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ABSTRACT

Optimization of irrigation uniformity studied is a modeled procedure that improves the quantity and quality of agricultural products simultaneously by enhancing the system's performance based on delivering appropriate water through the nozzles along with the center-pivot irrigation system. The ability to successfully optimize uniformity is highly dependent on various factors such as operating conditions, hydraulic parameters, and system specifications. Accordingly, there is a need for improved center-pivot systems performance, and the obtained results hold promise for the successful application of the provided methodology. The immediate objective of this research project is to improve the hydraulic performance of the center-pivot system so that a developed model should be provided. The optimization is based on the water distribution modeling, and Heermann and Hein uniformity coefficient calculation of three existing Mini-Center Pivot Systems 60 m, 50 m, and 46 m in length. A genetic algorithm has been used to maximize the uniformity coefficient under the center-pivot system when the design parameters were input and combined with the adjusted formula of Heermann and Hein, to determine the optimum sizes and spaces of nozzles that affect the efficiency of the system, and thus enable the enhancement of irrigation uniformity. One objective is to use comparisons between the Heermann and Hein uniformity coefficient values obtained by the proposed model, and experimentally validate the proposed model's performance. The results of this study show that the proposed model has the potential to increase the values of Heermann and Hein uniformity coefficients by more than 17% and 19% depending on the optimization of the dimensions and diameters, respectively. In using more reliable equipment and inducting models of data treatment for predicting climatic variables using probability distributions, this study will contribute greatly to future research on similar topics.

RESUME

L'optimisation de l'uniformité d'irrigation étudiée est une procédure modélisée qui améliore simultanément la quantité et la qualité des produits agricoles par l'amélioration de la performance de système basé sur la distribution d'eau appropriée à travers les buses le long de système d'irrigation à pivot central. La capacité à optimiser avec succès l'uniformité dépend fortement de divers facteurs tels que les conditions de fonctionnement, les paramètres hydrauliques et les spécifications du système. En conséquence, il existe un besoin pour l'amélioration de la performance des systèmes à pivot central, et les résultats obtenus sont prometteurs pour l'application réussie de la méthodologie fournie. L'objectif immédiat de ce projet de recherche est d'améliorer la performance hydraulique du système à pivot central afin qu'un modèle développé soit fourni. L'optimisation est basée sur la modélisation de distribution d'eau et le calcul du coefficient d'uniformité de Heermann et Hein de trois système d'irrigation à mini-pivot central existants de 60 m, 50 m et 46 m de longueur. Un algorithme génétique a été utilisé pour

maximiser le coefficient d'uniformité sous le système à pivot central lorsque les paramètres de conception ont été bien entrés et combinés avec la formule ajustée de Heermann et Hein, pour déterminer les tailles et les espaces optimaux des buses qui affectent l'efficacité du système, et ainsi permettre l'amélioration de l'uniformité de l'irrigation. L'un des objectifs est d'utiliser des comparaisons entre les valeurs des coefficients d'uniformité de Heermann et Hein obtenues par le modèle proposé et les valeurs obtenues expérimentalement pour valider la performance de modèle proposé. Les résultats de cette étude montrent que le modèle proposé a le potentiel d'augmenter les valeurs des coefficients d'uniformité de Heermann et Hein de plus de 17 % et 19 % en fonction de l'optimisation des dimensions et des diamètres, respectivement. En utilisant des équipements plus fiable et en introduisant des modèles de traitement des données pour prédire les variables climatiques à l'aide de distributions de probabilités, cette étude contribuera grandement aux recherches futures sur des sujets similaires.

الملخص

تحسين انتظام الري المدروس هو إجراء نموذجي يعمل على تحسين كمية ونوعية المنتجات الزراعية في وقت واحد من خلال تحسين أداء النظام بناءً على توفير كمية مياه مناسبة عبر الفوهات على طول نظام الري المحوري المركزي. تعتمد القدرة على تحسين التوحيد بنجاح إلى حد كبير على عوامل مختلفة مثل متطلبات التشغيل والمعلمات الهيدروليكية ومواصفات النظام. وبالتالي، هناك حاجة إلى تحسين أداء الأنظمة المحورية، والنتائج التي تم الحصول عليها تبشر بالتطبيق الناجح للمنهجية المقدمة. الهدف المباشر لهذا المشروع البحثي هو تحسين الأداء الهيدروليكي لنظام الري المحوري بحيث ينتج عن ذلك توفير نموذج مطور. يعتمد التحسين على نمذجة توزيع المياه، وحساب معامل التوحيد لهيرمان وهاين لثلاث أنظمة محورية صغيرة موجودة بطول 60 مترًا و50 مترًا و46 مترًا. تم استخدام الخوارزمية الجينية لتعظيم معامل الانتظام لأنظمة الري بالمحور المركزي وإدخال معلمات التصميم ودمجها مع الصيغة المعدلة لمعادلة هيرمان وهاين، لتحديد الأقطار والابعاد المثلى للفوهات التي تؤثر على كفاءة النظام، وبالتالي تمكين تعزيز تجانس الري. من بين الاهداف المهمة للدراسة هو استخدام المقارنات بين قيم معامل الانتظام لهيرمان وهاين التي تم الحصول عليها بواسطة النموذج المقترح والقيم المحصل عليها تجريبيا للتحقق من صحة أداء النموذج المقدم. أظهرت نتائج هذه الدراسة أن النموذج المقترح لديه القدرة على زيادة قيم معامل الانتظام لهيرمان وهاين بأكثر من 17٪ و19٪ اعتمادا على تحسين الابعاد والاقطار على التوالي. باستخدام معدات أكثر موثوقية وادراج نماذج لمعالجة البيانات للتنبؤ بالمتغيرات المناخية باستخدام التوزيعات الاحتمالية، ستساهم هذه الدراسة بشكل كبير في البحث المستقبلي حول مواضيع مماثلة.

DEDICATION

I dedicate my dissertation work to my family and many friends, whose have been a constant source of support and encouragement during the challenges of graduate school and life. I am truly thankful for having you in my life. A special feeling of gratitude for my loving parents, who have always loved me unconditionally and whose good examples have taught me to work hard for the things that I aspire to achieve.

I dedicate this work and give special thanks to my best wife and my wonderful son and daughter for being there for me throughout the entire doctorate program. Both of you have been my best cheerleaders. Last, but by no means least, my thanks go to my supervisor, Ayoub Guerrah, for his constant encouragement and advice.

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NOMENCLATURE

$h_j^{(k)}$	The volume of water received in the j^{th} collector
h_{moy}	The weighted average volume of water collected
A_i	The cross-section (m²)
S_{coll}	The surface of the collector
S_j	The distance from the pivot point of the jth collector
W_d	The nozzle's wetted diameter (m)
ΔP_{i_l}	Linear pressure loss (Pa)
ΔP_{i_s}	Friction-head loss due to nozzle or sprinkler (Pa)
$\Delta P_{i(l+s)}$	The total head loss (Pa)
C	Factor characterizes the type of center pivot
C_d	The discharge coefficient (often between 0.95 and 1.00)
CUH	The uniformity coefficient of Heermann and Hein (%)
D	The water pipe hydraulic diameter (m)
d	The nozzle's diameter (m)
f	The Darcy friction factor
$f(x)$	The function that expresses the objective (or aim) function
g	Accumulation due to gravity of 9.81 (m/s²)
$g_j(x)$	Inequality constraint function
h_0	The vertical elevation (m)
$h_k(x)$	Equality constraint function
j	A number assigned to classify a particular collector
K	Factor characterizing the fitting or valve dimension
L	The total length of the center pivot (m)
l	The nozzle distance from the pivot point
m	Number of collectors used during the data analysis
n	Number of nozzles
P	The water applied per revolution (m)
P_0	The inlet pressure (Pa)
P_i	The outlet pressure (Pa)
q_i	The discharge of nozzle (m^3/s)
Q_{in}	Inlet flow rate (m^3/s)
Q_{out}	The outlet flow rate (m^3/s)
qr_i	The section flow rate corresponds to a distance r from the pivot point (m^3/s)
R	The nozzle's radius (m)
Re	Reynolds number
r_i	The radius that corresponds to the flow rate qr_i in the center pivot
T	The system revolution time (h)
V	The average velocity (m/s)
v_0	The water inlet velocity at the pivot point (m/s)
V_i	Velocity head for a given discharge and pipe or fitting diameter (m/s)
x	The exponent of the orifice that characterizes the flow regime
X_i	The better sprinkler's position
x_{iL}	Lower bounds
x_{iU}	Upper bounds
ε	The degree of roughness
ϑ	Kinematic viscosity at 25 °C (m²/s)
μ	The fluid's dynamic viscosity (Pa s) or (kg m^{-1} s^{-1})
ρ	The fluid density (kg/m3)

GENERAL INTRODUCTION

GENERAL INTRODUCTION

Conventional (gravity) irrigation methods with low application efficiencies (between 40-60%) and modernized irrigation methods with high efficiencies (between 70-95%) like center-pivot, sprinkler, and trickle irrigation systems are the commonly used irrigation technologies. A good irrigation system is a system that delivers an adequate amount of water continuously and uniformly. In recent decades, optimization techniques play an important role in applying water efficiently for modernized irrigation technologies. However, the quantity and quality of crop productivity significantly improved by the utilization of highly efficient irrigation systems, therefore, the availability of appropriate irrigation uniformity in the different irrigation systems is crucial in terms of crop productivity, and addressing rapidly increasing global water scarcity problems. As a result, while choosing a sprinkler package or sprinkler application method, high uniformity of irrigation and application efficiency are frequently highlighted as top priorities.

The center-pivot irrigation system is one of the most widely used irrigation technologies in southern Algeria in which the popularity of these systems is the primary reason for high utilization. With more than 35,000 installations in El Oued, southern Algeria, the conventional Mini-Centre Pivot System (MCPS) is the most frequently used pivot irrigation system, contributing to 40% of Algeria's national potato production in 2015 [1]. Because of its extensive use and high water and energy consumption, the center-pivot irrigation system has an environmental impact. A center-pivot irrigation system requires expensive hydraulic pressure techniques and consumes a lot of energy as compared to surface irrigation, which distributes water by gravity. An evident design procedure for minimizing energy consumption and increasing water usage performance using progressively decreasing spaces between sprinklers along the lateral pipe of center pivot irrigation systems has been presented based on geometric and hydraulic input parameters to allow the selection of sprinkler characteristics and pipe diameter [2].

Sprinkler discharge rate, sprinkler distance, management, maintenance, and travel speed consistency all influence the uniformity of water application on the field as a whole. To enhance the system's water uniformity, a simulation model named 'DEPIVOT' that supports all operating parameters with examples has been investigated [3]. A genetic algorithm (GA) is a method used in engineering to address multi-variable optimization problems. GA is better utilized to solve multidimensional optimization problems with unknown (or extremely complex) analytical results and effective computational methods [4]. Few researchers [5-7] have successfully used GA to optimize designs in the irrigation field. A mathematical optimization model based on a genetic algorithm has been provided to contribute to system performance enhancement as well as cost reduction [8]. Using an enhanced model of MATLAB software, a prototype was created, assessed, and used to simulate any important wind's impact on the water application uniformity and average water depth applied under center pivot spray sprinklers [9].

The main objective of this thesis is to develop a methodology for optimizing the irrigation uniformity of a center-pivot irrigation system in a particular area based on sizing and dimensioning nozzles. This thesis proposes a comprehensive method that takes into account and combines a variety of interrelated factors (wind velocity, hydraulic parameters, system characteristics such as inlet flow rate and operating pressure, and system efficiency) as well as sprinkler variables (diameter, space from the pivot point, wetted diameter and elevation height). In addition, a comparison between the experimental measurements and the modeling calculation of the same system is used to validate the proposed model performance. The thesis is structured in two parts, with five chapters, preceded by a general introduction and followed by a general conclusion.

The first part of the thesis is a bibliographic synthesis composed of three chapters. The first chapter devotes in a general form the presentation of the center-pivot irrigation system and an analysis of the various previous works on factors that influence the performance of this system. The second chapter presents a bibliographic study on the hydraulic performance modeling carried out in the field of the center-pivot irrigation system. In the third chapter, we have reviewed the available optimization techniques with a concentration on genetic algorithm problem formulation to optimize the design of center-pivot irrigation systems.

The second part of the thesis is composed of Chapter IV and Chapter V to explain the two technological solutions proposed to enhance center-pivot irrigation system performance. The goal is to solve the optimization problem of the investigated systems when the diameter or the space of the nozzle is the only variable.

In the fourth chapter, we were interested in the experimental evaluation and the hydraulic comparison between the traditional and modern center-pivot irrigation systems. This chapter is devoted to the new nozzle-spacing configuration of existing systems based on theoretical analysis. In the fifth chapter, we find the details of the optimization results provided by the proposed model, their discussions, and their interpretations. On the other hand, a comparison between the experimental measurements and the modeling calculation of the same system is used to validate the proposed model performance. In this chapter, a new model, relating to the sizing and spacing nozzle of a center-pivot irrigation system has been provided.

The thesis is completed by a general conclusion encompassing the interest of all the results obtained during the study undertaken as well as the suggestions proposed to highly improve the efficiency of center-pivot irrigation systems.

PART I

STATE OF THE ART AND LITERATURE

CHAPTER I.

CIRCULATION OF WATER IN THE CENTER PIVOTS

I.1. INTRODUCTION:

The center-pivot irrigation system has many advantages, including low labor costs, and high water application efficiency. Many researchers have been using optimization methods in irrigation systems to evaluate the hydraulic performance of these systems in recent studies, as these models can take into account the interaction among several parameters affecting an irrigation system, such as atmospheric characteristics, pump unit, crop, and system geometry.

The increase of alternate demands for water uses imposes a larger value on water resources and tends to focus on wasteful practices. As a result, irrigation science will inevitably face the problem of maximizing efficiency in the future. Irrigation covers 15% to 20% of the world's farmed land and accounts for approximately 40% of overall agricultural production [10]. Center-pivot irrigation systems are frequently designed to maximize efficiencies and minimize labor and capital requirements to provide the most uniform water pattern available. The absence of uniform irrigation results in three distinct areas: over-irrigated, under-irrigated, and adequately irrigated. It might regard both over-and under-irrigated areas to be an economic loss since the first generates a loss of water under the roots, while the other affects the quantity and quality of the product. As a result, uniformity is often the most questioned. In this chapter, we describe the center pivot system function and components. In addition, the factors which influence the circulation of water in the system were highlighted.

I.2. BASIC CONCEPTS AND LAYOUT OF CENTER PIVOT SYSTEM:

Today, agriculture accounts for 70 % of all global water consumption, and in some developing countries, up to 95 %. The increased understanding of the instrumental importance of water in the conservation of environmental resources is contributing to the pressures on agricultural use. Center-pivot irrigation systems are one of the most common systems for irrigating general crops and were used on 46 % of all irrigated land and 88 % of sprinkle-irrigated land in the United States, according to the United States Department of Agriculture (USDA) 2008 census[11]. “History may record the development of the center pivot as one of the most significant advances in agriculture in the 20th century or it may record this development as the major disaster in agriculture in the 20th century. Depending on what happens to the cost of energy relative to the value of the crop under the system” as announced by [12]. In addition, sprinkler irrigation systems with different kinds, implementations, and models provide many choices for a variety of crops, from low to high-cost requirements in various soil types. In these irrigation techniques, sprinkler systems usually operate under medium to high pressure and water application performance ranges from 60 % to 85 % commonly [13-15]. To effectively supply crop water requirements and optimize yield, farmers with center pivots may apply light and repeated irrigation as necessary.

Center pivot irrigation is a type of overhead irrigation (sprinkler) composed of many pipe segments (generally galvanized aluminum or steel) linked together and supported by trusses, mounted on wheeled towers with sprinklers installed along their length. The principal parts include:

a) Spans of pipe between towers
b) Pivot point
c) Control Panel
d) Electrical control boxes
e) Tower drive wheels (The supporting structure and the drive units)

The center pivot is a fully mechanized, permanently mounted automatic irrigation system with low / medium pressure. The machine consists of a single long irrigation pipeline connected to a central tower, travels slowly in a circular pattern across the field, and irrigates the fields through frequently spaced sprinklers or sprayers mounted on it. The central tower is anchored to a small concrete base at a fixed water supply point (hydrant) at the center of the ground, with a pivot mechanism and the main control panel (electric). The whole irrigation pipeline is held above the soil by "A" frame towers travel on wheels, long spans, steel trusses, and/or cables. A sprinkler gun (downstream end) overhangs the end of the pipe. At a normal speed (last span) of 2-3 m / min, the whole device slowly rotates around the pivot point, self-propelled, distributing water in the form of overhead spray irrigation and covering the field in a circular pattern. The moving system features small individual power units installed on each wheeled tower. These systems are electric drives, but they may be mechanical drives or hydraulic drives (water, oil). The irrigation pipeline is still held straight by an automated alignment system. According to the length of the center pivot, the zone covered can range from 3.5 ha to 60 ha. Within a duration of 3 or 4 days, the device completes its circular motion around the pivot. Figure I.1 shows a schematic diagram for the different components of a center pivot system.

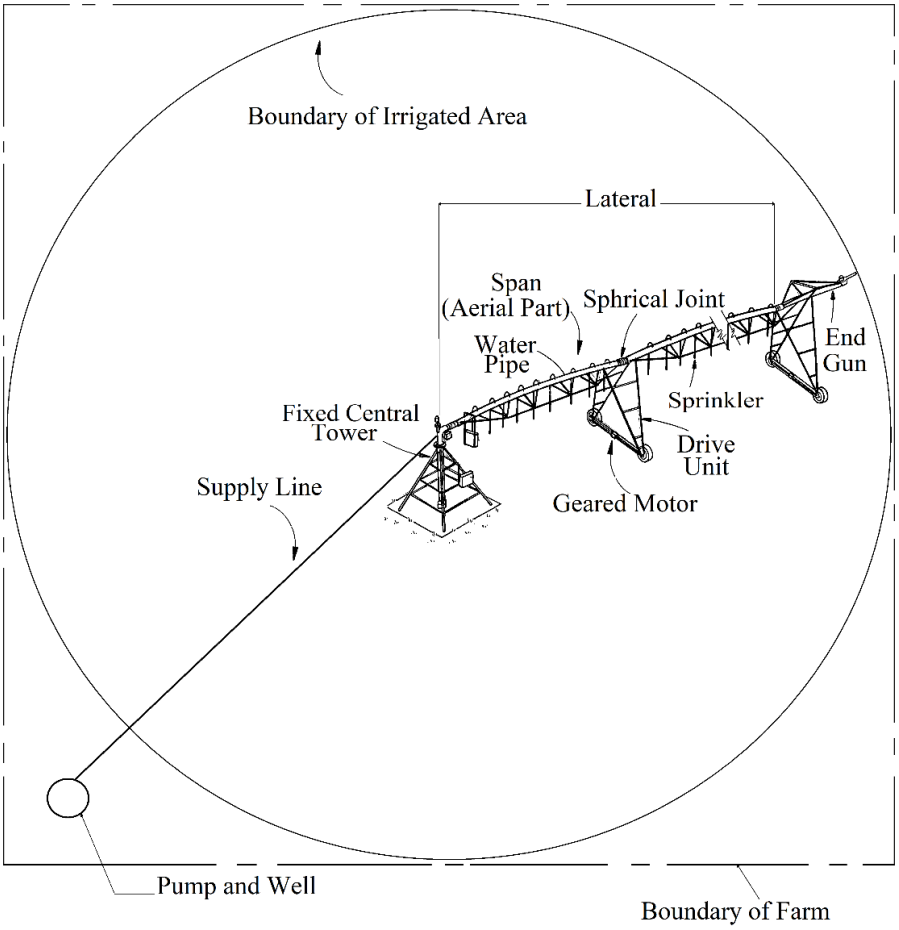

Figure I.1: The main components of the center-pivot irrigation system.

