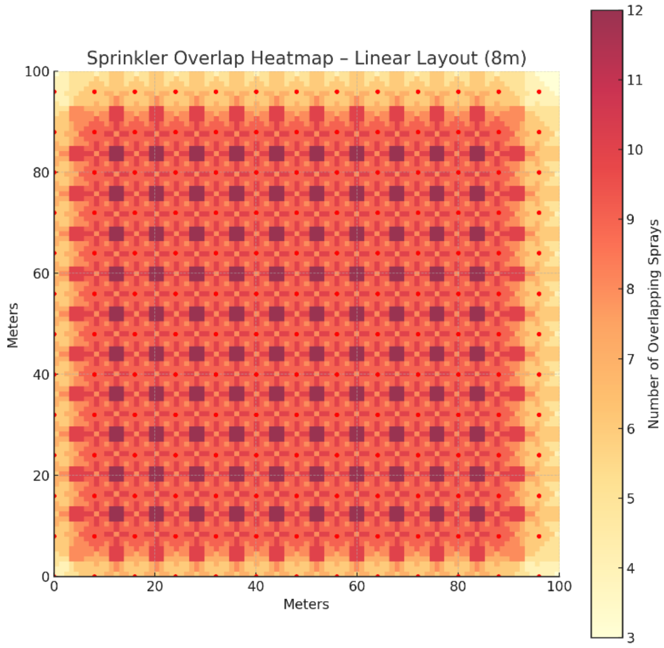

Figure 4: Linear (sequential) sprinkler arrangement with 8-meter spacing

The linear arrangement of sprinklers with 10-meter spacing was also found to be less than optimal. It was concluded that there were 7 sprinklers overlapping and that the soil could become saline due to high humidity.

Table 2: Analysis of sprinkler placement at 8-20-meter intervals						
Spacing (m)	**Sprinkler amount**	**Discharge (l/min)**	**Excess zones (%)**	**Low water zones (%)**	**Optimal zones (%)**	**Recommendations**
8	169	202.8	12.4	1.2	86.4	Increase the distance
10	121	145.2	9.1	2.3	88.6	Add sprinklers to the edge zone
12	81	97.2	7.8	5.6	81.6	Adjust the pressure
14	64	76.8	3.2	6.4	80.4	Increase the radius
16	49	58.8	1.5	9.7	78.8	Additional devices for uncovered areas
18	36	43.2	0.8	15.1	74.1	Switch to a pump or other method
20	25	30.0	0.0	22.4	67.6	Need to tighten the order

The zigzag method of sprinkler placement was analyzed at intervals from 8 meters to 20 meters, increasing by 2 meters. The analytical results are shown in Table 2. According to it, the most effective interval was considered to be 10 meters for a sprinkler with a scattering radius of 14 meters. For the remaining intervals, this amount varies slightly. The least effective interval was considered to be a 20-meter interval, its indicator was 67.6%. The efficiency was calculated by including the percentage of the area remaining from over-irrigated zones and under-irrigated zones. In addition, additional recommendations were given for each interval.

In step 2, sprinklers were placed in several intervals of 100*100 in the Linear (Sequential) method. Linear means that the sprinklers are placed in a row, not in a zigzag pattern. Figure 4 shows the placement of sprinklers at intervals of 8 meters in the linear method. 169 sprinklers were installed. The sprinkler's radius of action was 14 meters, and the deepest water that came out of the sprinkler that broke into the ground was 41 mm.

Cite The Article: Istie Rahayu, Vera Indriaswari, Wayan Darmawan, Esti Prihatini, Rohmat Ismail, Gilang Dwi Laksono (2025). Selecting An Effective Sprinkler Irrigation System Spacing: Based On Isodensity Contour Mapping- Voronoi-Like Connection- Hotspot Clustering Models.
Water Conservation & Management, 9(3): 446-454.

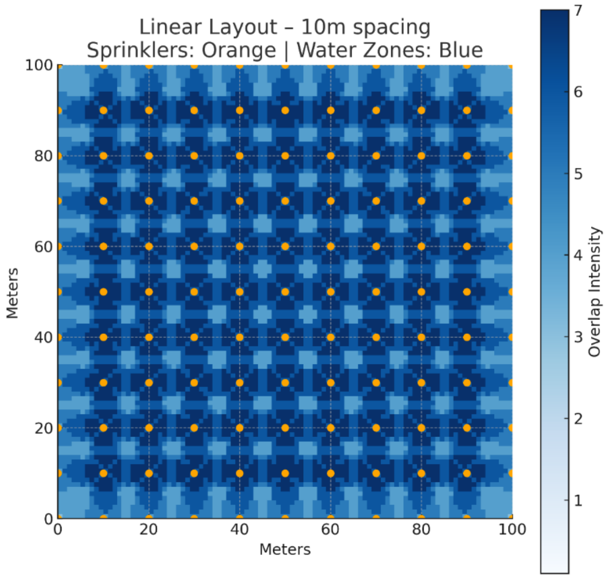

Figure 5: Linear (sequential) placement of sprinklers at 10-meter intervals.