Center-pivot irrigation systems near the ground significantly apply water, with limited losses, and water application precision is high. This gives the machines the highest water efficiency among irrigation devices. In addition, the center pivot market is set to experience robust growth during the forecast period due to its advantages over traditional irrigation systems.

Owing to their high costs, fewer types of center-pivot irrigation systems are available to be used on small farms. [16] In the irrigation test center, a new configuration known as Corner Pivot Lateral (CPL) was tested to provide a new cost-effective design for a semi-permanent irrigation sprinkler system for small farm owners. Moreover, the report [17] summarizes the global market for center pivot irrigation systems in terms of models, parts, implementations, type of crop, and geography.

I.3. PUMPS AND DRILLING:

To get a design flow rate and total head pressure at optimum pump efficiency, pumps for irrigation should be perfectly selected. Efficient pumping plants need pumps, systems, and power sources, which are properly matched. An excellent way to save resources is to increase the efficacy of the application of water. [18] The effect of the field slope on the center pivot operation was analyzed using a mathematical model for 29 separate pump-pivot systems. With systems running on a uniform uphill slope of 7 %, the pump power decreases by as much as 36 %.

Irrigation scheduling, application performance, pumping plant efficiency, and the pumping pressure necessary for the center pivot device are factors that decide pumping costs. All of these variables will reduce pumping costs as shown in Figure I.2.

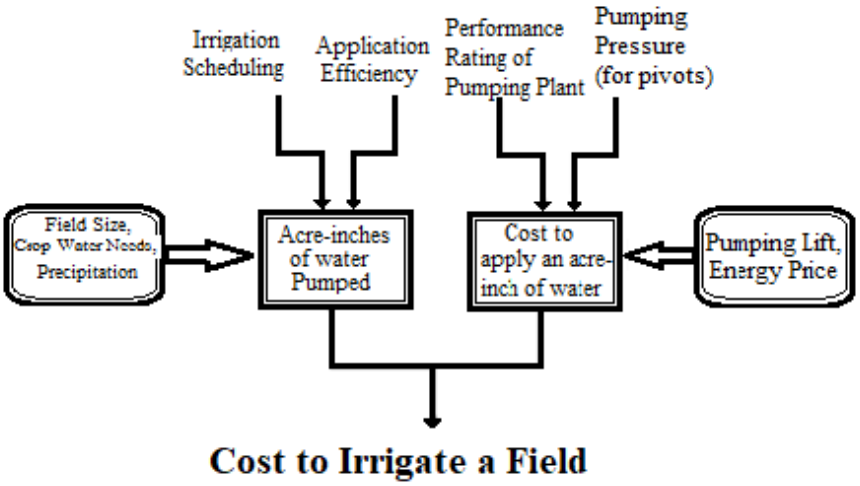

Figure I.2: Diagram of factors influencing the pumping cost of irrigation.

The study [19] proposes to minimize irrigation pumping energy by raising the size of the irrigation supply line from 0.203 m (0.665 ft) to 0.354 m (0.833 ft) which supplies water from the source to the normal center pivot irrigation system. Such an increase in the size of the pipe would minimize the pumping energy needed for irrigation and contribute to a more cost-effective design.

I.4. DEVICE CANALIZATION ASSEMBLY AND SPECIFICATIONS:

Based on the corrosivity of the irrigation water in center pivot systems, many types of pipes are available. Pivot laterals, pivot risers, and other aboveground components are frequently made of steel pipe. However, many factors need to be in the design and installation of pipes that efficiently transport water from the pump to the center pivot inlet while preventing pipe damage.

Depending on the system flow and length, the long irrigation pipeline (lateral) with water emitters (sprinklers, bubblers, or sprayers) may be 140 to 250 mm in diameter and the standard sizes are very common, between 160 mm (6 inches) and 200 mm (8 inches). According to the model, the pipeline length can range from 50 to 750 meters. It is made of galvanized light steel or aluminum high tensile material, with extra powerful couplers to resist the operating pressures of the device.

The pipeline is mounted on wheeled 'A-frame' towers with a minimum height of usually 3 meters above the land and a distance of 35-55 meters apart (length of spans). Often, 40 m is the common or "ordinary" span length. Truss rod arches maintain the equal distribution of weight and loads between the towers. On level land, for high-profile machines, the ground clearance ranges from 2.75 to 4.5 meters. The spans

are fitted at the ends with flexible joints that allow the pipeline to articulate and allow side-to-side, up and down, and rotational motion without pipeline stress (see Figure I.3).

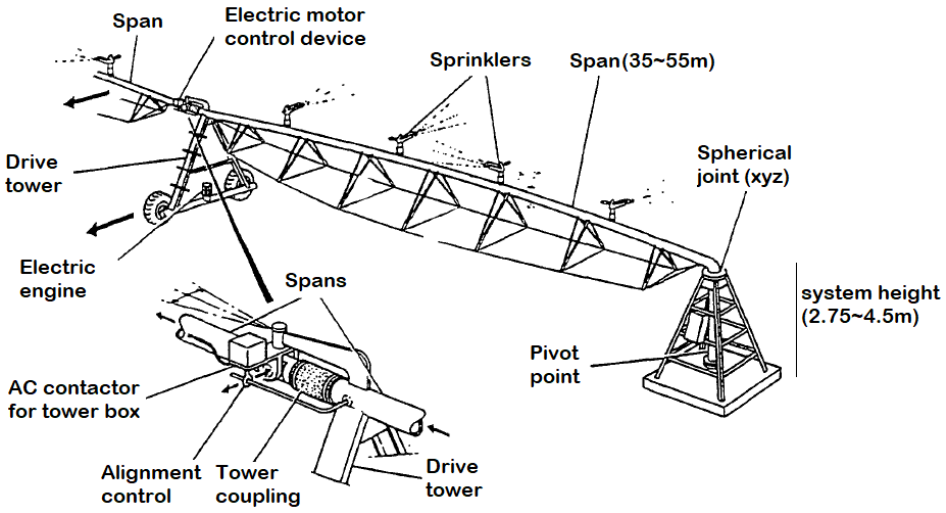

Figure I.3: Canalization assembly and specifications of a center-pivot irrigation system.

As water moves through pipes, the viscosity and the drag of the water along the pipe walls produce a loss of pressure. The combination of these elements causes a change in water velocity in the pipe. The water flows slowly near the pipe's wall, while the maximum velocity is found in the pipe's center. The loss of pressure due to friction is determined by the water flow rate in the pipe, the interior diameter of the pipe, and the pipe's roughness. Increased flow rates cause higher water velocities in the pipe and more friction loss. The viscosity of water is inversely proportional to its temperature and hence friction loss is dependent on the temperature of the water. Temperature impacts, on the other hand, are lower than the impacts of flow rate, pipe diameter, or pipe roughness. Consequently, friction loss charts are created using a standard temperature (73.4 °F= 23°C). For every 3 degrees Fahrenheit above (below) the reference temperature (73.4 °F), head loss lowers (increases) by about 1% [20]. For most applications, the values at the reference temperature are satisfactory.

As the basic empirical formula Hazen-Williams or Darcy-Weisbach is used to measure the loss of friction, a particularly simple equation is derived to explicitly measure the sufficient length of the different usable pipe sizes along with the lateral center-pivot such that the overall cost of pipelines and energy becomes minimal. The decrease in overall annual costs was up to 5.5 %, while the initial cost investment, as shown by[21], could be decreased by up to 11.2 %. According to[22], for the total pressure head variance and pressure head distribution over multi-diameter center-pivot laterals with or without an end gun, a general analytical hydraulic solution is proposed. The suggested analytical method is reasonably reliable for practical applications.

I.5. SPRINKLER THE CENTER PIVOT:

The efficiency of water application is largely dependent on the sprinkler package, for center pivots systems. The sprinkler package means the sprinkler's group that is built on the irrigation device. Sprinklers may be placed on the side of the pipeline, above the pivot pipeline, or suspended underneath the pipeline on drop tubes. A crucial design feature is sprinkler selection for a center pivot. Owing to the radial distribution of water and the gradual rise in the number of acres irrigated per meter of increased length, a larger volume of water must be supplied to each additional meter of the pivot.

Consequently, in direct relationship to the distance from the pivot point, the water application rate of the center pivot device increases. The center pivot system is one of three styles, based on the **arrangement and size of sprinklers**. In particular, the rotating pivot is equipped with increasing impact sprinkler sizes for the constant spacing of the sprinkler, increasingly closer spacing of the impact sprinkler for variable spacing, or spinner or spray-nozzle sprinklers to apply and disperse the water uniformly across the circular field[23]. Figure I.4 shows the water coverage of these structures schematically.

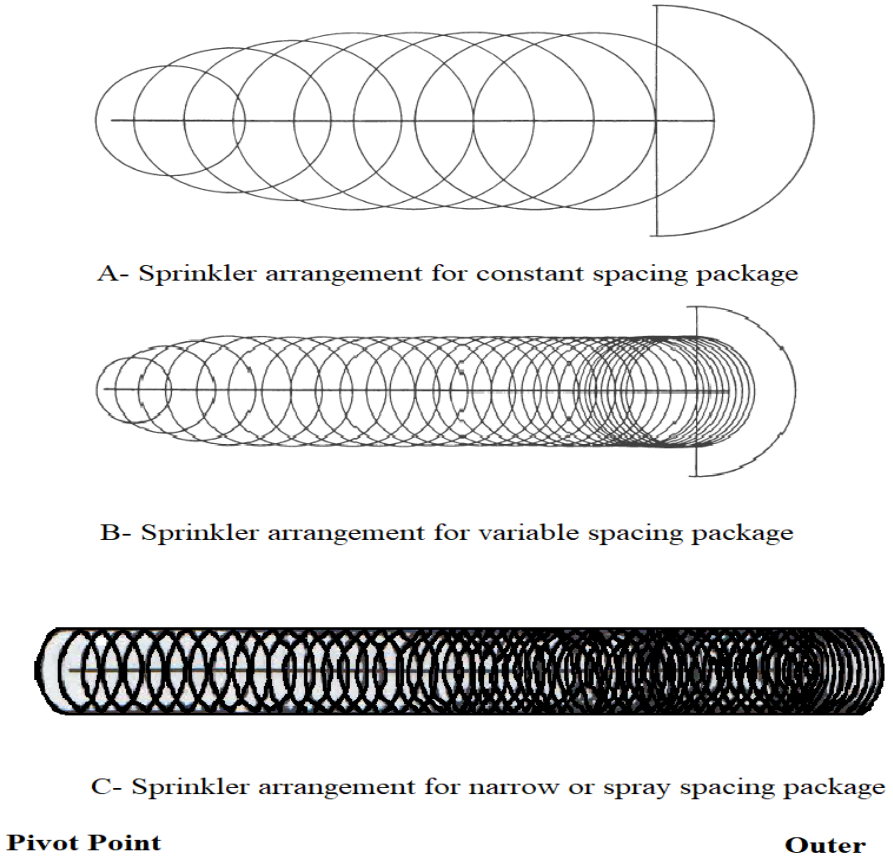

Figure I.4: Spacing packets of sprinklers.

The smaller **drops of sprinkler** decelerate faster than the larger ones, which amounts to sorting the drops by size, with the larger drops reaching longer distances from the sprinkler. The maximum distance

covered by medium-pressure sprinklers only covers around 40 to 60% of their potential in vacuum (wetted diameter) [24, 25], whereas larger nozzle diameters cover longer distances.

For most center pivot and linear systems, **two types of sprinkler models** are commonly used rotating and fixed spray plate sprinklers (RSPSs and FSPSs) as shown in Figure I.5. There is a wear plate mounted directly below the nozzle in both sprinkler forms, which discharges the water and produces a 360-degree water pattern.

Because the wear plate is fixed, fixed sprays have no moving parts and produce high instantaneous application rates on a small percent of area. Depending on the sprinkler type, a rotating spray wear plate rotates either fast or slow and even distribution throughout full coverage area produces low instantaneous application rates. Rotating sprays that produce a water pattern of low intensity create a wide wetted diameter (15.24 meters to 21.34 meters). This is a major advantage of rotating sprays. On medium to heavy types of soil, this type of sprinkler works well and reduces water runoff. Fixed sprays have a wet diameter of 4.57 to 12.19 meters, which works well on light soils where runoff might not be a major problem.

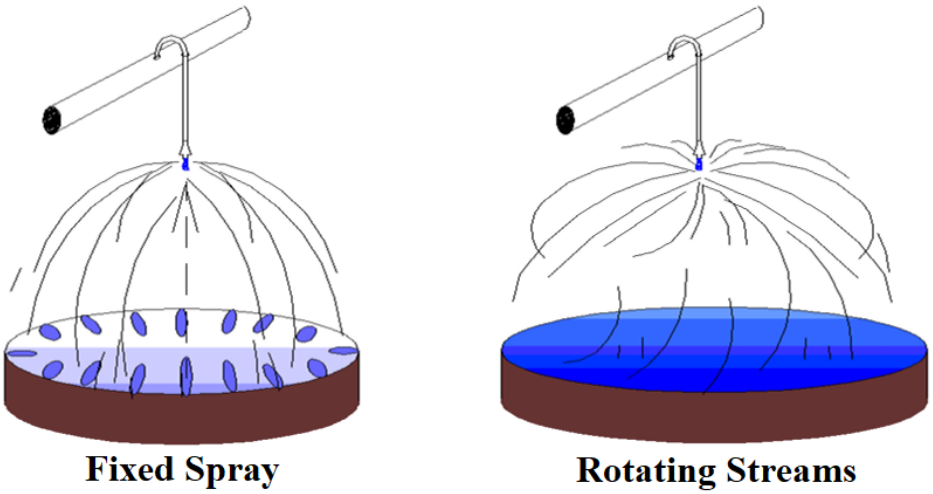

Figure I.5: Fixed spray and rotating streams comparison [26].

At medium to low pressures, newly designed sprinklers or spray heads can deliver high application uniformity with controlled drop sizes and medium-sized pattern widths. Kincaid [27] proposed a method for predicting spray pattern breadth for a certain type of spray device as a function of nozzle flow, pressure, and mounting height at any point along with a center-pivot irrigation system. Spray device nozzle sizes ranged from 4.76 to 6.35 mm, with nozzle pressures ranging from 103 to 207 kPa (15 to 30 psi). Nozzle mounting heights ranged from 1.2 to 2.9 meters. The first was an earlier style fixed-plate Nelson spray head, the second was the slowly rotating plate R3000, the third was the rapidly spinning plate S3000, the fourth was the Nelson N3000 (Nutator), and the fifth was the Senninger i-wob

sprinklers. To estimate when runoff might occur, the methodology can be used with center pivot design models. To assist in the design process and compare various configurations, a computer program is offered.

The water distributions of individual RSPSs and FSPSs with varied nozzles (2.78, 4.76, and 6.75 mm in diameter) were measured in [28] using a catch can method in low-wind field situations and various sprinkler intervals. The wetted radius of RSPSs and FSPSs, respectively, varied from 4.88 to 7.05 m and 5.02 to 6.85 m, and uniformities were 3.1 % and 6.2 % greater utilizing RSPSs than FSPSs with sprinkler intervals of 3.0 and 4.5 m, respectively. RSPS when compared with FSPS, it was able to receive larger sprinkler intervals (>3.0 m) while maintaining higher sprinkling performance.

To reduce energy (pumping) costs, fixed spray, and rotating spray sprinklers are designed to work at low pressure. The typical pressure range for many types of nozzles is 70 to 200 kPa (0.69 to 2.07 bar) such as Senninger 188° Spray, Valley Spray Nozzles, Senninger 360° Super Spray, Senninger Low Drift Nozzle, Valley Low Energy Nozzles LEN, Nelson D3000... as listed in [11]. Above 200 kPa, the discharge of these nozzles may need to be limited to avoid runoff (nozzles tend to mist). The majority of spray heads are mounted on drop pipes or tubes that minimize the heads below the span pipes to 1.22 to 1.52 meters from the level, depending on the crop.

For constant-spaced sprinklers, from the pivot point outward to the far moving end, the zone to be irrigated by each sprinkler, set at a uniform sprinkler spacing along with the pivot, becomes increasingly larger. The sprinklers must therefore be built for increasingly greater discharges, closer spacing, or both from the pivot point outward towards the far-moving end, to have a uniform implementation. Thus, with the distance from the pivot point, the wet radius of the sprinkler significantly increases.

Yan, et al. [29] with an FSPS of 36-grooved plate D3000, the discharge-pressure relationship, wetted diameter, effective distance, and water application rate were assessed. The 1.79 mm to 6.55 mm nozzle package was measured with a nozzle elevation of 1.2 m and a pressure regulator of 1.37 bar. The results of this study indicate that with nozzle size, the wetted diameter and average application rate increased, but there was no significant relationship with nozzle size between the effective wetted width and peak instantaneous application rate.

One spray near the pivot point occupies a small area and has a low rate of discharge. Each watering outlet covers a greater amount of acreage as the line stretches toward the far end. The application rate near the outer moving end is usually around $7x10^{-6}$ m/s. This exceeds, however, the intake rate of several tighter soils.

Sprinklers are all the same size with variable spacing, although the spacing between the sprinklers decreases to compensate for the variation in the area irrigated with the distance from the pivot point.

Therefore, for the entire device, the wet radius is identical. Different size nozzle openings are needed when using spinners or spray heads to compensate for variations in the irrigated area, but due to their lower wetted radius, the spacing is narrower along with the device.

For several purposes, sprinkler packages are planned and chosen. In the selection of a specific sprinkler kit or sprinkler application process, high irrigation uniformity and application efficiency are almost always cited as priority objectives. The output of four sprinkler packages placed on top of the lateral pivot and four packages suspended on drop tubes for a typical midsummer day was evaluated in the study[30]. Evaporation from the ground during the middle of the growing season is minimally influenced by the category of the package or the height at which the sprinkler systems are placed. For sprinkler systems that apply water for a longer duration due to a wider wetted radius, evaporative losses are usually higher.

Sprinkler height affects the size of the wetted field irrigated by the sprinkler and losses of wind drift. With no noticeable impact over the reasonable heights of 1.82 to 3 meters, rising sprinkler height raises the sprinkler wetted area marginally. Application uniformity is not substantially improved by sprinkler heights greater than 1.82 meters on short crops (height less than 0.91 m). Sprinkler heights of less than 1.82 m, however, significantly reduce application uniformity, particularly for sprinklers having low trajectory angle deflection plates. For taller crops, the maximum canopy height is the optimum sprinkler height.

Sprinkler heights greater than 1.82 meters greatly increase spray losses due to wind drift and evaporation. For sprinkler heights between 0.91 and 1.82 meters, spray losses range between 3 and 5 %. Spray losses rise to 10 %, at heights of 3.65 to 4.57 meters for sprinklers (spray and impacts) installed on the top of the center pivot. As wind velocity rises from 2.23 meters per second to 4.47 meters per second, spray losses will double. Sprinkler heights around 1.82 meters Provide good uniformity of application while preserving acceptable spray losses[31] for short crops.

I.6. NOZZLE THE CENTER PIVOT:

To obtain uniform water distribution, nozzle size, and type selection should be defined along with the main lateral center pivot. Configuration methods should also be put forward for sprinklers fitted with, without, and partly with pressure regulators. However, applications for the DYP-249 center pivot [32], Visual Basic 6.0 program [33], and the program named PIVNOZ [27] have also been created to select the nozzle package range of the center pivot irrigation device.

[34] Two system movement speeds and three variable-rate settings evaluated the uniformity along the length of a center pivot and a linear motion irrigation system. Using pneumatically actuated solenoid valves to switch groups of sprinklers ON and OFF at fractions of a minute corresponding to the cycle

rate, one variable-rate system is commercially accessible. To perform the same job, the other variable-rate method used the commercially available electric solenoid valves. Wind speed, cycling rate, or machine movement speed did not significantly affect the performance. However, because of the distinctly different application characteristics of the rotator, fixed plate, and wobbling low-pressure sprinklers, the uniformity is affected by the type of nozzle.

I.7. OVERHANG AND END GUNS:

A large quantity of any square area is not irrigated due to the circular nature of the center pivot irrigation system. 21.5 % of the area remains unirrigated if the field is square. In 65 hectares, about 20% (13 hectares from 65 hectares) of the area is unirrigated unless it has a special corner irrigation system, which adds considerably to the system's cost and complexity. The pivot's end gun can irrigate additional hectares (5%) to the 80% irrigated area by the center pivot. The 15% of the total field area is unirrigated for such corner systems [35]. The use of large part circle sprinklers at the end of the system has been one solution that has been used to improve the irrigated area ratio. These are sometimes referred to as end guns. The end guns are drawn irrigation fluid from the main pipeline sprinkler and are attached to it. The final arms, which can alternatively be used to irrigate huge parts of the corner areas, the irrigated area, and the irrigated area ratio, are raised.

Multiple corner-irrigating systems have been proposed for use with center pivot irrigation systems. One such suggestion proposes the use of a tool to evaluate end gun applications on center pivots and looks clearly at some common scenarios in which they can be used. The converse operation is: the end gun does not operate and the end gun operates. The percentage of the area irrigated is improved by the use of end guns on center pivots, but cycling on and off the final gun induces a change in the system's operating point[36]. In the study[37], a mathematical model to simulate the water distribution of any end gun sprinkler is built for no-wind conditions (wind speeds less than 0.9 m s-1) as long as the water distribution curve of the sprinkler is established. Minor variations are shown between the measured and simulated depths of water use.

I.8. HOW CENTER PIVOTS WORK:

Center pivots are well-engineered systems that supply water to wide circular fields efficiently. Each has a main water distribution pipe suspended from the direction of the crops over the field. Wherever the pipe moves, sprinklers or spray nozzles may be spaced along the pipe to apply water. Pipe sections are linked with flexible joints at each tower that allows the pipe to pass across a limited range without twisting or breaking. This versatility also allows vertical bending that allows moderate hilly slopes to be climbed by pivots.

In a circular pattern, the system moves and is supplied from the pivot point at the center of the circle with water. Generally, water is pumped from a source, such as a well or a river. At the pivot point, the

pump is attached to the pivot. The largest distance is covered by the outside set of wheels and therefore sets the main speed for the rotation. The inner wheelsets are placed between two segments at hubs and use angle sensors to detect when a certain threshold is crossed by the bend at the joint (the wheels should be moved to maintain the segments aligned). Most center pivots irrigate a quarter-mile (0.4 kilometers) radius of a circular area, although some can cover a wider area. Center pivots commonly have a length of less than one-third of a mile (0.5 kilometers). A process called Variable Speed Irrigation (VSI) offers most manufacturers a way to change the speed of the pivot, and thus the amount of water is spread over a given area. For groups of sprinklers on the pivot system during operation, some manufacturers produce packages that not only vary the speed but also turn on and off valves. This is known as Irrigation with a Variable Rate (VRI). More information on VSI and VRI systems is provided in the Irrigation Delivery Systems report.

In a half-circle (or more), a wiper pivot (or a "half-circle pivot") runs, reversing its direction when a lever reaches a stop in the ground. In certain cases, it is less costly to irrigate a long, narrow field with a single center pivot built to function in a half-circle configuration than to irrigate the area using two smaller, full-circle pivots.

Center pivot irrigation poses certain difficulties with most of its benefits. According to the Natural Resources Conservation Service (NRCS)[38], it is just plain trickier to irrigate in circular patterns than to irrigate in rectangles. Each sprinkler delivers water to an identically sized area in a rectangular system. The area increases in a circular system as the radius increases. Hence, each sprinkler applies water to a differently sized area of the field (see Figure I.6 below).

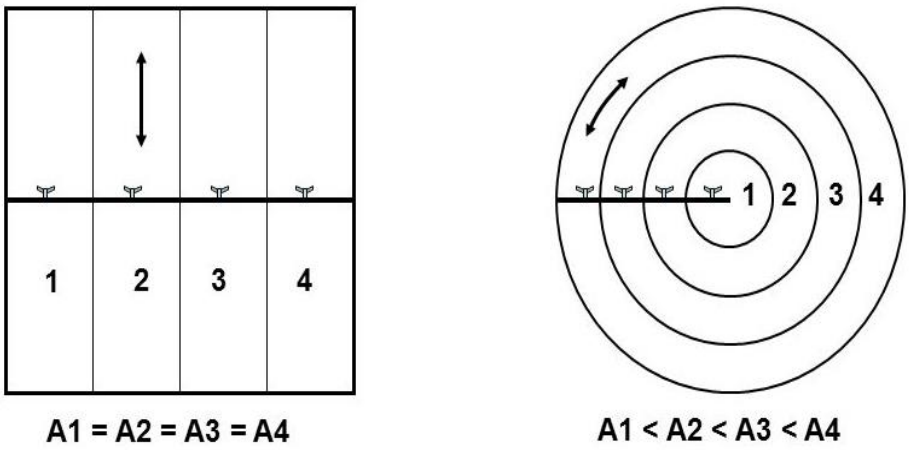

Figure I.6: Difficulties to measure circular systems' water application[38].

The irrigator measure and size sprinklers correctly along the length of the pivot to resolve this irrigated surface area problem, and to ensure uniform coverage. This preserves the uniform application of water along the center pivot's linear length. As shown in Figure I.7, as greater the circle radius, the more gallons

per minute (GPM) or liters per minute increased where the system capacity is 6 gpm per acre. However, the farmer should adapt and address frictional losses to improve the distribution of farmland. To maximize flow, this is achieved by sizing appropriately the nozzle diameter along length of pivot to maintain uniform applications along linear length of the center pivot system.

Radius (ft.)	Total Area (acres)	Spoke Area (acres)	Flow Required (gpm)
130	1.2	1.2	7.2
260	4.9	3.7	22.2
390	11.0	6.1	36.6
520	19.5	8.5	51.0
650	30.5	11.0	66.0
780	43.9	13.4	80.4
910	59.7	15.8	94.8
1040	78.0	18.3	109.8
1170	98.7	20.7	124.2
1300	121.8	23.1	138.6

Figure I.7: Calculations of areas and their relationships for consistent flow coverage [38].

When the pivot's outermost spans move further in a specified period than the innermost spans, the nozzle sizes at the inner spans are smaller and increase with distance from the pivot point. As the outer wheels set the speed of the rotation, this helps keep a uniform flow of water.

I.9. PLANT, SOIL, AND WATER RELATIONSHIPS:

As it provides food, clothes, and shelter for all, agriculture is an inseparable part of our lives. For agriculture, the soil is important and it is the location of many organisms. Soil aids plant growth by tightly holding the roots and providing water and nutrients. The capacity of the soil to absorb and retain moisture is determined by its sand, silt, and clay content and ratio. Knowing the six soil types and the rates of water absorption helps farmers.

I.9.1. SOIL CLASSIFICATION:

The sizes of soil particles have a very significant effect on their properties. The soil is graded based on the percentage of particles of different sizes. Six basic soil types exist sand, loam, peat, chalk, silt, and clay.

The molecules of sand are very large and create big spaces between them. The air fills these spaces. **Sandy soil** is also well aerated. Water freely flows through sandy soil. It warms up quickly in the spring, dries out quickly, and grows easily. Nutrients wash out rapidly together with the rapid runoff of water, unlike clay soil. Sand absorbs as much water as it is provided, but drains rapidly, making it unwanted for plants that need constant humidity.

A mixture of sand, clay, and another form of soil particle known as silt is **loamy soil**. It has a strong structure, absorbs water, drains well, and retains humidity. Loam is filled with nutrients and has hummus in it. It also has the right water holding capacity for plant development. It is easy to grow and in the spring, it warms easily. For gardening, it is the perfect soil. Loam absorbs a great deal of water and preserves the proper amount of humidity. For rising plants, the finest topsoil is loam.

The **peat soil** is acidic. It prevents decomposition, which means a high proportion of organic matter is found in it. Mostly, the peat is organic. A deficiency of nutrients results from this shortage of decomposition. The color of peat is black. Peat warms up easily in spring and maintains a significant amount of water. When fertilized regularly, peat is an outstanding soil for plants.

Silt is present in riverbeds as a deposit. The size of the molecules of silt varies between sand and clay. **Silty soil** makes your hand appear smooth. This drains fine, retains moisture, and is richer than sand in nutrients. The soil texture of Silt is fragile and compacts readily. It is simpler than clay to cultivate. With proper treatment, it makes an outstanding gardening ground.

Chalky soil, meaning that it is alkaline, has a pH of 7.5 or more. It is stony, free-draining, and is mostly found on limestone and bedrock as an overlay. This reduces the plants' supply of manganese and iron micronutrients. A deficiency of these minerals might be suggested by yellowing leaves on a crop. Treating the soil with fertilizer rectifies this problem. The stony characteristics make silt one of the soils with the least absorption.

Being much smaller, the **clay soil** particles pack closely together, leaving little space for air. Water can be retained in the small openings between the clay particles, unlike sandy soil. Clay soil is listed as one of the hardest garden soils and as heavy soil. Clay is slow to absorb water because of its compact existence and consumes the least amount of water of all six forms of soil. During the spring, it is hard when dry, sticky when wet, drains poorly, and warms slowly. Owing to bad drainage, it contains the most nutrients of any soil. In clay soil, some plants excel, while others will grow with generous modification.

Depending on its composition, the soil may be of any kind. A significant tool is used to determine soil structure, such as the soil textural triangle (Figure I.8). It displays soil types with mixtures of three significant soil components, namely: clay, silt, and sand. It forms layers by combining soil and water. It is possible to calculate these layers (height) and then get the percentage of the three components present in the blend. Data is then used to map the textural triangle of the soil[39].

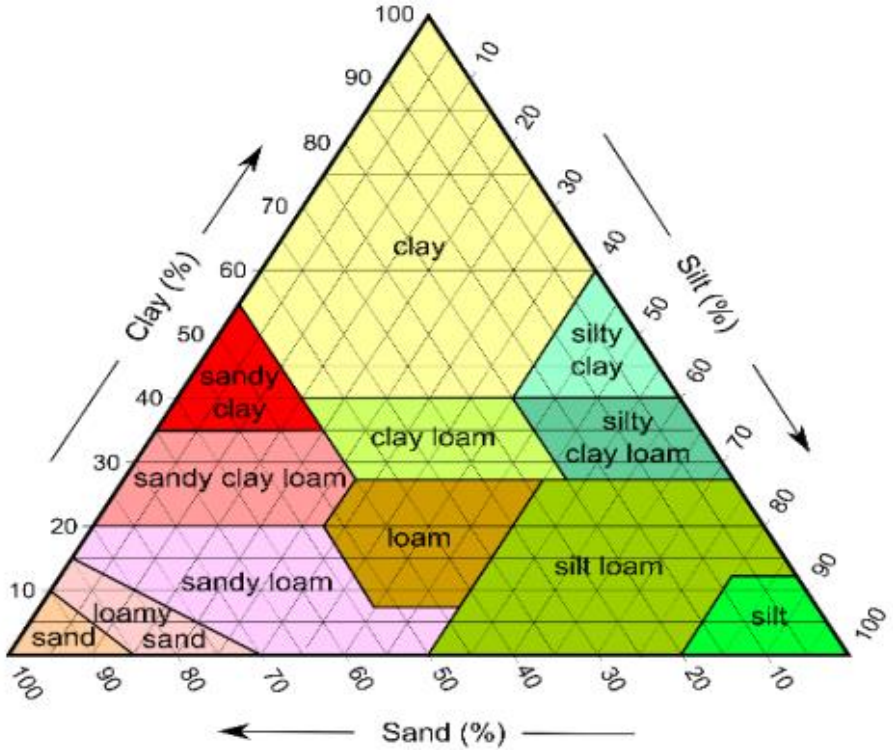

Figure I.8: Soil types as used by the USDA for Clay, Silt, and Sand composition [39].

The textural classification triangle in the illustrated USDA (United States Department of Agriculture) is the only soil that is a mixture of equal quantities of the three component-loam soils. In the opinion of the food production community, this is regarded as the perfect soil. The macro (non-capillary) pores, coarse capillary pores, and fine capillary pores may be defined as soil pore sizes[40]. Non-capillary pores are characterized as rapidly draining pores (RDP), while slowly draining pores (SDP) and water-holding pores (WHP) are represented by coarse capillary pores (CCP)[41].

I.9.2. WATER - SOIL REACTION:

Water intake is described as the flow of water from the soil surface into and through the soil. It is the description of many factors, such as infiltration, permeability, and percolation.

I.9.2.1. INFILTRATION:

Infiltration indicates water entering and flowing downwards to the surface of the soil. A surface feature of soil is infiltration. This method is of great practical significance as the amount of run-off over the soil surface is dictated by its rate. Infiltration is the amount of water entering the soil from the surface. The penetration rate is initially higher, but it decreases afterward because the soil gets wet.

The infiltration rate is divided into four groups according to the rate of entry of water from the surface into the soil.

a) **Very Slow:** such as quite a clay soils. Represent the soils, with less than 0.25 cm per hour.
b) **Slow:** The rate of infiltration is 0.25 cm to 1.25 cm per hour, e.g. The High Clay Soils.

c) **Moderate:** The rate of infiltration is between 1.25 and 2.5 cm per hour. Sandy loam/ silt loam soils, for example.

d) **Rapid:** The rate of infiltration exceeds 2.5 cm per hour, e.g. deep/sandy silt loam soils.

Infiltration under center pivot irrigation occurs within a matter of minutes. However, where water is applied to the surface via sprinkler drops, the infiltration rate is measured by using a sprinkler or rainfall Infiltrometer. Infiltration is water entering the soil. The infiltration rate depends on soil type and the amount of water already stored in the soil, therefore, important factors affect determining the infiltration characteristics of soil, including organic matter and structure such as:

a) **The compactness of soil surface:** A compact soil surface allows less infiltration, while more infiltration from the loose surface of the soil takes place.

b) **Impact of raindrop:** The raindrop effect is said to be the force (speed) with which the raindrop falls on the earth. The standard size ranges in diameter from 0.5 to 4 mm. The raindrop speed is 9.144 m per second and the force is 14 times the weight of its own. When the raindrop effect is greater, it causes pores (capillaries) to be sealed and closed, particularly in readily dispensable soils, increasing in infiltration rate.

c) **Soil cover:** Since capillary sealing is not observed, the soil surface with vegetative cover has a greater rate of infiltration than bare soil.

d) **Soil Wetness:** Infiltration is lower if the soil is wet. Infiltration is more effective in dry soil.

e) **Soil temperature:** Much water is absorbed by hot soil than in cold soil.

f) **Soil texture:** The infiltration rate in coarse-textured soils is higher compared to heavy soils. The number of macro-pores is greater in coarsely textured soil. The cracking caused by drying in clay soils also increases infiltration in the initial stages before the soil swells again and infiltration decreases.

g) **Depth of soil:** Shallow soils allow less water to penetrate the soil than soils that are too deep.

Infiltration is improved by coarse surface textured, high water-stable aggregates, more organic matter in the surface soil, and a higher number of micropores. It can be controlled by management practices because it is a dynamic and very variable soil character. Cultivation methods that loosen the surface soil allow it more susceptible to penetration, – for example, the infiltration of organic material mulches increases.

I.9.2.2. PERMEABILITY:

What is known as permeability is described as a feature that defines which determines how quickly air and water pass through the soil. If the water has reached the top layer, it reveals its quick or slow permeability by its subsequent slow or rapid motion within the soil. Permeability is dependent on the distribution of pore size in the soil. The higher the amount (non-capillary pores) of macropores, the greater the permeability. Due to their compactness and low organic matter content, the movement of

water becomes sluggish in subsoil layers, but with deep-rooted plants, also in such sub-soil layers, there is an increased permeability. With the rising fine texture, permeability increases. Soil absorption also varies with the state of the soil (see Figure I.9 below).

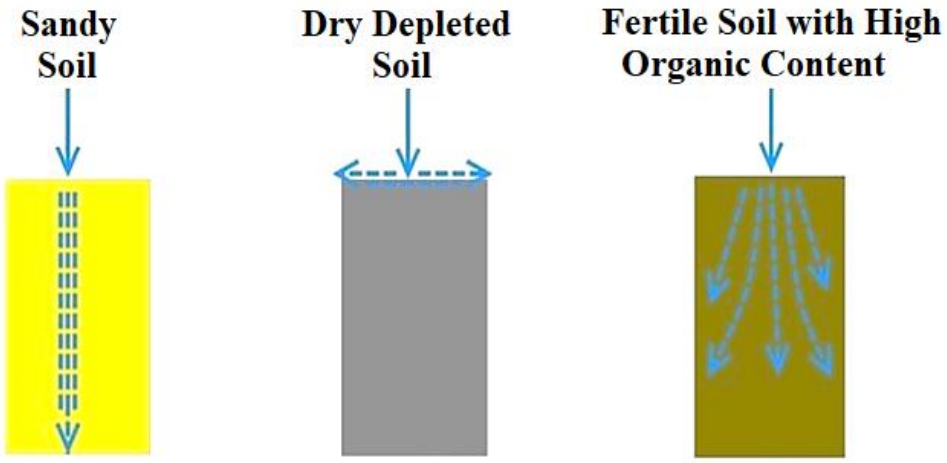

Figure I.9: The absorption of soil by different soil conditions (deepgreenpermaculture.com).

In sandy and dry soil, minimal absorption takes place because sandy soil is unable to keep water and dry soil has compact soil, which limits the capacity to absorb water. However, water was absorbed evenly and uniformly in fertile soil because of its natural structure and the distribution of pore size within the soil.