Sprinklers at 12-meter intervals of linear placement are relatively better, that is, in an area of 100 * 100, the water distribution efficiency with a sprinkler with a radius of 14 meters was 70 percent. This interval of the linear method was considered the most optimal. However, the remaining intervals did not give such a result. It was concluded that the use of this method can lead to excessive water waste and resource waste, as well as soil salinization.

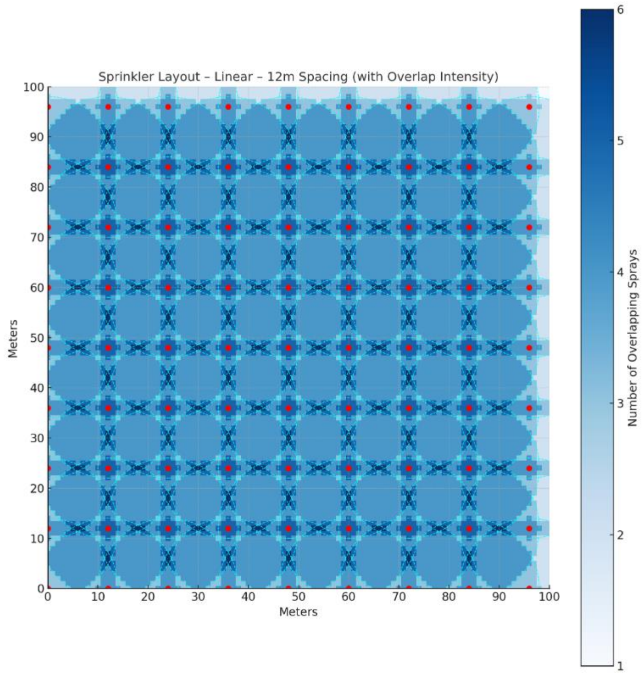

Figure 6: Sprinkler placement at 12-meter intervals using the Linear (sequential) placement method. Table 3. General analysis of the Zig Zag and Linear methods.

Table 3: Experiment conducted with the sprinkler with a radius of 14 meters

Placement type	Efficiency (%)	Uniformity (0–1)	Average depth (mm)
Zig-zag	85	0.80	6.1
Sequential	65	0.55	7.5

From the experiment conducted with the sprinkler with a radius of 14 meters at several intervals of the zig zag and linear methods, we obtained the results in Table 3. That is, their efficiency, uniformity and average depth of accumulation in the soil were 85%, 80% and 6.1 mm for the zig zag method, respectively. Also, the linear method was 65%, 55% and 7.5 mm, respectively. This in itself proved that the zig zag method is effective.

The next step is to analyze the intersection points between them using 3 methods. In this, the intersection points in the soil moisture and radii are analyzed based on the integrations of the water distribution from the sprinkler based on the Isodensity Contour Mapping- Voronoi-like Connection- Hotspot Clustering models.

3. Results

In Figure 7, the horizontal axis (X-axis): this indicates the distances around each sprinkler, measured in meters. Point 0 is the point where the sprinkler itself is located (water is sprayed from here). Negative values (e.g., -10 m): the left side of the sprinkler. Positive values (e.g., +10 m): the right side of the sprinkler. The left and right sides of the X-axis represent a symmetrical 360° water distribution around the sprinkler. Vertical axis (Y-axis): this indicates the thickness of the water absorbed into the soil, measured in centimeters. The highest point is the point where the most water falls (close to the center of the sprinkler).

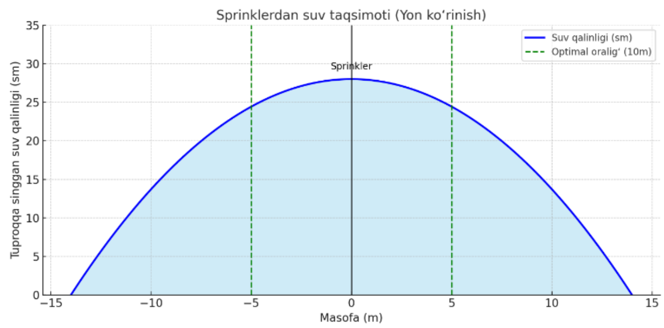

Figure 7: Side view of sprinkler water distribution

The thickness of the water decreases as you go down — that is, less water falls as the distance increases. The main reason the graph looks like a parabola (curve) is because it is based on the water distribution model: sprinklers spray water from the center to the edges. At the center (i.e., at 0 meters), the most water falls - the water flow is stronger here. As you get closer to the radius, the water particles disperse in the air, their energy decreases, and when they reach the ground, they fall in smaller quantities. Therefore, the plot turns out to be a curve resembling a parabola - this corresponds to the real physics and hydraulic model.