Some of the significant factors that influence the permeability or how quickly air and water pass through the soil under a center pivot system.

a) **Several micropores:** The permeability increase with the greater the number of macropores.
b) **Soil aggregates:** The greater the size of the pores of the capillaries, the greater the permeability.
c) **Depth of soil:** As the sub-soil, layers are more compact and have less organic matter, the permeability decreases with depth.
d) **The coarseness of soil texture:** Permeability is higher in coarse-textured soil, but lower in fine-textured soil.
e) **Salt concentration:** Salt concentration is adversely affected by permeability. If the sodium is high in water, it will result in ready soil dispersion and thus decrease permeability.
f) **Soil moisture status:** If the soil becomes drier, permeability decreases and increases as the soil becomes wet.
g) **Organic matter content:** In the soil, a matter that is more organic results in higher permeability.

Permeability is considered slow if it is less than 2.5 cm per hour and moderates if it is less than 5.0 cm per hour. Permeability may also be regulated to some degree by effective management practices, such as infiltration. Permeability is decreased by continuous tillage, while permeability is improved by the growth of deep-rooted crops such as pulses or legumes, grasses, and tresses. With its moisture status, the permeability of the soil varies and typically decreases as the soil becomes drier when air enters the soil and reduces the permeability.

I.9.2.3. PERCOLATION:

Percolation is known as the downward movement of water through saturated or almost saturated soil due to the forces of gravity. When water is under pressure or when the tension is much less than around 1/3 of the atmosphere, percolation occurs. Until it approaches the free water table, percolating water goes deep into the earth. Studies of percolation are necessary and important for two reasons:

a) Percolating water is just a source of groundwater recharge, which can once again be profitably used for irrigation by springs and wells.
b) Percolating water brings, deep into the lower layers, plant nutrients such as calcium, and magnesium and deposits them beyond the reach of traditional field crop roots. There is a rapid loss of water by percolation in sandy or open textured soils.

Even though irrigated water reached the soil profile, it suffers additional losses because of profound percolation and unequal distribution. As a result, despite enhanced irrigation adequacy, there is even more deep percolation from the field. The net depth of application is what remains after evaporation and deep percolation losses are removed from the gross depth of application. In follows the factors that influence percolation.

a) **Climate:** if rainfall were greater than evaporation, then percolation would be considerable. There is almost insignificant percolation in the dry zone.
b) **Nature of soil:** sandy soils allow more percolation because they occupy a large number of macro-pores. The macro-pores serve as the primary gravitational flow channels. Furthermore, clay soil allows less water to percolate.

Percolation is the process of water absorption by the soil. It depends greatly on the type and the composition of the soil. The rate of percolation is calculated by using Equation I.1 defined as follows:

$$\textit{Percolation Rate (mL/min)} = \textit{Amount of water (mL)} / \textit{Percolation Time (min)} \quad \text{(I.1)}$$

For example, suppose that it took 20 minutes for 200 mL to percolate for a specific sample.
Percolation rate = 200 mL/ 20 min = 10 mL/ min.

Figure I.10 highlights the method used for the measurement of the percolation rate.

Figure I.10: Percolation rate measurement.

I.9.3. SOIL - PLANT REACTION:

Wind, rainfall, temperature, light, and moisture influence the soil. Some significant climatic factors impact the profile of the soil and bring about changes in the structure of the soil. The meteorological factors, as well as soil components, decide the different types of vegetation and crops that may grow in any area. Knowing how much water the plants need is an essential component of successful landscape watering. You may need to water to varying depths and widths depending on the size and form of the plant (tree, shrub, or groundcover). As it has a larger root zone, the region in which the plant's feeder roots are concentrated, a large tree needs more water than a small groundcover. Table I.1 shows the water flow needed for the wet root zone in liters.

Diameter [m]	**0.3**	**0.6**	**0.9**	**1.2**	**1.5**	**1.8**	**2.4**	**3**	**3.6**	**4.2**	**4.8**	**5.4**	**6**
Plant	**Liters of water required to wet the root zone**												
Trees	5.6	18.9	41.6	60.5	83.2	98.4	143.8	223.3	321.7	435.3	567.8	719.2	889.5
Shrubs	3.7	15.1	30.2	45.4	64.3	75.7							
Groundcover/ cacti	1.8	7.5	13.2	18.9	26.4	34							

Table I.1: The appropriate liters of water for wetting root zone [42].

I.9.3.1. A SIMPLE METHOD FOR REMEMBERING DEEP OF WATER:

a) Water up to a depth of 0.3-meter on small plants such as groundcovers, cacti, and annuals. (soil should be watered to a 0.2-meter depth).

b) Water medium plants to a depth of 0.6 meters, such as shrubs.

c) Water large plants to a depth of 0.9meter, such as trees.

In Figure I.11, rooting depths are shown as schematic drawings of individual plants using estimated geometric mean values for six types of growth types (from left to right): succulents, annual herbs, perennial herbs, dwarf shrubs, shrubs, and trees.

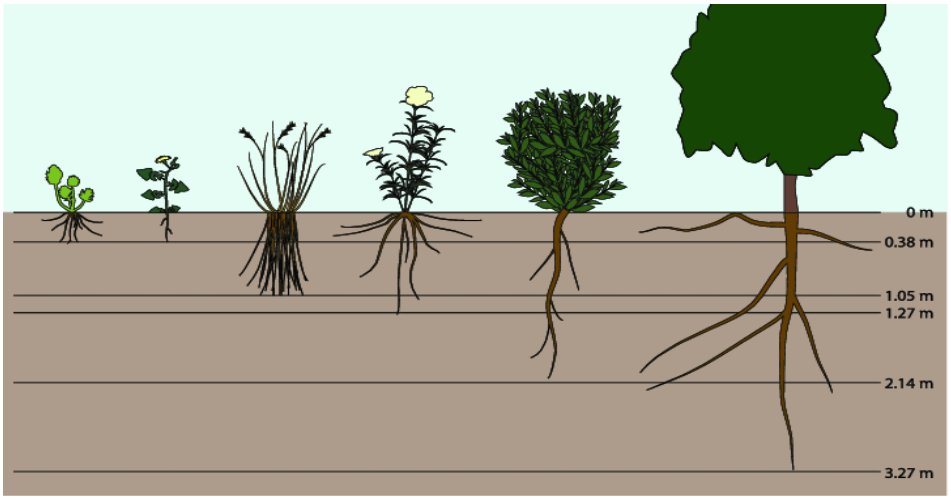

Figure I.11: Rooting depths of individual plants in six growth type groups using estimated geometric [43].

A simple way to measure how deep you have watered is to use a soil probe — a sharpened piece of rebar or a very long screwdriver works well. Push the probe into the soil an hour after watering. It can slide quickly through wet soil, but pressing through dry soil will be difficult or impossible. Water the plants and lawn before you can slide the probe to the recommended depth quickly.

I.9.3.2. WATER REQUIREMENTS OF A CROP:

The water requirement of a crop, which is the total amount of water needed from the time of sowing until the harvest, must be known. Naturally, different crops, depending on the environment, type of soil, method of cultivation, effective rain, etc., can have different water requirements at different locations in the same country. Over its entire life cycle, which is also named the crop period, the total water needed for crop growth is not uniformly distributed. In fact, before harvesting, the watering stops at the same time and the period from the first irrigation during sowing to the last before harvest is called the base period.

A certain crop grown in a hot and sunny climate requires more water per day than the same crop grown in a cooler, cloudy climate. However, there are other climatic factors-apart such as sunshine and

temperature, which affect the crop water need. The humidity and the speed of the wind are these influences. The requirements for crop water are higher when it is dry than when it is humid. In windy climates, more water will be used for crops than in calm climates. As discussed earlier, the need for crop water or evapotranspiration of crops consists of plant transpiration and evaporation from the soil and crop surface. Evaporation will be more significant than transpiration if the plants are very small. Transpiration is much more essential than evaporation when the plants are fully grown. Evaporation is more important than transpiration throughout planting and during the initial stage and the need for evapotranspiration or crop water during the initial stage is approximated to be 50 % of the crop water needed during the mid-season stage when the plant is properly formed. An example of a potato's growth stages was shown in Figure I.12.

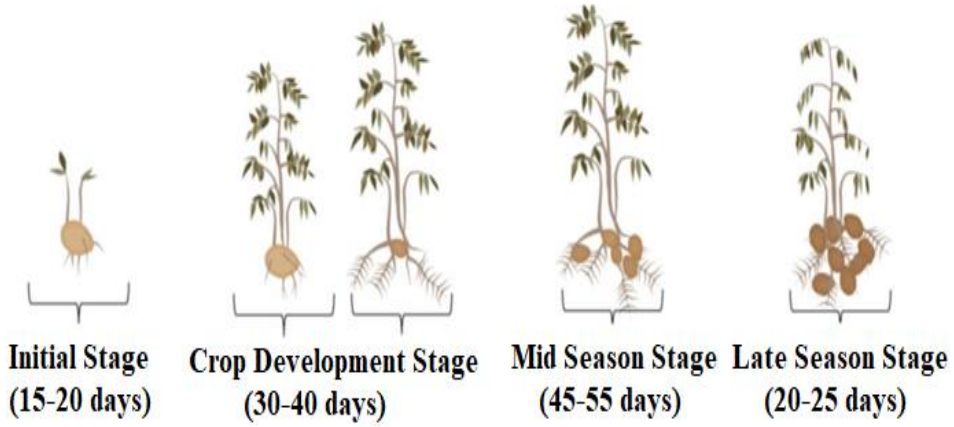

Figure I.12: Potatoes growth stages.

The need for crop water is gradually growing from 50 % of the total need for crop water to the overall need for crop water during the so-called crop growth period. At the end of the crop development cycle, which is the beginning of the mid-season stage, the maximum crop water requirement is reached. A distinction can be made between two groups of crops during the late-season stage, which is the time during which the crop ripens and is harvested:

a) **Freshly harvested crops:** For crops such as cabbage, lettuce, etc, the need for crop water during the late-season stage remains the same as it has been since the mid-season stage. The plants are freshly harvested and thus require water until the last time.
b) **Dry harvested crops:** For example, cotton, maize (for the production of grain), sunflower, etc. These plants are permitted to dry out during the late-season stage, and sometimes even die. Therefore, their water needs through the late-season stage are limited. If the crop is not allowed to die, the need for water during the mid-season or peak time is just about 25 % of the need for crop water. During the late-season stage, of course, no irrigation is provided to these crops.

Data on crop water needs can often be collected locally and it is therefore not important to quantify them. To offer some indication, however, of the seasonal water requirement values for the most essential field crops. As a reference, it is possible to use Table I.2.

Crops type	Total growing period (days)	Crop water need (mm/total growing period)
Alfalfa	100-365	800-1600
Banana	300-365	1200-2200
Barley/Oats/Wheat	120-150	450-650
Bean	75-110	300-500
Cabbage	120-140	350-500
Citrus	240-365	900-1200
Cotton	180-195	700-1300
Maize	125-180	500-800
Melon	120-160	400-600
Onion	Green 70-95 and dry 150-210	350-550
Peanut/Groundnut	130-140	500-700
Pea	90-100	350-500
Pepper	120-210	600-900
Potato	105-145	500-700
Rice (paddy)	90-150	450-700
Sorghum/Millet	120-130	450-650
Soybean	135-150	450-700
Sugarbeet	160-230	550-750
Sugarcane	270-365	1500-2500
Sunflower	125-130	600-1000
Tomato	135-180	400-800

Table I.2: Estimated values of the water requirements of seasonal crops [44].

I.10. CENTER PIVOT SYSTEMS BENEFITS AND RESTRICTIONS:

The uniformity coefficient is a measure of the average deviation of water application at specific locations from the average application depth. On average, for well-designed center-pivot systems, the uniformity coefficient ranges from about 88 to 94% [11]. Based on wind speed and direction, sprinkler form, operating pressure, and tillage practices, the typical value of uniformity coefficient for use with center pivot design is 90%.

For center pivot systems, some of the common **benefits or advantages** are:

a) Automated operation potential decreased operational labor, up to 50% less than many other approaches.

b) Efficient supply of water and high uniformity of water application.

c) The capability of applying to shallower depths.

d) Greater ability to organize and schedule irrigation applications.

e) It is possible to use low-pressure systems with nozzle pressures as low as 10 PSI.

f) It is easy to perform uniform chemical (chemigation) applications.

g) Pivot systems can operate as part-circle structures and the systems can either work in forward or reverse directions.

h) The system needed a little annual setup.

i) The system allows a high degree of reliability and dependability.

Center-pivots systems have some **limitations** and **disadvantages** as well listed here:

a) Except if advanced corner solutions are used, corners are not irrigated.

b) In areas with long or multiple pivots and high pumping rates, groundwater exhaustion has been observed.

c) If adequate soil surface storage is not given, high application rates at the outer end of a center pivot, up to 7×10^{-6} meters per second, can create runoff and erosion.

d) Relatively high losses by pipe friction.

e) Due to the higher application rate, soil surface compaction can increase toward the outer edge of the pivot circle.

f) Might have operational problems requiring human intervention.

g) There is an increase in possible water evaporation losses with heavy applications, therefore, more intensive soil moisture control, such as the use of tensiometers, must be carried out to avoid soil moisture shortages.

h) If the applied wheel pressure exceeds the healthy soil bearing pressure, drive wheels can cause ruts in some soils.

i) Topography should be uniform with slopes not exceeding 10 % as more runoff and potential drive and tire rutting issues are caused by severely undulating topography.

j) Particularly with corner systems, the systems require high initial costs and maintenance.

For a pivot, the cost per acre varies directly with its length. Small pivots have a high per-acre price and much less price than longer pivots. The installed cost may average between $75,000 and $80,000 plus freight on a quarter-mile (402-meter-long) pivot that irrigates 126 acres. This will put the cost per acre at between $595 per acre and $635 [45].

I.11. CONCLUSION:

Center pivot system can be viewed at several points (cost, energy consumption, sprinklers arrangement...) and each point offers a different conclusion regarding water distribution uniformity and the impact of this point on the system's efficiency. It is essential to consider these points in enhancing irrigation efficiency to contribute to the reduction of no beneficial uses. In other cases, improving irrigation efficiency can lead to the consumption of a larger portion of the applied water which can increase consumptive use of the basic concepts and specifications of the center pivot were not investigated, or the factors that influence the water uniformity distribution were not considered in the improvement procedure. Moreover, the reactions between soil, water, and the crop should be studied to know the irrigation requirements of the center pivot system.

CHAPTER II.

HYDRAULIC PERFORMANCE MODELING OF THE CENTER PIVOT IRRIGATION SYSTEM

II.1. INTRODUCTION:

It is important to understand the hydraulics of the center-pivot irrigation systems when choosing the appropriate type and size of the sprinkler or spray nozzles when deciding to use pressure regulators when considering whether to use the end gun corner system and when adapting the pumping unit to the center pivot. Besides, it is necessary to quantify friction losses to optimize system discharge requirements and balance pipe costs against energy costs. However, many factors for the design of the sprinkler or water distribution package are possible, but the follows are important in determining optimal system performance: application rate and depth, pressure requirement, friction head losses, irrigation capacity of the system, overlapping circles, wind effect, and application uniformity.

II.2. PRESSURE REQUIREMENTS AND FRICTION LOSS IN SET PIVOT IRRIGATION SYSTEMS:

It is essential to determine the required lateral inlet pressure head, head differences related to elevation, and pressure (friction or head) losses in the distribution system to choose a pump and power unit that will operate a system efficiently. The total dynamic head (TDH) with which volume of flow should pump water is the total of the correctly chosen set of these, the movement of the laterals and main lines, or variations in the number of sprinkles worked when the operating conditions differ greatly. Center-pivot irrigation systems should determine both the maximum and minimum TDH.

A pump is necessary for most irrigation systems to move water from its source and create the pressure needed to deliver water through a center-pivot irrigation system. Pumps transform mechanical energy from a power source into hydraulic energy, which is used in irrigation systems. Horizontal centrifugal pumps and vertical turbine or submersible pumps are two types of pumps used to distribute water for irrigation. Consider the system illustrated in Figure II.13 to see an example of a system. The pump must generate sufficient pressure to transfer water from the pumping elevation in the well to the pump platform.

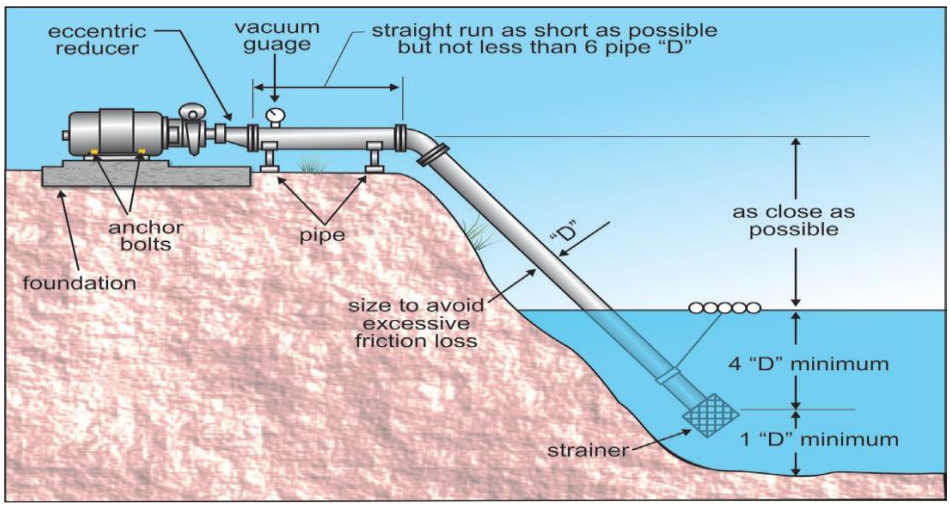

Figure II.13: Horizontal centrifugal pumps lifting water from a pond [20].

Elevate water from the pump foundation to the center pivot lateral's level, and overcome pressure loss along the pipeline caused by friction in the pipeline's pipes and fittings. As shown in Figure II.14, the pump must also produce the pressure necessary to operate the sprinklers on the pivot lateral, overcome pressure loss in the pivot lateral, and elevate water to the highest level at the pivot lateral's end. Some variables stay constant, like the height of the pump relative to the pivot input or the depth of water under the pump platform relative to the stable water level. The amount of flow through the system does not influence those numbers. The rate of flow through the system affects other factors including friction loss and the pressure necessary to operate the enter-pivot system.

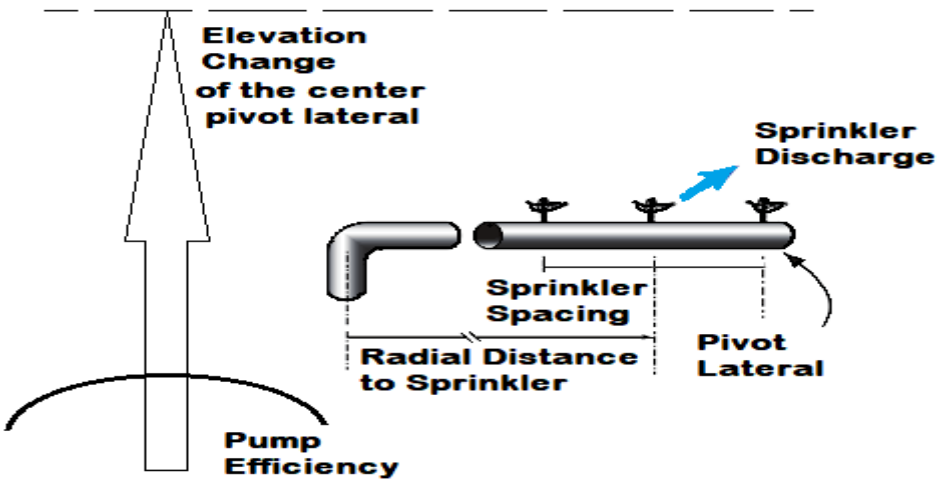

Figure II.14: Influence of elevation change for a typical center pivot system.