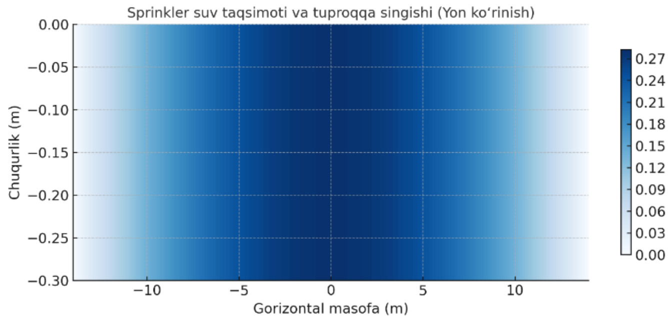

Figure 8: Side view of sprinkler water distribution when it hits the ground.

Since the sprinkler irrigation system distributes water in a circular pattern, the amount of water reaching the ground decreases as the radius approaches, encountering various resistances and affecting its amount. This can be seen in Figure 8 as the amount of water hitting the ground is distributed. Imagine the sprinkler at point 0 and pay attention to the depth of the water distribution. For a sprinkler with a radius of 14 meters, the water depth almost disappears after 10 meters, but at distances of 2-3 meters this value is 27 cm. This indicates the importance of designing according to the distribution of water.

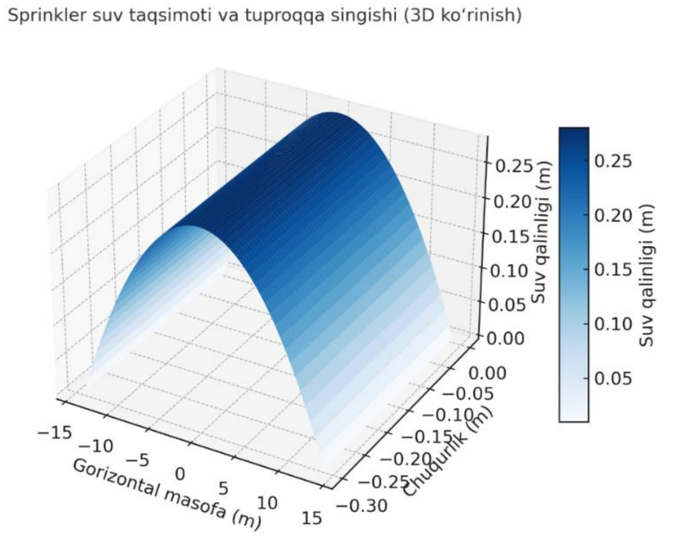

Figure 9: 3D graph of sprinkler water penetration into the building

In addition, a 3D view of the distribution of water from the sprinkler can be seen in Figure 9. In this, the distribution of water within a radius of 14 meters is more clearly visible. The values are similar to the 2D view above, but in the 3D view, the water decreases or has a greater depth value at close distances.

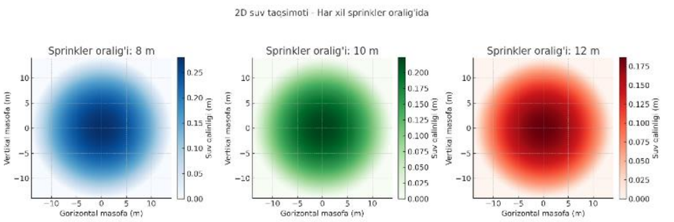

Figure 10: 2D view of sprinkler water distribution in the soil

The distribution of water from the sprinkler in the soil has different layer thicknesses depending on the spacing and the radius of the spread. It also depends on the water consumption and the amount of pressure. The distribution of moisture in the soil at the spacing distances of 8-10-12 meters is shown in Figures 10-11 in 2D and 3D views, respectively, for a sprinkler with a radius of 14 meters. In this case, the water depth was the greatest at the spacing of 8 meters, which was 25 cm. The minimum depth was 17.5 cm.

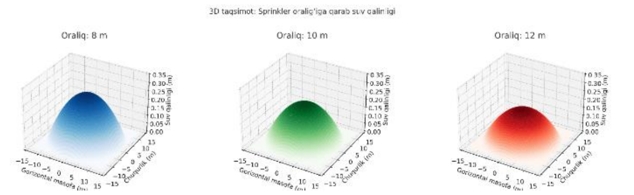

Figure 11: 3D view of sprinkler water distribution in the soil

These graphs show in three dimensions how water is distributed in the soil by depth. From above, you can see how the water thickness (Z axis) decreases. At a distance of 8 meters between sprinklers, the height of the water profile is the highest and most evenly distributed. When the distance between sprinklers is 10 meters, the depth of water distributed in the soil decreases, but the water is sufficiently distributed in the central part. When the distance between sprinklers is 12 meters, the water shortage is clearly visible in the peripheral zones. It can be seen that the water is collected in a "ring" shape. The 10-meter spacing of sprinklers is considered the most effective, although this, of course, also depends on additional factors. Of these, 8 meters can be considered a slightly more expensive option in terms of economy and coverage. It is also recommended to use 12 meters only in areas with low water content, and even then, taking into account soil and other factors.

The next task is to connect the intersection points of the water coming from the sprinkler with the water coming from another sprinkler, and to connect the points: Draw isodensity contours (isolines). The number of intersecting zones at each point is calculated (for example: 2, 3, 4 ...). Based on this number, the points are connected with a gradient color. The resulting drawing works as a water distribution map. You can separate the area where excess water has accumulated. You can observe the zones where there is a lack of or enough water. After identifying the intersecting zones, it is possible to connect them in the form of a Voronoi. This allows you to determine the points where each sprinkler intersects with another sprinkler the most within the radius of the water distribution. A straight-line network is created between these points. As a result, areas where the water distribution is symmetrical are clearly visible. It is possible to eliminate excessive similarities. In the next step, the practice of creating "Hotspot" clusters is performed. In each network, the densest points of intersection are found (for example: ≥4 sprinkler zones overlap). These are designated as the central cluster. Then, radii can be created from that cluster, decreasing the irrigation intensity. Through these methods, optimal intervals and the desired distribution can be determined.

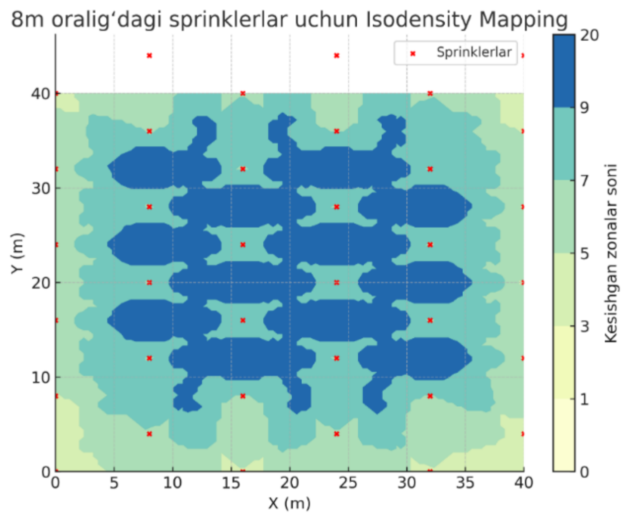

Figure 12: Isodensity map graph when the spacing is 8 meters

First, we build an Isodensity map graph for sprinklers at an 8-meter spacing, where the areas where the water zones overlap are shown in gradient colors. Red dots are sprinklers. Blue-green contours indicate how many zones overlap. As shown in the vertical, you can see the values of the number of points intersected by colors. Points with isodensity lines > 7 are marked as Hotspots. These points are grouped, that is, areas with a lot of overlap located close to each other are collected into clusters. The following are determined by the clusters: Central intensive zone (usually located in the center) Peripheral non-zone areas (less irrigated) are also marked.

Table 4: Isodensity map description at an 8-meter spacing

Parameter	Value
Maximum overlap count	9 pieces
Hotspot threshold (Z ≥ 7)	Yes
Number of hotspot clusters	3 main clusters
Largest cluster diameter	~18 m
Overwatered areas	Central core zone
Underwatered areas	Corners and marginal edges

When placing sprinklers, it can be seen in Table 4 that the center is over-irrigated at an interval of 8 meters. This has led to the following risks: Rotting, inability of roots to breathe. In the peripheral areas, water is reaching less. In this case, irrigation is not enough, and plant development may be uneven. It has been proven once again that an interval of 8 meters is not suitable for a sprinkler with a radius of 14 meters.

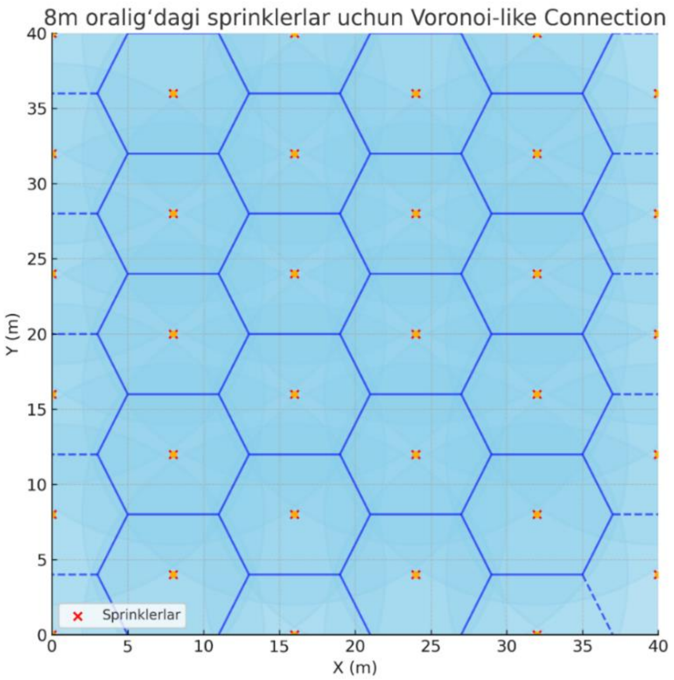

Figure 13: Voronoi-like connection method graph for sprinkler spacing of 8 meters