Figure II.15 illustrates the head-capacity curves for pumps with 3, 4, and 5 stages. The TDH necessary flows are related to the curve of the system, which is shown in Figure II.15 for an example system.

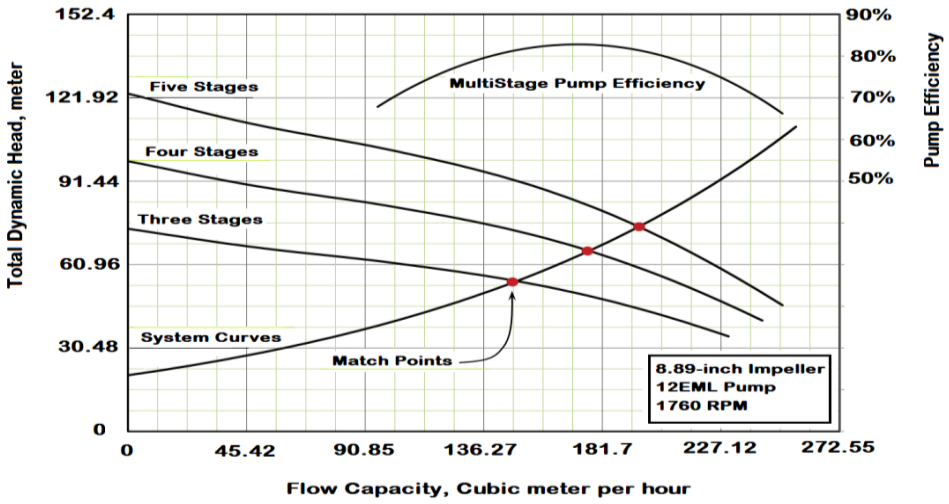

Figure II.15: Characteristic curves used to determine the flow and head where the pump and the system match.

Pump curves indicate how much head the pump can generate at particular flow rates. The pump's output must correspond to the irrigation system's head requirements. Consequently, the system curve is the amount of head needed for different flows within the center-pivot irrigation system.

Evaluating the spatial distribution of friction head-loss along center-pivot irrigation systems is a significant phase in analyzing the system's energy-use performance. The hydraulic simulator named EPANET 2.0 with head-loss spatial distribution predicted by four different analytical models compared head-loss spatial distribution along with the various center pivot lateral line configurations. V. Buono Silva Baptista et al. [46] computed this simulator using two main friction head-loss equations: Darcy-Weisbach and Hazen-Williams. The four analytical solutions, however, measured head-loss values identical to those determined by the EPANET 2.0. hydraulic simulator. This analysis revealed that the four analytical models had the same deviation in comparison to the EPANET 2.0. calculated values when the flow regime is completely turbulent and using the Darcy-Weisbach equation to estimate the friction head loss.

II.2.1. NOZZLE, FITTING, AND VALVE LOSSES:

All these must provide allowances for friction losses in all elbows, tees, crosses, reducers, increasers, adapters, and valves in succession between the water source and the main sprinkler. In laterals, it must consider friction head losses in main lines, sub mains, and section lines. Losses in the column (between the ground surface and the pump bowels) must also be considered when using deep-well turbine pumps. In the pump itself, pump manufacturers make provisions for losses. The form of sprinkler applicator and the mode of application define specific components of water loss. "Net" evaporation of the canopy could be in the 5-10 % range [47].

In some cases [47], total evaporation losses were between 10 and 20 %. The irrigation performance of non-runoff LEPA (low energy, precision application) systems was 93-99 % of the range. With evaporative losses of less than 10 % in most cases, LESA (low elevation, spray application) or LPIC (low pressure, in-canopy) systems can be effective.

In fittings and valves, losses can be determined by Equation II.2:

$$\Delta P_{i_s} = K\rho\frac{v_i^2}{2} \tag{II.2}$$

where

ΔP_{i_s}: friction-head loss due to nozzle or sprinkler [m]

g: accumulation due to gravity 9.81 [m/s²]

K: resistance coefficient for the fitting or valve

V_i: velocity head for a given discharge and pipe or fitting diameter [m/s]

The velocity head can be calculated using Equation II.3:

$$\frac{V^2}{2g} = K\frac{Q^2}{D^4} \quad \text{(II.3)}$$

However, in so many center-pivot calculations, losses are minimal and ignored in fittings, nozzles, and valves along the sides (minor losses).

II.2.2. LOSS OF PRESSURE IN A WATER PIPE:

The most typical lateral center pivot uses a pipe diameter of 168 mm, 400 m long, and occupies a 50 hectares circle inscribed within a 65 hectares square "quarter-section" of the field [35]. In addition, if the pivot were on flat terrain, the pressure from the pivot inlet to the pivot's distal end would be reduced. The first part of a center-pivot lateral is when a large percentage of the pressure loss occurred. The first 28% of the pipeline is where half of the entire pressure loss occurs, and the first half of the pipeline is where 80% of the total loss occurs [20]. Because most of the pressure loss has already occurred, the outer portion of the pivot will receive about the same pressure in the pipeline. As a result, if the pressure is measured at the pivot lateral's outer half, the measurement is accurate for the outer spans.

The pressure loss caused by friction must be around 48.26 kPa and 82.73 kPa as a general rule of thumb [20]. When the pressure loss is little more than 48.26 kPa, the initial cost can be reduced by using a smaller pipe. If the pressure loss is greater than 82.73 kPa, the additional operating costs related to excessive friction loss, when amortized over the pivot's lifecycle, will almost definitely pay for a larger pipe at the time of installation. As a result, the desired pressure loss range of 48.26 to 82.73 kPa defines the practical range of flow rates for particular pipe size.

Bu using the Darcy-Weisbach formula, pressure losses in water pipes can be measured. The Darcy friction factor should be defined to use this formula. For the turbulent flow, the best estimation of the Darcy friction factor is the Colebrook-White equation. Only numerical root-finding methods can solve this equation [48]. The darcy-Weisbach equation shows that ΔP_{i_l} is proportional to (L/D) and v_i^2, and this equation still as useful today as in 1850 to determine the pressure loss in a pipe as given in Equation II.4.

$$\Delta P_{i_l} = f\left(\frac{L}{D}\right)\left(\frac{\rho v_i^2}{2}\right) \quad \text{(II.4)}$$

In equation II.4, the pressure drop is ΔP_{i_l}, f is the Darcy friction factor, ρ is the fluid density [kg/m^3], D is the water pipe hydraulic diameter, and V is the average velocity. The friction factor of Darcy (f) is dependent on the flow regime. The friction factor can be calculated for a fully developed laminar flow (Reynolds number Re < 2300) from the Hagen-Poiseuille equation as shown in Equation II.5.

$$f = \frac{64}{Re} \tag{II.5}$$

Here, *Re* is a number for Reynolds.

Equation II.6 defines the *Re* number as follows:

$$Re = \frac{v\,D}{\vartheta} = \frac{\rho v D}{\mu} \tag{II.6}$$

In equation II.6, the fluid's dynamic viscosity is μ. In equation II.5, with the Reynolds number, the friction factor changes inversely. The friction factor can be defined by the Colebrook-White equation for the transition region ($2300 \leq Re \leq 4000$) and the turbulent region ($Re \geq 4000$) in both smooth and rough pipes. The friction factor can be defined by the Colebrook-White equation (White 1937) as shown in Equation II.7.

$$\frac{1}{\sqrt{\mathrm{f}}} = -2\log\left[\frac{\frac{\varepsilon}{\mathrm{D}}}{3.7} + \frac{2.51}{\mathrm{Re}\sqrt{\mathrm{f}}}\right] \tag{II.7}$$

Where ε: is the degree of roughness, for smooth steel pipes, $\varepsilon = 0.0014$ and ε/D is the relative roughness, which is the ratio of the pipe's mean roughness height to the diameter of the pipe. As seen from equation II.7, the friction factor is a function of the Reynolds number and pipe roughness (ε). As the value of (f) exists on both sides of the equation, we cannot directly solve the Colebrook-White equation because of its implicit type. For example, the Newton-Raphson method may resolve Equation II.7 using a numerical root finding method.

Moody (1947) defined an appropriate relationship between Reynolds' ranges and the relative roughness as shown in Equation II.8.

$$f = 5.5x10^{-3}\left[1 + \left(2x10^{4}\left(\frac{\varepsilon}{D}\right) + \frac{10^{6}}{Re}\right)^{\frac{1}{3}}\right] \tag{II.8}$$

The plot of the relative roughness (ε/D) of a pipe against Reynold's number is the Moody chart or the friction factor. In the chart's fully turbulent region, the blue lines (see Figure II.16) plot the friction factor for flow, whereas the straight black line plots the friction factor for flow in the chart's fully laminar region. Lewis Ferry Moody plotted the details from the Colebrook equation in 1944, and the resulting chart became known as **The Moody Chart** or the **Friction Factor Chart** sometimes. This chart was the first solution that allowed the user to receive a reasonably precise friction factor for turbulent flow conditions based on the Reynolds number and the pipe's relative roughness.

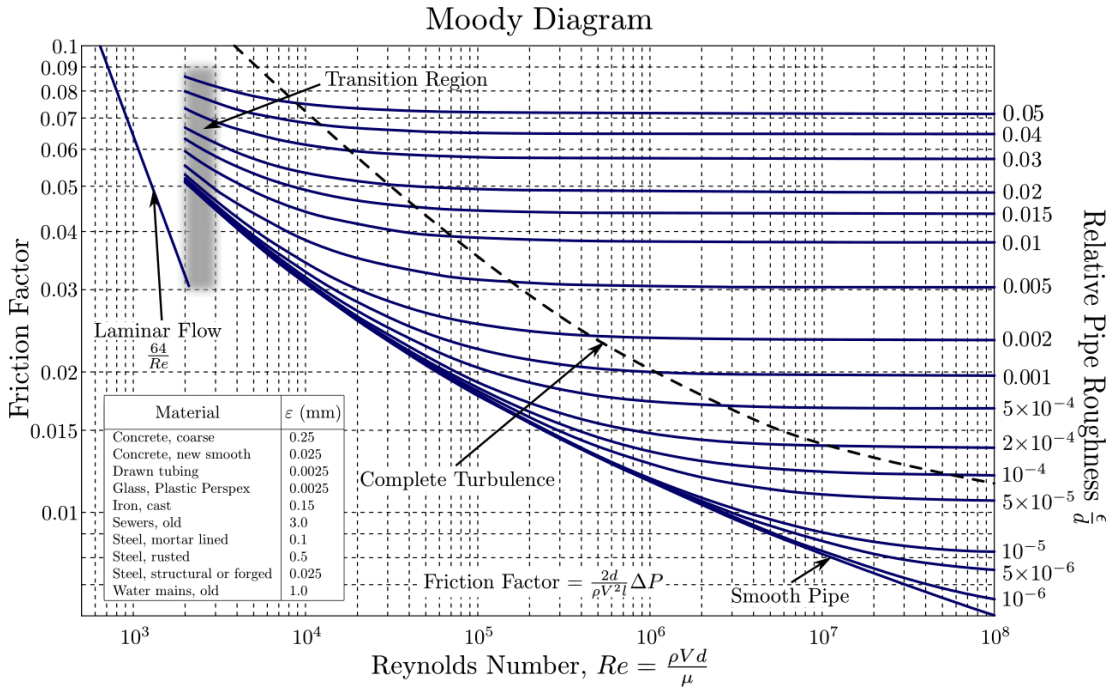

Figure II.16: Moody Chart.

II.2.3.THE ENERGY BALANCE EQUATION:

Nozzle discharge is based on the pressure of the system. Nonetheless, the appropriate choice of sprinklers needs data on the sprinkler pressure. The lateral pressure ranges from the pressure at the end nozzle to the pressure at the pivot point. At the pivot point, the pressure is determined by the minimum necessary pressure and type of nozzle chosen for the system, the friction, and elevation losses along the lateral. First, it is useful to analyze the energy balance equation used, to sum up, these losses and explain the relationship between total water energy points. Three components comprise total water energy: Pressure head, velocity head, and elevation potential. The sum of these three components is called the total energy of the water or the Bernoulli Equation. However, this equation can be considered a suitable statement of the conservation of energy principle for moving fluids. Various versions of the Bernoulli equation for different types of flow exist. The total energy of water does not change when water flows through a pipeline, either uphill or downhill unless any energy is lost due to friction or other limited loss systems. The Bernoulli equation between two points on a pipe is written as given in Equation II.9.

$$P_0 + \frac{1}{2}\rho v_0^2 + \rho g h_0 = P_i + \frac{1}{2}\rho v_i^2 + \rho g h_i + \Delta P_{i(l+s)} \quad \text{(II.9)}$$

The Bernoulli equation above can be provided to estimate the pressure at any point (i) and expects that point (i) is downstream of point (0). Equation II.10 defines the total friction-head loss as follows:

$$\Delta P_{i(l+s)} = \Delta P_{i_l} + \Delta P_{i_s} \quad \text{(II.10)}$$

Depending on the energy equation when considering the differences in elevation is ignored and Specifying the height of the nozzles is the attitude reference frame (*h(i)*=0), the velocity of water flowing in a center pivot lateral which evaluate how much pressure is lost due to minor losses is calculated using Equation II.11.

$$v_i = \sqrt{\frac{2\left(P_0 - P_i - \Delta P_{i(l+s)}\right)}{\rho} + v_0^2 + 2gh_0} \qquad \text{(II.11)}$$

in which:

h_0 is the vertical elevation [m] (can be positive or negative), P_0 is the inlet pressure [Pa], P_i is the outlet pressure [Pa], and $\Delta P_{i(l+s)}$ is the total head loss [Pa].

The pressure head must be adapted to the height difference depending on the energy equation's relationship. The pressure distribution varies when there are elevation variations. However, suppose the end sprinkler's overall elevation difference along the lateral is within 10% of the pressure head at the end sprinkler (American Society of Agricultural Engineers ASAE Minimum Performance for Sprinkler Systems). In that case, the result defined by Equation II.11 is still considered appropriate.

II.2.4. HEAD LOSS IN THE PUMP:

The pressure or head loss is much greater than expected in many pump-pressurized systems because of additional variations in friction losses in the mainline and also because most pumping systems add less pressure to the water when the total discharge is increased (i.e., when the end gun or corner system is turned on). The curve of the pump is a function of head discharge.

Pump characteristic curves are a helpful tool in the irrigation system, such as the center pivot. It shows the head and discharges range for a given pump and the efficiencies within this range at which the pump works. Pump curves typically provide a power curve that indicates the horsepower necessary to run the pump and should provide the unit's required net positive suction head requirement. The loss of energy for the pump and the electric motor is not identified as part of the pressure head's lateral loss. The efficiency of the pump and the motor or engine considers these energy losses. The relation between the pressure and the discharge is known as a pump's performance curve. For optimal efficiency, pump and system discharge should correspond. Often, to generate the irrigation system's total pressure, one pump stage is not sufficient. On the other hand, a pump with multiple stages is highly required.

II.3. SPRINKLER DISCHARGE:

The decline in well capacity in several irrigation areas and manufacturers' desire to decrease pressure requirements to reduce irrigation pumping costs have encouraged the creation of various sprinkler discharges for center pivot irrigation systems while having the capacity to disperse restricted water supply over a wide area effectively and uniformly. For these packages, two important design modes are

widely used. The first is a fixed (uniform) spacing along with the center pivot with variable nozzle sizes or diameters to vary the sprinkler's discharge. The second is the almost constant discharge of the nozzle and head selection with variable spacing (e.g., farther apart near the pivot point and closer together on the pivot's outer lengths). Combining these two other design modes is a third design mode - named semi-uniform spacing[11].

Constant spacing of the outlet is very common, particularly for closely spaced systems (~1.5 m) used with the application methods of LEPA (low energy, precision application), LESA (low elevation, spray application), or LPIC (low pressure, in-canopy). The spacing of the sprinkler outlet is frequently spaced up to 10 ft (3 m) apart for non-LEPA/LESA kind systems with constant spacing [47]. This spacing mode is still used for low-angle effect sprinklers or spray heads on drops placed on pipelines (typically mounted just below the truss rods). The larger sprinkler discharge rate at the outer end requiring large nozzles with larger droplets may be one problem with this spacing design. In certain situations, it may result in the need for higher operating pressures. Because of soil crusting and/or runoff problems from the high instantaneous application rates, these two variables-larger nozzles, and higher functional pressures-can cause infiltration problems[47].

II.3.1. SPRINKLER APPLICATION MODES:

The "sprinkler packages" application modes for center pivot can be defined as either 1) overhead or over-canopy methods or 2) near-canopy or in-canopy methods. The model of sprinkler installed is affected by the chosen application method's mode. The type of mode and sprinkler can affect the spacing needed. The factor of application modes thus influences the performance of the "package"[47]. An explanation of the relative application rates modified and adopted from[31] under a center pivot system for different sprinkler types is shown in Figure II.17.

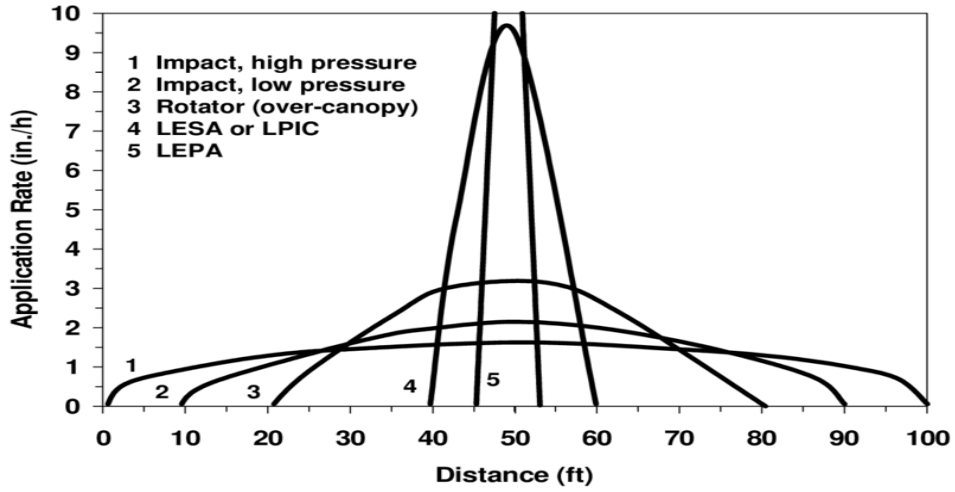

Figure II.17: Illustration of relative application rates for different kinds of sprinklers under the center pivot irrigation system [31].