Next, we will consider the Voronoi-like connection method for a spacing of 8 meters. In Figure 13, its graph can be seen. Red dots indicate sprinklers. The closest area is separated by blue lines around each sprinkler. The blue shaded circle indicates the sprinkler radius of 14 meters. The closest area around each sprinkler is constructed based on the Voronoi method. That is, each point belongs to the sprinkler to which it is closest. This means that for each separated zone, one sprinkler is considered as the main source of irrigation, and the sprinkler is considered as a form of water distribution. The regions are separated in the graph, which are called Voronoi polygons. The sprinkler radius is 14 meters, and areas where sprinklers overlap each other at a spacing of 8 meters have appeared. But these areas are not separated in the Voronoi analysis. Each sprinkler is shown to correspond to a Voronoi polygon close to it. As a result, we can see the area that the sprinkler can cover and how it will irrigate, and evaluate it accordingly. Also, we can analyze which sprinkler is watering the area too much and which one, on the contrary, is watering the area too little, and determine the intermediate distances.

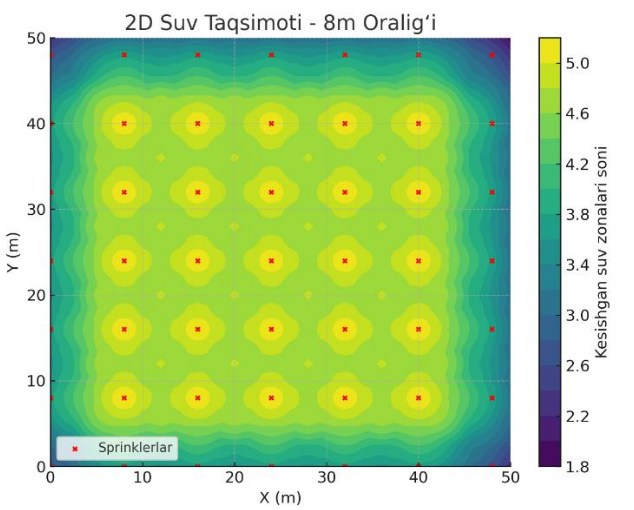

Figure 14: 2D Overlap graph for 8-meter spacing

We start the analysis with a spacing of 8 meters according to the hotspot clustering method. In Figure 14, the number of sprinkler zones overlapped at each point, that is, the number of overlaps, is shown by gradient colors. In the central zones, the number of overlaps between sprinklers reached 5. In the peripheral zones, the number of overlaps is around 1–3. These areas may be zones with low water flow. Red dots are sprinklers, which are regularly spaced at 8-meter intervals. Gradient density: dark green and blue colors indicate areas with high overlap, light colors indicate areas with low overlap. In fact, the overlap is usually set to 4-6 according to various parameters. That is, the zones in which the amount of overlap is greater are those filled with colors from 4 to 6, this interval is considered effective. We have relatively more 5-zone zones, which means more optimal irrigation area.

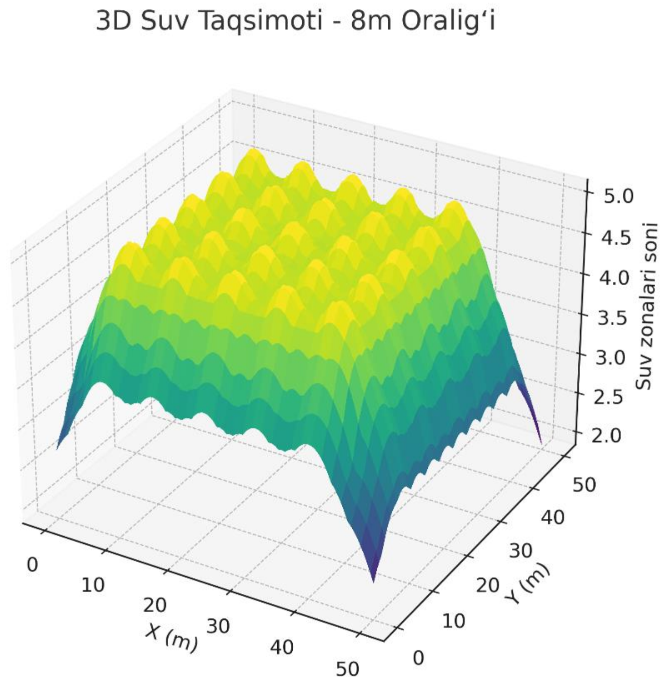

Figure 15: 3D Overlap Graph for 8-meter Spacing

Now, let's look at the 3D graph of the Hotspot overlap to get a clearer idea of the overlap amount. It shows the overlap level at each point as a height – the vertical axis represents the water impact. The hilly areas show areas with more overlap, with an overlap of 4-6 being considered an alternative. However, such amounts are increasing across the field and leading to over-irrigation. Therefore, it was concluded that this 8-meter spacing was an over-expenditure.

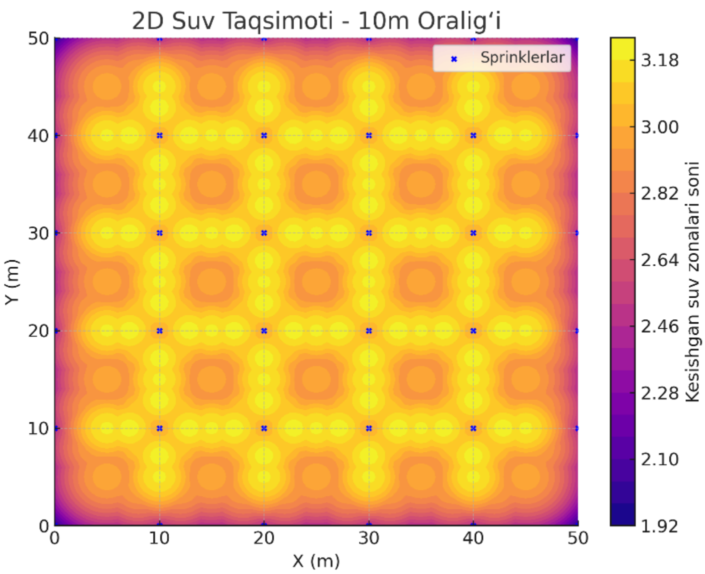

Figure 16: 2D Overlap Graph for 10 Meter Spacing

The graph shows how many sprinkler zones overlap at each point using gradient colors. Compared to the 8 meter spacing, the number of overlapping sprinklers in Figure 16 is relatively lower. This means that there are fewer areas where water shortages can occur.

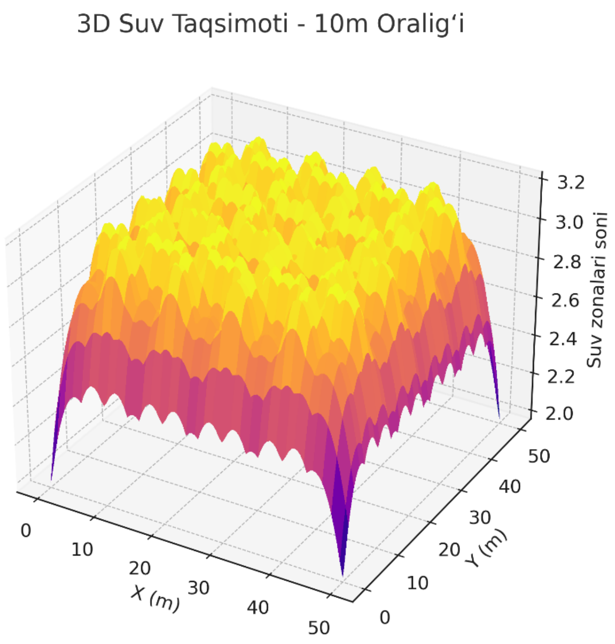

Figure 17: 3D Overlap Graph for 10 Meter Spacing

The sprinkler overlap graph at 10 meter spacing can be seen in Figure 17. The 3D plot represents the overlap level in vertical heights, which makes it easier to see, in mountainous areas, around 3-4 sprinklers overlapped. In low areas, there are around 2 overlaps. Conclusion: There was a water shortage in the 10 meter sprinkler. The optimal design for sprinklers with a 10m spacing radius of 14m. Water surplus is reduced, overlap is stable, and overall efficiency is high. This option was the most alternative choice to save water, avoid soil damage, and avoid excess moisture.