It is difficult to display the LEPA application rate in the graph above because it is a "point" discharge, and its peak has been shown to exceed the rate range. Overhead or overhead canopy techniques are those application forms placed on the center pivot pipe itself or assembled on drops that are frequently just under the truss rod elevation above the soil surface. Depending on the height of the device and crop level, these explanations are still arbitrary. Whether only overhead or over-canopy chemigation is required or whether no chemigation choice is needed is one of a wide variety of factors for this model. On drop tubes from the center pivot pipeline, the near-canopy or in-canopy application methods are often installed. The primary difference is whether the sprinkler devices are positioned near the ground (LEPA or LESA) in the canopy of the crop or the canopy of the mature crop (LPIC) or just above the maximum crop height.

For uniform distribution of water over the circular area, the moving lateral pipeline is equipped with impact spinners or spray nozzle sprinklers. In the area irrigated by each sprinkler, when the system is equipped with a uniform sprinkler spacing along the lateral, the size of the spray nozzle grows progressively larger towards the moving end. Consequently, to obtain a uniform application, the sprinklers should be designed to provide significantly greater discharge.

Equation II.12 establishes a relation between the kinematic characteristics of a fluid's motion and the density of the fluid. The mass conservation equation also termed the continuity equation expressed as follows.

$$Q_{in} = \sum_i^n Q_{out} \tag{II.12}$$

The flow of volume [m^3/s] that passes through the given cross-section is given by Equation II.13.

$$Q_{in} = \sum_i^n A_i V_i \tag{II.13}$$

where

A_i is the cross-section defined in Equation II.14 as follows:

$$A_i = \pi \frac{d_i^2}{4} \tag{II.14}$$

Where

R is the nozzle's radius [m] and *d* is the nozzle's diameter [m]

A particular form of pipeline manifold where the flow decreases along its length is a center-pivot irrigation system. Nevertheless, as with other forms of sprinkler systems like hand lines, wheel lines, and linear moves, the flow reduction is not linear with distance along the lateral.

As the flow through the discharge, opening or orifice is dependent on the opening size and the operating pressure, the performance of every kind of sprinkler nozzle is expected. Equation II.15 defines the nozzle discharge that can be measured for a circular orifice as given in [49]:

$$q_i = \mathrm{C}_d(29.83) * 10^{-3} * d^2 * (P_i)^{0.5} \quad \text{(II.15)}$$

where

q_i is the discharge of nozzle in [m^3/s]

C_d is the discharge coefficient (often between 0.95 and 1.00)

d is the nozzle diameter in meters

P_i is the pressure of the nozzle in pascal.

As the flow varies by the diameter square, doubling the diameter quadruples the flow, thus doubling the pressure increases the flow by around 40% as the flow varies by the pressure square root. However, the nozzle's pressure, size, and dimension from the pivot point may have a major effect on the wetted diameter.

Jensen [50] indicated that in an orifice emitter, the flow is typically completely turbulent. Orifice flow rates are best characterized by calculating the flow levels empirically as a function of operating pressure. Equation II.16 illustrates the function of orifice flow as follows:

$$q_i = \mathrm{K} * (P_i)^x \quad \text{(II.16)}$$

Here, q_i is the nozzle flow rate, K is a factor characterizing the orifice's dimensions, and (x) is the exponent of the orifice that characterizes the flow regime. Plotting "q versus P_i" on a log-log plot specifies the coefficients K and x. The straight-line slope is x, and at P_i = 1.0 the intercept is K. The orifice discharges exponent x = 1.0 for laminar flow, while for the turbulent flow x= 0.5, and for compensating flow x= 0.

The manufacturer often uses advanced, sophisticated, and validated computer software to determine and select the right nozzle discharge along with the center pivot system. The program uses detailed nozzle and regulator characteristics databases and all necessary equations for evaluating all friction losses. The specification of the nozzle's particular size by the end-user is generally strongly discouraged by the manufacturer.

Fukui, et al. [51] provide a method for determining the rate of water application and the coefficient of uniformity of overlapping irrigation sprinklers where, under windless conditions, the geometry of the sprinkler configuration, trajectories of water drops from the sprinkler nozzle, and the discharge profile

of a single sprinkler are experimentally observed. The evaluation of simulated discharge profiles indicates that, with triangular sprinkler discharge profiles, the uniformity coefficient's maximum value has been obtained at low spacing values, transferring to trapezoidal profiles as the spacing increases.

II.3.2. SPRINKLER PATTERNS:

The primary objective of irrigating is to have the maximum uniform water pattern available. Consequently, if sprinkler devices are correctly chosen for local field conditions, center pivot irrigation systems can be very effective and uniform. Two significant factors to consider when choosing sprinkler packages are runoff capacity and evaporation losses during water application. To divert the water and create a 360° wetting pattern, the jets of most spray heads used on center-pivots impinge on plates. Such nozzles can generate narrow widths of the pattern but consequently extremely high application rates.

The influence of application pattern shape on center-pivot irrigation uniformity was investigated by D. Heermann et al. [52]. In this study, four distribution patterns typical of devices that apply peak application depths away from the nozzle were studied (triangular, elliptical, donut-shaped, and piecewise linear). They discovered that sprinkler systems' spacing was more significant than single sprinklers' pattern shapes to achieve uniform water application. Elliptical patterns consistently resulted in the highest uniformity, representing impact sprinklers with spreader nozzles, whereas donut-shaped patterns resulted in the lowest uniformity. Compared to other applications, system spacing for donut-shaped patterns decreased to achieve a reasonable uniformity coefficient.

II.4. PRESSURE REGULATOR:

Even when the ground slope is relatively mild, the decrease in pressure along with the device due to intermittent end gun or corner system activity can demand the use of pressure regulators on all nozzles along with the center pivot lateral. Individual sprinkler pressure regulators are installed in the latest designs of center pivot systems to assume "equal" sprinklers working at identical pressures. As a result, installing individual sprinkler pressure regulators is an additional option for enhancing uniformity. The pressure-regulator technique, unlike the reduced-spacing solution, has no first-order effect on the application intensity. This is typically a benefit. The use of pressure regulators at every outlet of the nozzle along the lateral center pivot can affect how the Bernoulli equation is applied. Figure II.18 shows an example for the drop Configurations of a sprinkler.

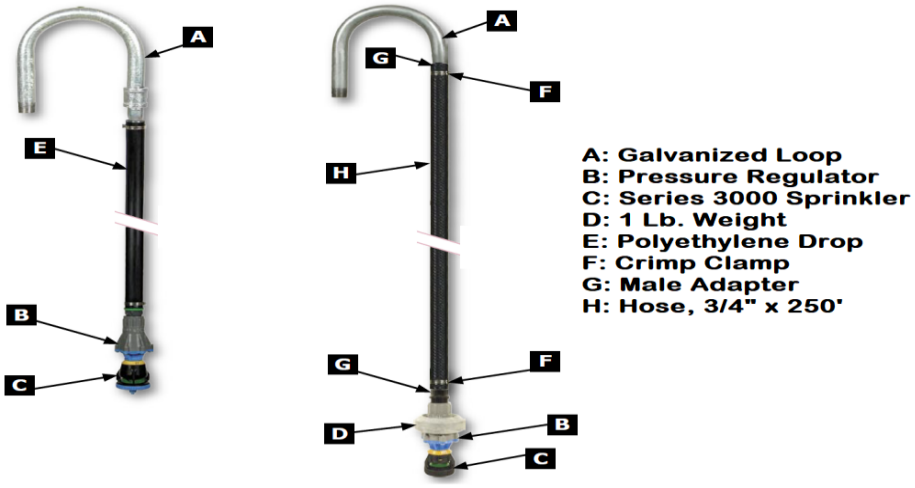

Figure II.18: An example for the drop Configurations of Nelson Series 3000.

For use on center-pivot laterals, spring-loaded pressure regulators have been formed. They are cost-effective to serve, operate effectively between 0.1 and 1.0 L/s and can withstand surges. Preset pressure range from 6, 10, 15, 20, 25, 30, 40, and 50 psi are required on such appropriate regulators (40, 70, 105, 140, 170, 205, 275, and 345 kPa). The regulator's goal is to keep the downstream pressure stable, which is a function of the regulator's flow rate. In addition, the pressure regulator's discharge is proportional to the rate of flow. The flow rate is predictable and it can be easily used when designing the sprinkler/nozzle/regulator package.

The diminishing of pressure along the lateral, especially without the use of a pressure regulator, is one of the issues affecting uniformity under a center pivot and a linear movement irrigation system in the field. An imaginary example described in [53] indicated that the pressure-regulator method has an economic advantage over the reduced-spacing method when the solid-set system uniformity is U = 60% and may be increased to U = 85% when the system is equipped with pressure regulators.

Regulators decrease pressure by around 34.47 kPa, therefore the pressure in the lateral should be at least 34.47 kPa higher than the regulator's estimated pressure [20]. The regarded regulator pressure, the 34.47 kPa loss in the regulator, the friction loss in the pivot lateral, and the difference in elevation between the pivot's distal end at its highest level and the elevation at the pivot inlet should all be considered in the operating pressure at the pivot inlet.

The effect of irregular operation management and configurations on the uniformity of center pivot sprinkling irrigation was investigated by Li Lianhao and all [54], who used the Heermann-Hein uniformity coefficient (CUH) and the Distribution uniformity coefficient (DU) as of measurement indicators. The finding of this research suggests that can regulate the inlet pressure with the same pressure by a pressure regulator, which kept the uniformity of the system constant. However, if the

pressure regulator operated abnormally, the flow discharge was subject to great pressure loss, which can reduce the uniformity of the system, and while the pressure regulator was removed, there was a major irregularity in the sprinkling irrigation depth, causing in a reduction in the performance and the uniformity of the irrigation system. The lateral pressure in all nozzle positions will be sufficient when pressure regulators are assembled upstream of every nozzle.

If the field is basically flat, pressure regulators are not needed and a sprinkler's discharge must not range by more than 10% as it moves over the field, according to a common rule of thumb. Regulators are not necessary if the elevation change in the field is less than this limit [20] (see Figure II.19). The on-off operation of an end gun frequently causes pressure head variation of around 10 to 15 feet along the lateral. If an end gun is attached to the pivot, regulators may be needed for design pressures less than 206.84 kPa (2.06 bar).

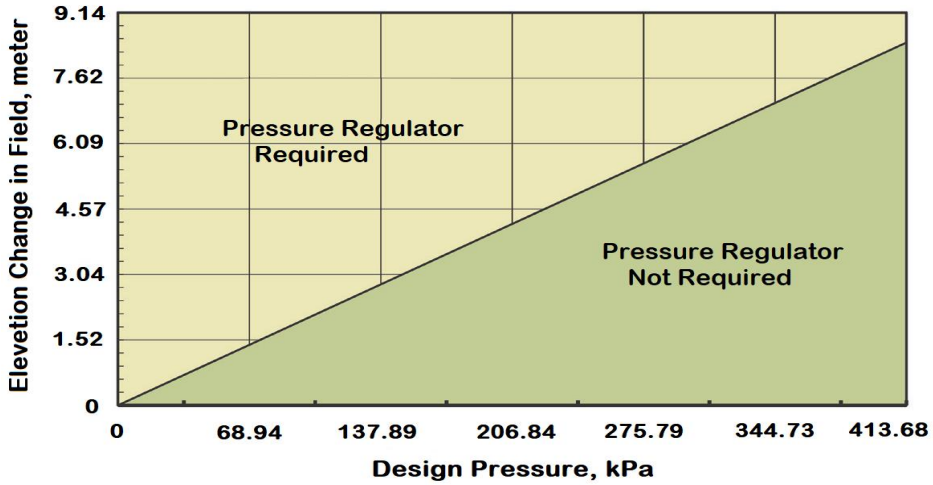

Figure II.19: Recommendations regarding when to apply pressure regulators, according on elevation changes in the field [20].

Manufacturers may have inlet pressure specifications for pressure regulators. As the center pivot lateral rotates, at the pivot point, the pressure can change. Still, the discharges of each nozzle should stay relatively constant due to the effect of pressure regulators, which must always maintain within a range to prevent sprinkler damage (15 PSI = 1.034Bar is data for Nelson sprinkler) as shown in Equation II.17.

$$P_1 = P_2 = P_3 = \cdots = P_n \tag{II.17}$$

The effective wetted diameter is typically reduced when working outside the required pressure range, whether high or low. Calculating the pressure at a certain point along a center pivot lateral is sometimes useful. It may also be needed to evaluate the design against the pressure measurement, and calculate, or validate the proper nozzle size.

II.5. SPRINKLER OVERLAP PATTERNS ON A CENTER PIVOT SYSTEM:

The uniform application of water is one of the primary goals of center-pivot nozzle selection. The necessitates nozzle spacing small enough to ensure that differences in individual nozzle wetting patterns are dampened by adjacent nozzles' assistance. Water application by adjacent nozzles must overlap by 100 to 150% at the least. A 100% overlap means that the water from at least two (2) separate nozzles supplies any point on the field.

Lower pressures and lower angles of water stream trajectories are used in modern sprinkler designs with single or double nozzle configurations to provide a large wetted diameter. The effective wetted diameter of a sprinkler refers to the zone of nozzle coverage. The center-pivot irrigation device will provide more uniform application patterns at lower water application rates when these sprinklers are properly overlapped (see Figure II.20). The wide wetted diameter and limited water application rate may be necessary to avoid irrigation water runoff.

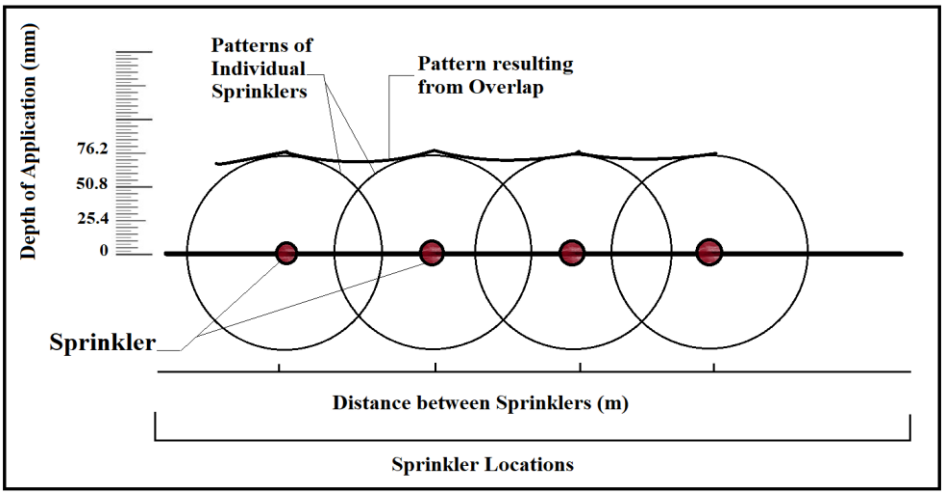

Figure II.20: Sprinkler overlap patterns for the center pivot system.

Sprinklers function as a group in center-pivot irrigation systems. It must grant overlap between individual distribution patterns to achieve uniform water application along the lateral pipeline and between lateral positions. Consequently, sprinklers' distance should be chosen to ensure an excess of more than 100% of sprinkler pattern overlaps between all the sprinklers. Because of the wide wetted radius, it is difficult to reserve water application to small areas without undesired application to nearby areas. Furthermore, needless overlapping may have a negative effect on application uniformity. Nevertheless, since center pivot systems rotate in steps rather than continuously, it needed water application devices with a wide enough wetted radius to ensure overlapping and good application uniformity in system movement direction [55].

The spacing between sprinklers in center pivots irrigation systems offers more than 100% overlap in most situations. The overlap combined with movement across the field will result in a high degree of uniformity. For many of the modern sprinklers, however, more than just overlap determine spacing. Low-pressure spray heads' spacing is best along with a center pivot lateral when the spacing is less than 20 to 25% of the wetted diameter. The overall pattern distribution and the operating conditions determine the final selection of each sprinkler. In center-pivot irrigation systems, overlapping sprinkler coverage in rectangular or triangular configurations offers sufficient water distribution as long as the right sprinkler is selected and then adequately operated. The overlap for high-pressure effect sprinklers should be 50 to 60% of the no-wind wetted diameter. Whereas under high wind conditions, the sprinkler spacing should be decreased to around 40 to 50% of the wetted diameter, according to a general rule[49]. The individual sprinkler as well as the operating conditions determine the overlap of low-pressure sprinklers. These sprinklers can need more overlap than impact sprinklers, which usually demand 50 to 60% of overlap.

One of the significant objectives of center-pivot sprinkler choice is to apply water uniformly. Since the 1960s, the evaluation of center-pivot performance has been a subject of research in the United States. Bittinger and Longenbaugh [56] Published a study that produced an analytical form of rainfall under a sprinkler by assuming that rainfall was triangular or elliptical as a function of radius to simulate rainfall under center pivots to establish ideal sprinkler spacing to achieve regular rainfall.

Heermann and Hein [57] developed Bittinger and Logenbraugh's work in 1962 [56] by accounting for the overlapping effect of adjacent sprinklers in 1968. The distribution patterns of the sprinklers remain triangular or elliptical, and the movement is continuous. They created the name "uniformity coefficient," which they named after themselves (Heermann and Hein uniformity coefficient).

II.6. COEFFICIENT OF UNIFORMITY AND PULVERIZATION:

The uniformity of water application is a factor that calculates how uniformly water is spread across an irrigated area. However, irrigation systems should distribute water evenly and reasonably to reach crop water requirements without overwatering or causing runoff. Therefore, water is distributed to a field more effectively and evenly with center pivot irrigation systems. Uniform water application aims to achieve a uniform crop at a low cost. If irrigation is not uniform, there may be under-or over-irrigated areas, obtaining smaller quantities of produce at a bad quality and a different period than the rest of the field. Even if drainage is good and soil fertility is high, over-irrigation can still provide a uniformly high-quality crop. The cost of wasted water (and leached fertilizers) adds excessively to production [53].

Seginer [58] discovered the optimal seasonal water application as a function of water cost and uniformity, and Chen and W. Wallender [59] developed a procedure to maximize seasonal water application and uniformity at the same time. Furthermore, an experiment was carried out by Chen, et al.

[60] to investigate the effects of working pressure plate structure, and nozzle diameter on sprinkler flow rate. Wetted radius (estimated using two empirical equations), and water application distribution, as well as to evaluate the hydraulic performance of fixed spray plate sprinklers (FSPS) at low pressure. This investigation is based on the water application depth and irrigation uniformity coefficient.

The term "coefficient of uniformity" (CU) refers to how evenly water is spread over a given area. It is defined by measuring the relative deviation of average water applied against the average depth of application. Another coefficient commonly used to evaluate the water application uniformity in the center-pivot irrigation system is the distribution uniformity (DU), which is identified as the difference between the lowest quarter and the average water applied. Heermann and Hein's uniformity coefficient (CUH) is used in this study.

The Hermann and Hein uniformity coefficient (CUH) is a commonly used coefficient to describe water uniformity distribution [61]. The most typical interval of water application efficiency for such systems is about 90% [62, 63]. The required coefficient of uniformity should be greater than 80%, any other type of system with fewer results should not be used [35].