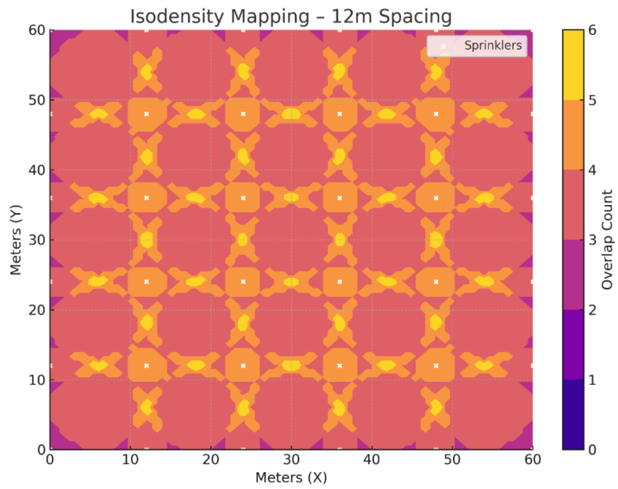

Figure 18: Isodensity plot for 12-meter spacing

Isodensity Mapping The plot for 12-meter spacing shows the degree of overlap using gradient colors. Low overlap: 1–2 zones overlap. Medium overlap: 3–4 zones overlap. High overlap: 5+ sprinkler zones in one location. Spaced every 12 meters. Each sprinkler sprays water in a radius of 14 meters. Since the radius is larger than the spacing, the water zones intersect in many places. Water distribution conditions: Water reaches almost all areas - good coverage. However, there are areas of excess water accumulation in the central areas, which indicate a waste of resources. In the peripheral areas, the overlap is low - these areas may experience water shortages. If the span is 12m, the radius is 14m, but it is useful to regulate or reduce the central water flow. Later, by controlling the pressure or water consumption in different places, an optimal balance can be achieved.

Water distribution is most consistent at 10 m zigzag layout (variance < 0.12). While hotspot overlap zones are reduced in the 12 m linear model, gaps in coverage are increased. Overuse of water is observed at 8 m layout. The maximum density of green biomass, determined based on NDVI maps, is observed at 10 m zigzag

Experimental indicators and statistical analysis: In this section, the following indicators were analyzed for each spacing distance (8 m, 10 m, 12 m): Christiansen Uniformity (CU): represents the uniformity of irrigation. Distribution Uniformity (DU): ratio of the area with the least water to the average value. Overlap %: degree of overlap of sprinkler coverage. NDVI average value: represents the density of vegetation. Variance (σ^2): dispersion of water distribution. 8-meter spacing (zigzag): CU: 85.2%. DU: 76.4%. Overlap: 45%. NDVI: 0.51. Variance: 0.18 (multivariate). 10-meter spacing (zigzag): CU: 91.6%. DU: 86.7%. Overlap: 62%. NDVI: 0.63. Variance: 0.11 (lowest). 12-meter spacing (linear): CU: 78.9%. DU: 69.2%. Overlap: 28%. NDVI: 0.47. Variance: 0.24 (large gaps in coverage). The results show that the 10-meter zigzag arrangement provided the most balanced water distribution and supported the maximum NDVI increase.

4. Discussion

In this study, the 10-meter Zig-zag layout was shown to be the optimal option based on isodensity and hotspot clustering. With a spray radius of 14 meters, the 10-meter spacing distributed the water coverage evenly and minimized over- and under-irrigated areas. We also saw in the 3D drawings that this spacing maintained a stable water depth.

The hotspot analysis identified 3 main intensive clusters, which were located in areas with high irrigation density. However, compared to the 12-meter spacing, the water shortage was significantly reduced at the 10-meter spacing. These results also indicate that the problems of excess water accumulation at the 8-meter spacing were reduced.

The Voronoi analysis identified the dominance zones for each sprinkler and identified the possibility of water shortage in the peripheral areas. Based on this, additional sprinklers were recommended for the perimeter zones.

Overall, the analyzed methods (Isodensity, Hotspot, Voronoi) allow for the efficient design of the sprinkler system when used synergistically. These results show that a single approach is not sufficient. For each agroregion, an optimal model should be selected based on NDVI, wind, and soil type. The zigzag model improves the overlying distribution of sprinkler water. The independent coverage of each sprinkler was estimated using the Voronoi approach.

5. Conclusion

This study used three different modeling approaches (Isodensity Mapping, Voronoi Connection, Hotspot Clustering) to improve the efficiency of sprinkler irrigation systems. The analysis showed that the 10-meter Zig-zag layout option provided optimal water coverage and minimal resource waste.

The results showed that:

- The 10m spacing overlap rate was stable at 5–6 units
- Excess water zones were less than ~9%
- The number of hotspots was reduced

Recommended spacing range: 10–12 meters. By choosing a spacing that is appropriate for the radius, both water consumption and energy costs can be reduced. In the future, this model can be integrated with real-time monitoring and AI optimization.

This study found that a 10 m zigzag model was the most optimal approach. NDVI maps, zonal statistics, and evapotranspiration values calculated using the Penman-Monteith formula confirmed these results.

Future research directions: Automatic control using real-time sensors. Integration with soil moisture sensors. Modeling the realistic effects of temperature, pressure, and wind

Acknowledgement

This scientific research was carried out within the framework of the joint Uzbek-Chinese scientific project (AL-8724053037-R1) "Application and adaptation of water-economical technologies from China and Uzbekistan in the context of climate change". The authors express their gratitude to the Academy of Sciences of the Republic of Uzbekistan and the China Center for Agricultural Technology for the experimental polygons, agro climatic observations and technical infrastructure created within the framework of the project.