This research adopted Heermann and Hein's modified formula to measure the water distribution uniformity as highlighted in Equation II.18. This adaptation of the CUH equation is the basis for the ISO standard, Test Procedure for determining the uniformity of water distribution of center-pivot and moving lateral irrigation machines with sprayer or sprinkler nozzles ISO (11545, 2009) [64].

$$CUH = 100 * [1 - [\sum_{j=1}^{m}(S_j \left| h_j - h_{moy} \right|)/\sum(h_j * S_j)]] \quad [\%] \quad (II.18)$$

where

CUH is the uniformity coefficient of Heermann and Hein (%)

m is the number of collectors used during the data analysis

j is a number assigned to classify a particular collector (usually starting with the collector located nearest to the pivot point ($j = 1$) and finishing with $j = m$ for the collector far from the pivot point)

h_j is the volume (or the mass) of water collected in the j^{th} collector

h_{moy} is the weighted average volume of water collected

S_j is the distance from the pivot point of the j^{th} collector.

Equation II.19 Computes h_{moy} as:

$$h_{moy} = \sum_{j=1}^{m}(S_j * h_j)/\sum_{j=1}^{m}S_j \quad (II.19)$$

If the pressure of the device is not maintained at the design pressure, uniformity decreases. The pattern may also be affected by nozzle wear and incrustation build-up. Canopy interference also reduces the uniformity of distribution. Therefore, the uniformity of the application will be determined by several designs and operational factors (for example, wind speed, alignment of the pivot, wind direction, topography (tilt of the sprinkler axis with the ground slope, soil type, etc.), and the pressure at the outlet, etc.). Sprinkler size and distance, sprinkler system type - its diameter of throw, application pattern shape, operating pressure, nozzle, spray plate design, and the application device's elevation above the ground are the main sprinkler factors affecting uniformity. Each crop canopy interference also reduces distribution uniformity. If these general factors are not strictly followed, the system's efficiency may suffer and possibly result in increased runoff and reduced yields from under-watering due to poor uniformity.

II.7. THE INFLUENCE OF WIND ON THE CENTER PIVOT SYSTEM:

Operating conditions and environmental factors affect the center pivot system's uniformity, so wind speed is the most uncontrollable environmental factor that affects sprinkle irrigation uniformity. Except near the irrigated area's boundary, some evolved, or developed center pivot systems are not highly sensitive to wind. Still, conventional center pivot systems can be very vulnerable to wind variations if not properly controlled.

In moving systems, wind speed and direction have less of an effect on overall field water distribution uniformity than in stationary systems. Wind drift and evaporation losses (WDEL) values ranging from 0.7 to 45% of applied water have been reported in various research studies. Misconceptions and misinformation about the quantity of water lost by wind drift and evaporation between irrigation specialists, the agricultural irrigation industry staff, and the public contribute to the large variety of sprinkler irrigation WDEL values reported in the studies.

Using a combination of applied water collectors, bromide tracer, and air samplers for determining wind drift and evaporation loss from center pivot sprinklers was developed and field-tested by the methodology [65] under limited wind speed conditions. The minimal tests indicate that the volume balance errors varied from 0.1 to 7.1%, suggesting that the technique is effective for calculating WDEL for center-pivot irrigation systems, except at high wind velocities, where validation tests, as well as identification and reduction of the reason for the large volume balance errors, are required. The system should be designed to allow for extra downtime so that it does not have to run at extremely high wind speeds, minimizing water distribution's uniformity. Under different wind conditions, Table II.3 gives the overlap between adjacent sprinklers for high water uniformity.

Average wind speed [Meters per second]	**Maximum spacing (% of sprinkler's wetted diameter)**
0 to 2.23	70 to 80
2.23 to 4.47	60 to 65
4.47 to 6.7	50 to 55
Over 6.7	45 to 50

Table II.3: The maximum distance among adjacent sprinklers at different wind velocities [49].

Figure II.21 illustrates the widespread impact of wind. The wetted area is transferred downwind as predicted, but the diameter of coverage perpendicular to the wind is decreased.

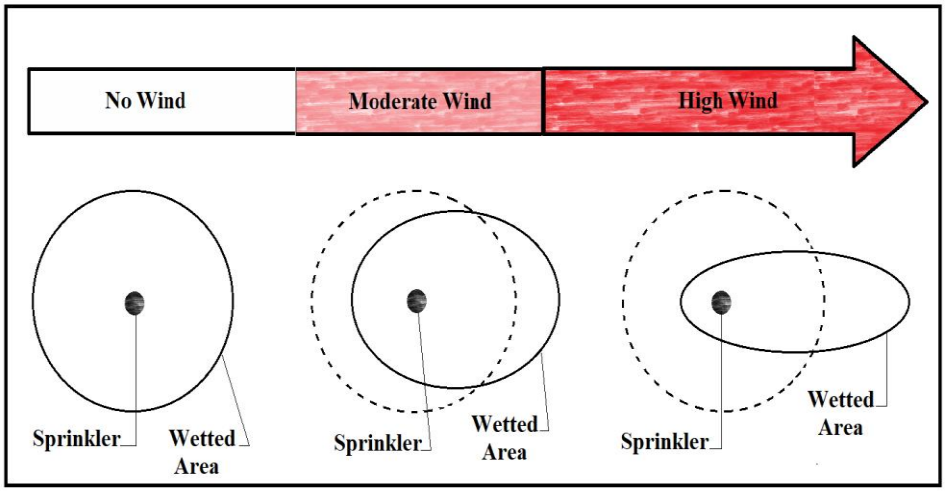

Figure II.21: Effect of wind on the shape and distribution of a sprinkler's wetted area.

The narrowing of the wetted area perpendicular to the wind affects the homogeneity of water distribution in the center pivot irrigation system [66]. If the sprinklers are not positioned closer together while the wind is parallel to the lateral, the coverage diameter will narrow, resulting in poor uniformity. Sprinklers fixed in the lateral must be closer together to compensate for the smaller wetted area. It is normal for all water to be distributed downwind from the sprinkler when there is a strong wind.

The wetted diameter of the sprinkler and the wind speed defines the maximum spacing of a sprinkler system. A sprinkler's wetted diameter is determined by the nozzle size and operating pressure. Wetted diameter information can be found on the sprinkler manufacturer's charts. Each sprinkler's watered area must significantly overlap the adjacent sprinkler's watered area. This overlap may appear to be a waste at first, yet it is a critical requirement. Sprinkler systems that provide uniform water coverage would be impossible to design without this overlap. If the wind speed is between 2.23 and 4.47 m/s, multiply the sprinkler head watering diameter by (0,6) to get the absolute maximum distance (ΔX_{max}) that any two adjacent sprinklers should ever occur. For illustration, spray heads with a radius of 12 m should never

exceed ΔX_{max} = 14.4 m (24 m diameter * 0.6 = 14.4 m). The group of sprinklers should be positioned at 45 % of the diameter of the sprinkler system in a windy area. Sprinklers should be spaced no more than the maximum percentage of wetted diameter, as shown by [24, 49].

As a result, the lateral should be aligned perpendicular to the prevailing wind, and sprinklers should be spaced closer together along the lateral. For acceptable uniformities, general specifications for maximum spacing have been established in the table above (Table II.3).

II.8. CONCLUSION:

Optimal system performance is a growing challenge in irrigation systems. Many procedures have been developed to help producers reduce their irrigation water use, and maximize the uniformity of available water supplies. In this chapter, we describe the hydraulic parameters for modeling a center pivot system. in addition, application rate and depth, pressure requirement, friction head losses, irrigation capacity of the system, overlapping circles, wind effect, and application uniformity were studied to illustrate how pivots should operate and discuss issues in center pivot performance that we are observing in producer fields. The Optimization model has been developed to help the center pivot system achieve the greatest return from the limited irrigation water supplies.

CHAPTER III.

OPTIMIZATION TECHNIQUE

III.1. INTRODUCTION:

Computer science, engineering design, business planning, artificial intelligence, machine learning, and industries are just a few of the fields that benefit from optimization research. However, throughout the previous few decades, optimization methods have developed. In addition, some new optimization techniques have begun to demonstrate their efficacy, and become integrated into new mainstream methodologies.

Determining the optimum technique to solve a problem is a common difficulty in many applications. This frequently includes selecting the optimal solution in terms of maximizing or minimizing an objective function, such as decreasing time or cost, increasing device efficiency, or improving the quality of a product... Finding the right modelling solution can help solve many of these issues.

III.2. FORMULATION (STATEMENT) OF AN OPTIMIZATION PROBLEM:

The goal of the optimization problem then is to find variable values, which minimize or maximize the objective function while satisfying all the restrictions. For a single-objective, constrained, non-linear optimization problem the usual form is listed below in Equation III.20.

$$\text{To find} \quad X = \begin{Bmatrix} x_1 \\ x_2 \\ x_3 \\ . \\ . \\ x_n \end{Bmatrix} which\ minimizes\ (maximizes)\ f(x) \tag{III.20}$$

Subject to the constraints indicated in Equation III.21:

$$\begin{cases} g_j(x) \leq 0 & j = 1,2,\dots,m \\ h_k(x) = 0 & k = 1,2,\dots,p \\ x_{iL} \leq x_i \leq x_{iU} & i = 1,n \end{cases} \tag{III.21}$$

where

f(x) is the function that expresses the objective (or aim) function

$g_j(x)$ an inequality constraint and $h_k(x)$ an equality constraint function

x is the design vector (an n-dimensional vector) that represents the n design variables that are changed to get the optimum result (It is not obligatory for the design variables to be continuous)

x_{iL} and x_{iU} are the upper and lower bounds, of the design variables, also known as side constraints, determine the searchable design space.

Without any limitations or constraints, optimization problems can also be formulated. Unconstrained optimization problems are the name for such problems.

The objective and constraint functions might be explicit or implicit, as well as explicit or implicit. Frequently, the solution process is divided into multiple parts that are carried out in order. Recognizing and defining problems, building and solving models, and evaluating and executing solutions are all common steps. Figure III.22 represents numerous problems in the modeling process that are transformed into an optimization model via a multi-stage procedure. To begin with, it should provide clear information about the core issue to explain the problem to be answered by the modeling method. Furthermore, to identify and clarify the components of a tractable mathematical model, it is frequently required to reduce and restrict the problem slightly, as well as quantify any residual qualitative declarations.

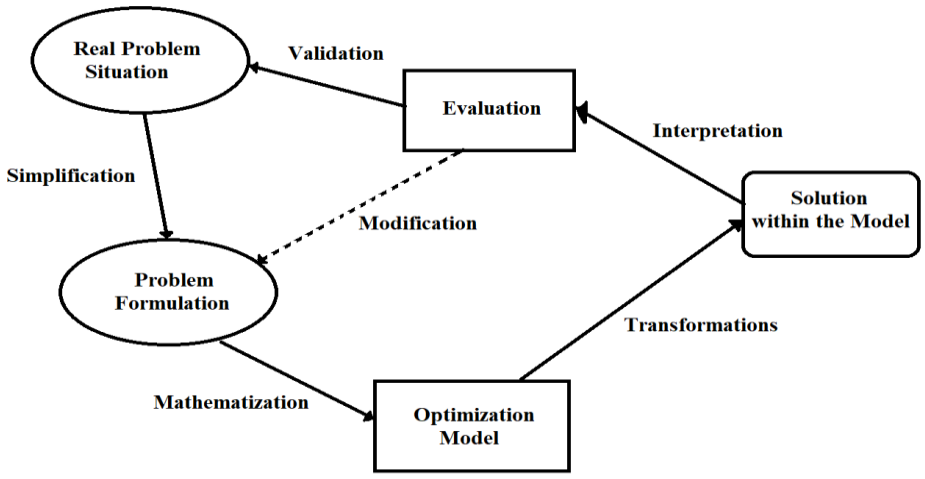

Figure III.22: The process of mathematical modeling.

The data in the optimization issue is frequently uncertain, and it is not always simple to gather or quantify it. Perhaps the uncertainties are intentional (as in financial decision-making), but it is also possible that the data is unclear because not enough effort was put into ensuring correctness. Furthermore, problem solvability and problem realism are frequently in disagreement.

Data must be provided for the problem to be solved using an optimization process, including model constants and parameters in functions characterizing the objective function, as well as possibly some limitations. If an optimal solution exists for an optimization problem, an algorithm of optimization offers the values of the decision variables that optimize (maximize or minimize) the objective function while meeting all constraints or restrictions. The obtained results are analyzed and evaluated, which may result in model changes and, more importantly, queries about the optimal solution's applicability.

The procedure for formulating and solving mathematical programming problems is summarized in the steps below.

a) Make a list of all variables after analyzing the process to determine the process variables and specific characteristics of interest.
b) Define the optimization criterion and indicate the objective function in terms of the variables listed above, together with their coefficients.
c) Create a valid process model, which connects the process's input-output variables and associated coefficients using mathematical expressions.
   - ✓ Constraints on both equality and inequality should be included.
   - ✓ Utilize physical principles that are well known.
   - ✓ Determine the number of degrees of freedom by identifying the independent and dependent variables.
d) If the scope of the problem statement is too vast:
   - ✓ facilitate the model and the objective function
   - ✓ divide it down into practicable sections
e) For the mathematical formulation of the problem, use an appropriate optimization algorithm or method.
f) Test the result's sensitivity to changes in the problem's coefficients and hypotheses.

III.2.1. OBJECTIVE FUNCTION, F(X):

The effort (typically time or memory) needed to solve a particular issue represents the complexity of an algorithm. Under specific constraints, the difficulty or complexity of an issue is the lowest potential effort required to achieve the objective function. In modeling optimization, objective functions inform us how to rate decisions

a) We require a quantifiable measure because a qualitative measure like "great" or "bad" is insufficient
b) Although many objectives are common in real life, a scalar objective function is favored for solving the optimization problems
c) The difference between max and min problems is neither fundamental nor practical as highlighted in Equation III.22.

$$Max\ f(x) = \min -f(x) \tag{III.22}$$

A single objective function is used in many optimization problems. The following are two notable exceptions:

a) *In the absence of a clear objective function:* There is no purpose to creating an objective function because the user does not need to optimize anything. A feasibility problem is the most common name for this situation.

b) *The existence of many objectives.* It is common practice to rephrase multi-objective problems into a single-objective problem, either by weighting the goals or by considering part of the goals as constraints.

III.2.2. MAIN CONSTRAINTS, G(X) ≤ 0, H(X) = 0:

Other than variable boundaries, the main constraints of optimization models define the restrictions and interactions that limit the values of decision variables.

III.2.2.1. INEQUALITY CONSTRAINTS, G(X) ≤ 0:

a) These one-way system constraints are required for optimization.
b) Inequality restrictions with the form ≥ 0 and ≤ 0 are the same.
c) Many of these inequalities can exist, hence *g(x)* is a vector (indexing is also used for limitations)
d) We should be cautious to avoid mistakenly formulating a problem with no feasible region or unbounded solution.

III.2.2.2. EQUALITY CONSTRAINTS, H(X) = 0:

a) These explain the interactions between the model's variables.
b) By convention, equality restrictions are stated with a zero right-hand side.
c) Many of these inequalities can exist, hence *h(x)* is a vector (indexing is also used for equality restrictions).
d) No more (independent) equality restrictions can be added to the model than the number of decision variables.

III.2.3. DECISION VARIABLES, X:

Variables are necessary. We cannot specify the objective function or the problem limitations if there are not any variables.

III.2.3.1. DECISION VARIABLES: INDEPENDENT VS. DEPENDENT:

Decision variables are divided into two groups during the formulation stage:

a) *Independent variables* are variables whose values can be altered separately to influence the system's behavior.
b) *Dependent variables*, the behavior of dependent variables are defined by the values chosen for independent variables.

Independent and dependent variables do not need to be separated at the solution stage. Therefore, the solution method simply sees a multi-variable optimization problem.

III.2.3.2. DECISION VARIABLES: DISCRETE VS. CONTINUOUS:

For continuous optimization problems that involve the optimal configuration of parameters or continuous decision variables, there is no limit on the number of alternatives available. However, it is necessary to determine the optimal values for continuous variables.

a) An uncountable or fixed set of values defines the discreteness of the variable (for example, all-or-nothing, either-or decisions)
b) If a variable can take on any value during a given interval, it is said to be a continuous variable.
c) Mixed-integer programs are problems that have both discrete and continuous variables.

III.2.3.3. EXAMPLES OF DECISION VARIABLES:

a) *Design*: reactor volume, number or distance of sprinklers, heat exchanger area, etc.
b) *Operations*: pressure, temperature, flow, valve opening, etc.
c) *Management*: sales price, feed type, purchase price, etc.

III.2.3.4. VARIABLE BOUNDS, X_{MIN}, X_{MAX}:

The scope of definition for decision variables is defined by variable bounds: the range of values for which the variables are acceptable.

III.3. OPTIMIZATION ALGORITHM CLASSIFICATION:

Because most optimization algorithms are iterative, hundreds or thousands (or even millions) of objective evaluations are required. Different algorithms may have varying levels of performance and demands. Newton's gradient-based technique, for example, is particularly effective at finding solutions to smooth objective functions, but it might become trapped in local modes if the objective is extremely multimodal. The Nelder-Mead simplex technique can be employed if the objective is not smooth or has a kink since it is a gradient-free technique that can perform well even for situations with discontinuities, however, it is slow and can become stuck in a local mode [67].

The trust-region approach, the interior-point methodology, and others are among the algorithms to solve nonlinear optimization, but these methods are largely a local search approach. It can be extremely efficient in a certain situation where the objective is convex. Convexity features are used to the advantage of sequential quadratic programming (SQP) and quadratic programming (QP). Figure III.23 summarizes the different types of algorithms, which can be used to settle various problems of optimization.

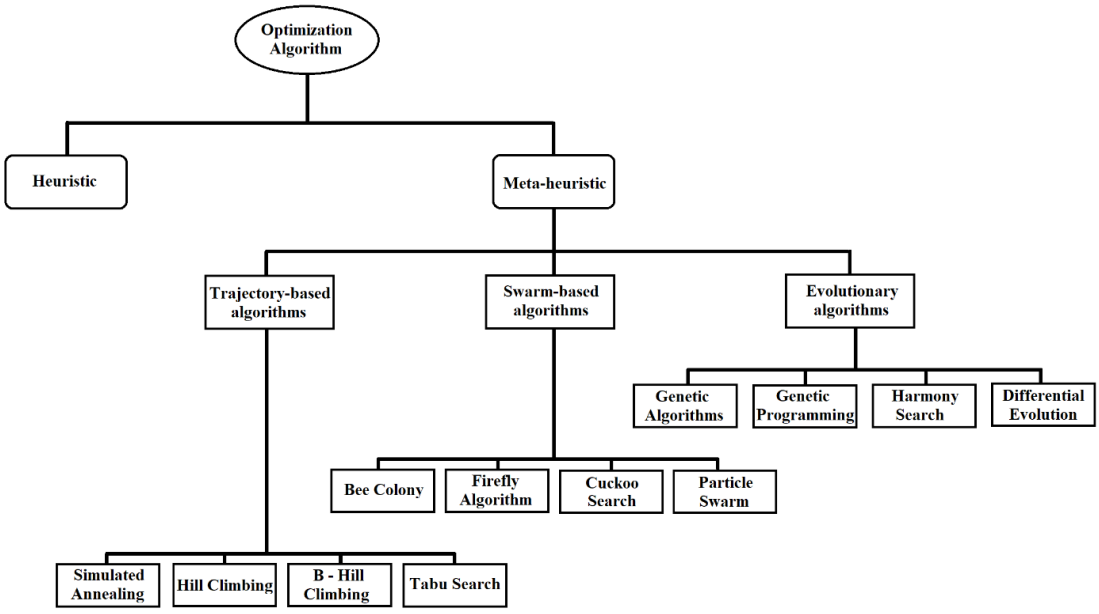

Figure III.23: Various types of algorithms used in optimization methods.