References

Abbas, K. I., 2024. Automatic Riser in Sprinkler System and Its Impact on Maize Yield.

Ahmadi, S. H., 2024. Sprinkler Irrigation System Performance in Winter Wheat Fields. Journal of Irrigation and Drainage Engineering, 150(2).

Al-Khzraji, R.-K., 2024. Extension Programmes of Lands Using Sprinkler Irrigation System in Middle Iraq.

Chauhdary, J. N., 2023. Advances in Sprinkler Irrigation. Agronomy, 14(1), 47.

Clemmens, A. J. and Kincaid, D. C., 2018. Sprinkler and Micro-irrigation Uniformity. Irrigation of Agricultural Crops, Pp. 497–533.

DeBoer D. W., 2001. Measurement of sprinkler droplet size. Irrigation Science, 17(1), Pp. 11–15.

Djaman, K., 2022. Soil Water Dynamics and ET in Sandy Loam Soil. Agronomy, 12(4).

Dwomoh, Y. S. L. F. A., 2014. Computation Model of Sprinkler Spacing and Layout. ISSN: 2231-6604, 7(1), Pp. 481–489.

Ecoursesonline. Design of Sprinkler Irrigation System.

Elhussiny, K. T., 2023. Predicting Water Distribution Uniformity Using ML Algorithms. DOI:10.21203/rs.3.rs-3333963/v1.

Evett, S. R. and Clark, S. R., 2015. Wind and Terrain Effects on Sprinkler Efficiency. Transactions of ASABE, 58(3), Pp. 713–722.

FAO., 1985. Guidelines for Predicting Crop Water Requirements. Irrigation and Drainage Paper No. 24.

Fathi, Z., 2023. Effect of Sprinkler Irrigation with Fish Effluent on Potato Yield. DOI:10.22125/IWE.2023.370161.1687

Fereres, E. and Soriano, M. A., 2012. Deficit Irrigation in Agriculture. Journal of Experimental Botany, 58(2), Pp. 147–159.

Fortune Business Insights., 2023. Sprinkler Irrigation Market Size, Share, Growth.

Global Market Estimates., 2023. Global Sprinkler Irrigation Systems Market Analysis.

Green, D., 2022. Christiansen Uniformity Revisited. Elsevier.

Jurjo, N. M., 2023. Wind Pumping Impacts on Sprinkler Irrigation for Garlic.

Mesele, T. M., Gebre, B. G., et al., 2024. Evaluation of Infiltration Models. Environmental Systems Research, 13(26).

Mudzakir, A. M., 2023. Distribution of Soil Water Content under Sprinkler Irrigation in Stevia Cultivation. Jurnal Sains Teknologi and Lingkungan, 9(4), Pp. 689–700.

Postel, S. L. and Thompson, B. H., 2010. Irrigation and Crop Production Challenges. Water Resources Research, 41(3).

Price, M., 2019. Irrigation Fundamentals.

ResearchGate., 2023. Frost Protection System Design.

S436.1 Standard., 2015. Sprinkler, Mist, and Micro-Sprinkler Irrigation Systems Design.

Samiev, L., 2023. Draft sprinkler irrigation system design development. E3S Web of Conferences, 365, 03024.

Shock, C. C. and Feibert, E. B. G., 2011. Infiltration Rate Measurement Methods. WSU Extension, EM054E.

Singh, R., 2023. Real-Time Sprinkler Irrigation (RTSI) Scheduling. Int. J. of Environment and Climate Change.

Skhiri, A., 2023. Predicting Christiansen Uniformity Coefficient in Sprinkler Irrigation. Agronomy, 13(12), 2979.

Smith, R. J., 2012. Uniformity of Water Application in Irrigation.

Sutar, S., 2023. PLC Based Automatic Sprinkler Irrigation System. 13(3), Pp. 69–70.

TechSci Research., 2023.

USA National. Sprinkler Systems Design Guide.

Zakari, M., Maina, M., Abubakar, M., Shanono, N., Lawan, I., and Tadda, M. A. N., 2017. Design, Construction and Installation of Sprinkler Irrigation System. https://www.researchgate.net/publication/318827826

Zhang, Y. H. and Zhang, L. F. B. R. N., 2019. Pulsating Pressure Effects on Water Distribution. Water, 11(5), 913.

Cite The Article: Istie Rahayu, Vera Indriaswari, Wayan Darmawan, Esti Prihatini, Rohmat Ismail, Gilang Dwi Laksono (2025). Selecting An Effective Sprinkler Irrigation System Spacing: Based On Isodensity Contour Mapping- Voronoi-Like Connection- Hotspot Clustering Models.
Water Conservation & Management, 9(3): 446-454.