III.3.1. HEURISTIC OPTIMIZATION:

Heuristic algorithms are frequently used in applications and are very easy to use since they address the problem as a black box that can only be accessed through a problem-dependent fitness function. Heuristic refers to a computer process for choosing the optimum solution by iteratively trying to improve a candidate solution against a set of quality criteria. Without making assumptions about the problem being optimized, heuristics search large spaces of candidate solutions to discover optimal or near-optimal solutions at a rational computational cost, but they cannot guarantee feasibility or optimality, and in many cases, they cannot even assume how near a feasible solution is to be optimal. Heuristics use stochastic search optimization in some form. Among these are evolution strategy, evolution programming, genetic programming, genetic algorithms, and differential evolution [68, 69]. These methods, on the other hand, are based on natural optimization processes and can be applied to almost any optimization problem. Direct search, derivative-free, and black-box optimization methods are other approaches with the same meaning as the heuristic optimization technique.

III.3.2. OPTIMIZATION PROBLEMS USING GENETIC ALGORITHMS:

Traditional iterative optimization techniques are extremely sensitive to algorithm initialization and frequently result in undesirable solutions due to convergence to local optima. As a result, academics are proposing and investigating new optimization methods. Evolutionary computing, of which genetic algorithms (GAs) are a part, appears to be well suited to restricted, nonlinear optimization problems. A genetic algorithm created in the 1960s and 1970s by John Holland and his co-workers is a search heuristic influenced by Charles Darwin's theory of natural evolution. To investigate adaptive and artificial systems, Holland was likely the first to utilize crossovers and recombination as well as mutation

and selection techniques. These genetic operators are critical components of the genetic algorithm as a problem-solving method. This algorithm is based on the process of natural selection, in which the fittest individuals are chosen for reproduction to generate children for the following generation.

From discrete systems (such as the traveling salesman problem) to continuous systems (such as the efficient design of airfoil in aerospace engineering), from financial markets to multi-objective engineering optimization, and from graph coloring to pattern recognition, many variants of genetic algorithms have been developed and applied to a wide range of optimization problems.

Genetic algorithms have many advantages over traditional optimization algorithms, including the fact that they do not necessitate derivative information or a formal initial estimate of the solution region, and that, due to the stochastic nature of the search process, they can search the whole solution space with a higher likelihood of finding the optimal solutions. Also, parallelism and the ability to deal with difficult problems. Whether the objective or fitness function changes with times (stationary or non-stationary), linear or nonlinear, with random noise or continuous or discontinuous, genetic algorithms can deal with many types of optimization problems. Genetic algorithms, on the other hand, have significant disadvantages such as the selection criteria for the new population, as well as the formulation of the fitness function, the use of population size, and the choice of important parameters such as the rate of mutation and crossover, should all be done with care. Any incorrect selection will make the algorithm hard to converge or will just yield useless results.

Using a natural selection process that simulates biological evolution, a genetic algorithm (GA) solves both constrained and unconstrained optimization problems. The algorithm changes a population of individual solutions regularly. For each round, the genetic algorithm selects individuals from the present population at random to serve as parents for the following generation's children. The population "evolves" toward an optimal solution over consecutive generations. The following are the main characteristics of a genetic algorithm:

a) Rather than working directly with parameters, the genetic algorithm works with the parameter set coding rather than the parameters themselves.
b) Genetic algorithms begin their search by using a population of points rather than a single point.
c) Instead of derivatives, the genetic algorithm employs payoff information.
d) Instead of deterministic transition rules, the genetic algorithm depends on probabilistic transition rules.

On high-performance computers, genetic algorithms are difficult and time-consuming to apply. They must be as similar to the mathematical description of the problem as possible, as well as be a basic and

easy-to-use language. This category of languages includes *C/C++* and *FORTRAN*, which are lower-level compiled programming languages (This language is frequently referred to as a third-generation language) that are widely used in academia, industry, and commerce. This category of languages is also used to implement GA. Although compiled low-level languages (such as embedded systems) have many advantages in terms of speed and efficiency *MATLAB* is a high-level "scripting" or "4th generation" language that is now widely used in research and industry [70]. Figure III.24 indicates the main steps of the genetic algorithm optimization method.

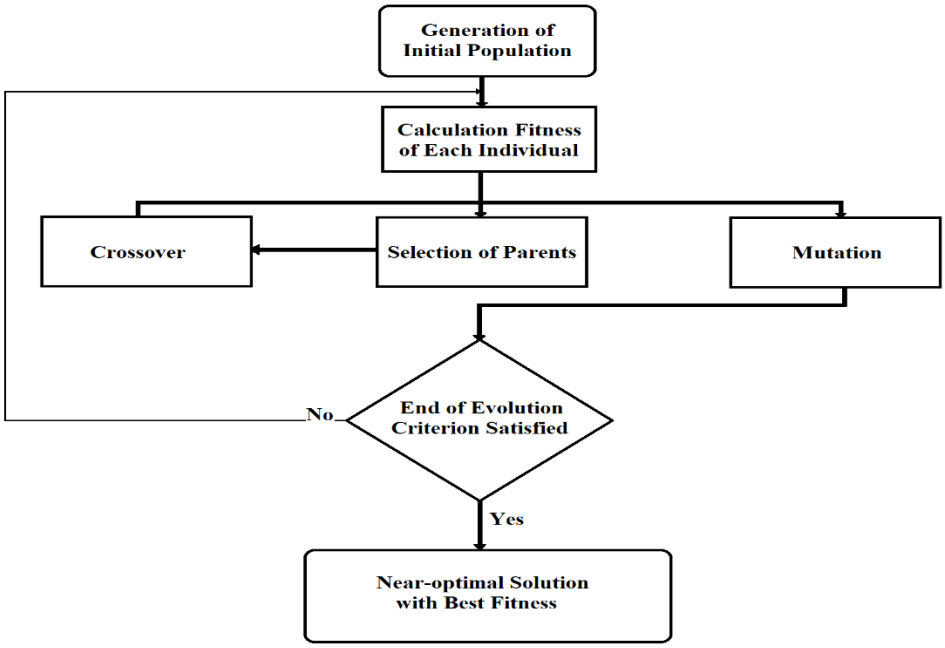

Figure III.24: Main steps of the genetic algorithm optimization method.

III.4. USING GENETIC ALGORITHMS TO OPTIMIZE IRRIGATION SYSTEM DESIGN:

The discharge required for the farm, as well as the pressure required, the duration time, and the water delivery period for each crop determine the water delivery procedure for irrigation fields. Indicators such as irrigation uniformity, water resource sustainability, economic return, and crop production are used to determine irrigation efficiency. According to El-Zahaby, et al. [71], the optimum design for the developed irrigation system network is provided. The optimization is based on the right pressure and used the right combination of pipe sizes at the lowest possible cost. Consequently, as compared to the manual design of the examined case, the application of the genetic algorithm optimization approach saves 41% of the irrigation system cost.

The research [72] proposed a novel method for long-term irrigation scheduling utilizing genetic algorithms, in which the effectiveness of genetic algorithms in the context of optimization of nonlinear crop models is investigated, as well as the application requirements and implementation of the method.

The genetic algorithms' performance is compared to that of the Monte Carlo optimization method. Genetic algorithms have been discovered to be simple to implement and to converge to near-optimal solutions at a surprising speed. The findings show that genetic algorithms can be used to optimize irrigation scheduling over long periods.

The term "optimal design and operation" relates to choosing the right pump model, capacity, and some units, and also scheduling irrigation pump procedures to achieve the lowest design and operating costs for a specific set of demand curves. Moradi-Jalal, et al. [73] Introduced WAPIRRA Scheduler, a novel management methodology to get the optimal design and management of water distribution networks. The model uses the most recent innovations in the genetic algorithm (GA) optimization method to automatically select the lowest cost of pumping stations while meeting target hydraulic performance requirements on an annual basis. The findings show that the created model may successfully lower the cost of energy used for pumping in a complicated water supply system while maintaining acceptable service levels. Furthermore, the model's application to a real-world project showed significant cost and energy savings.

As new essential agricultural equipment, mobile sprinkler irrigation systems that are light in weight and small in size have been widely used. Yuan, et al. [74] demonstrated that the genetic algorithm has both theoretical and practical importance in the design of the sprinkler irrigation system to achieve a suitable configuration and low energy consumption. This study introduced a dual purpose of sprinkler irrigation and drip irrigation. The optimal configuration (number of the sprinklers was 7, and the number of the drip irrigation tubes was 34), on the other hand, was found using a genetic algorithm and the energy consumption was reduced by 9.4% under the best configuration.

Water that is a natural, limited, and chargeable resource must be used rationally to assure agricultural production. Furthermore, research and development of strategies to optimize the cost of localized irrigation systems can secure water extension. An implementation of a genetic algorithm (GA-LCLI) based on minimizing the system's annual cost was proposed for optimizing the pipe size specification in a hydraulic network of a localized irrigation device [75]. The findings indicate that the execution runtime and cost of irrigation systems have improved. Compared to traditional irrigation methods, the center pivot system is an innovative irrigation technique commonly utilized in precision agriculture because of its high irrigation efficiency in terms of water consumption and minimal labor [76]. When water application is properly matched to the spatially distributed crop water demand, gains in water usage efficiency can be realized. As a result, increased irrigation efficiency will help in the production of crops of high quality while also reducing the need for supplementary agricultural and financial investments. Hassan-Esfahani, et al. [77] introduced a modeling method for optimal water distribution to maximize irrigation uniformity while reducing yield loss. The model was put to the test on a field equipped with a

center pivot irrigation system to irrigate alfalfa and oats. Based on the results of the model's simulation and optimization using genetic algorithms, the study area irrigator could use up to 20% less water (conserved quantity over total quantity of water) during the growing season than conventional operating procedures, without lowering the advantages.

A fixed flow of water into pressurized irrigation systems can decrease energy exhaustion while meeting pressure constraints. To assist local water management organizations in the decision-making procedures and to charges related to water and energy request. Pardo, et al. [78] created a modeling method based on MATLAB application with a genetic algorithm to discover the ideal time to open and close valves to minimize a fitness function that quantifies the variations between the objective and true injected flows. a methodology for modeling a modern sprinkler irrigation system on a farm located in Scipio, Utah, was first published in [79]. This model has two main modules: one that uses Artificial Neural Networks (ANN) to improve a soil water balance model and the second that uses Genetic Algorithms (GA) to optimize water distribution and define optimal crop water application rates related to crop type, growing stage, and sensitivity to water stress. The model's output utilized up to 30% less water than conventional operating procedures while maintaining the irrigator's benefits.

III.5. CONCLUSION:

A uniformity assessment model of water distribution for center-pivot irrigation systems considering environmental and operating conditions, hydraulic parameters, and system specifications will propose to determine optimum nozzles spaces and sizes of conventional Mini-Center Pivot Systems in El Oued, southern Algeria. The uniformity of irrigation is also largely influenced by the sprinkler size and arrangement. Therefore, the impact of sprinkler choice, size, and arrangement on the water application depth of a center pivot system was discussed. In addition, detailed information considering the hydraulic performance modelling of a center-pivot irrigation system and optimization technique should be conducted for improvement design in the field of interest. Finally, some examples of studies using genetic algorithms to optimize irrigation system design were provided.

PART II

EXPERIMENTATION AND OPTIMIZATION

CHAPTER IV.

EXPERIMENTAL EVALUATION

IV.1. INTRODUCTION:

Since the invention of the center-pivot irrigation system, various technological improvements have been achieved to minimize the obstacles in the implementation while also conserving water, energy, and time. However, the system performance can be influenced by the choice of appropriate design specifications and the application of an acceptable irrigation management plan.

The variability of water distribution or water delivery around the total irrigated area in a center-pivot irrigation system is a challenge for enhancing the system's design using optimization modelling. This part of the thesis is presented in a manuscript style in which each of the predetermined objectives is exclusively addressed in a separate chapter. In addition, the materials and methods used to obtain the desired results are carefully detailed in the previous chapters. The primary goal of this research is to develop a method for enhancing the uniformity of water distribution over a whole center-pivot irrigation system, as well as to investigate the impact of improved design on the system's performance. As a result, the following are the main objectives of this thesis segment:

a) To develop a theoretical procedure for analytically determining the spaces of the nozzles for enhancing irrigation uniformity under specific operating conditions, such as inlet flow rate, wind speed, and the overall radius of the center-pivot irrigation system.
b) To create a model for Mini-Centre Pivot System design optimization based on identifying the diameters and spaces of nozzles and comparing them to the real (actual) diameters and spaces of nozzles of the same center-pivot irrigation system type.

In this chapter we will present the study area and system characteristics and, after that, the factors which influence the uniformity coefficient of Heermann and Hein were discussed to evaluate the water distribution of the center pivot systems studied.

IV.2. PRESENTATION OF THE STUDY AREA:

Field experiments were conducted in Debila (78 km^2), 507 km from Alger, in El Oued, southern Algeria, on the conventional Mini-Center Pivot System (MCPS) with 60, 50, and 46m of length and 22, 20, and 17 nozzles, respectively. At an elevation of 57 meters, the area's boundary is 6.952533°E along the longitude and 33.514810°N along the latitude. The research area is depicted in Figure IV.25.

Figure IV.25: The study area's location.

IV.3. SYSTEM CHARACTERISTICS AND DESCRIPTIONS:

The applied method of this study is for irrigating small- and medium-sized farms that are widely used and less costly because their manufacturing cost is low. For an artisanal Mini-Centre Pivot System, the mechanism is lower than the medium operating pressure between 1.0×10^5 and 1.7×10^5 Pa. In southern Algeria, particularly in the El Oued region, a device made by local artisans has been built mostly to irrigate potatoes. The system consists of one span including the main water pipeline, nozzles, a supporting trussing structure, a pivot point anchoring the machine to a permanent field spot, and a drive unit usually located at the end of the second third of the lateral pipe far from the pivot point (the system presented in Figure IV.26). The lateral pipe was 60 mm in diameter and the irrigation water was supplied at a constant pressure of 125 kPa. All the studied systems are generated with a rate of 23 m^3/h of a water inlet flow. The nozzle used in these systems was set 1.3 m above the ground surface and the variable distance between the nozzles begins with less than 4.6 m near the pivot point and decreases to about 1 m at the outer or moving end of the lateral pipe. Local artisans manufactured these nozzles. The conception of a commonly used conventional Mini-Centre Pivot System in El Oued, southern Algeria was studied in [1].

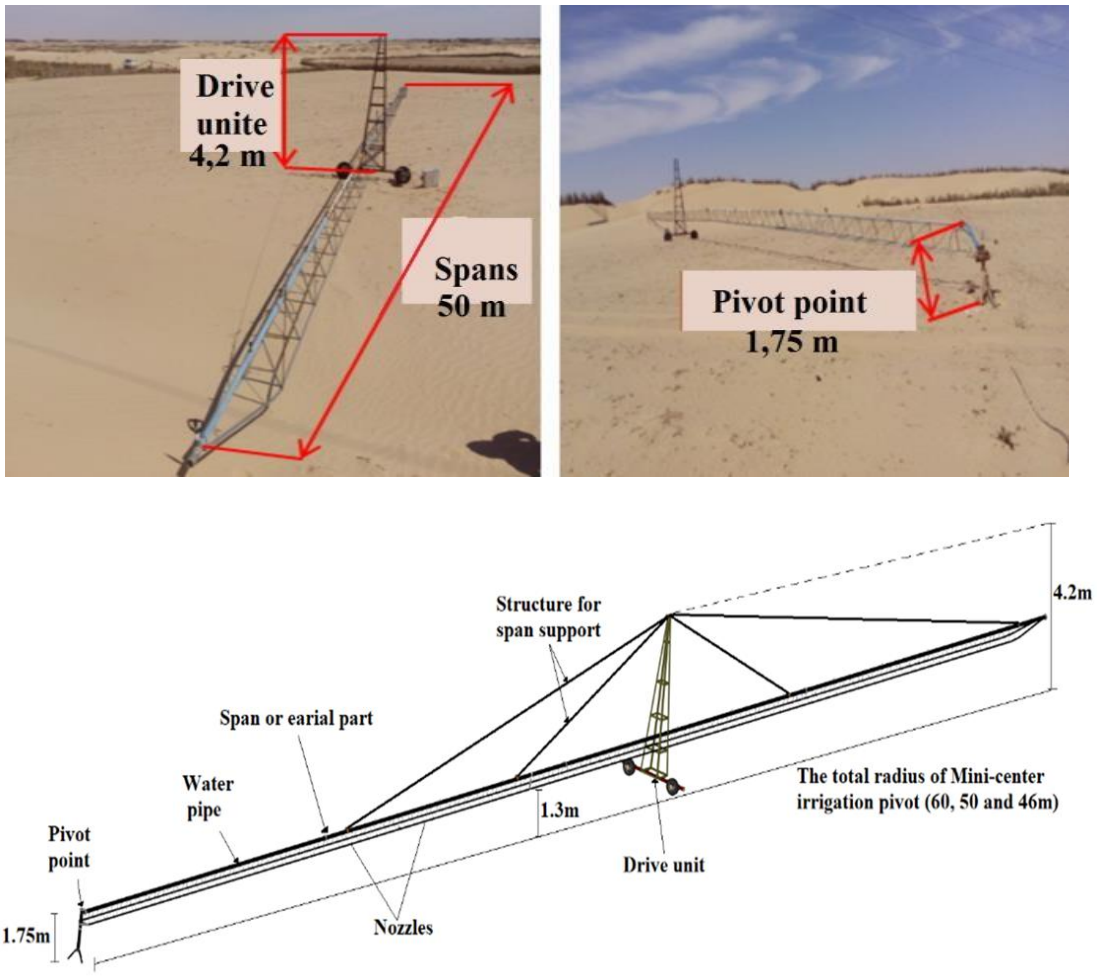

Figure IV.26: The conventional Mini-Center Pivot Systems used in the study.

The nozzle is a critical part of the system since the enhancements in this study only vary based on nozzle size and space. The most frequent type of nozzle utilized for the Mini-Centre Pivot System in El Oued is the fixed spray nozzle. These nozzles are installed without the need for a pressure regulator in many existing systems. Local artisans created these nozzles to provide the maximum amount of sprayed water. The nozzle's wetted diameter, on the other hand, is 4.6 m, and the droplet size of this nozzle can be reduced or increased with the use of a flat head screw. As a result, a wide range of diameters – from 3 to 15 mm – is accessible. The Mini-Centre Pivot System's nozzles are shown in Figure IV.27.

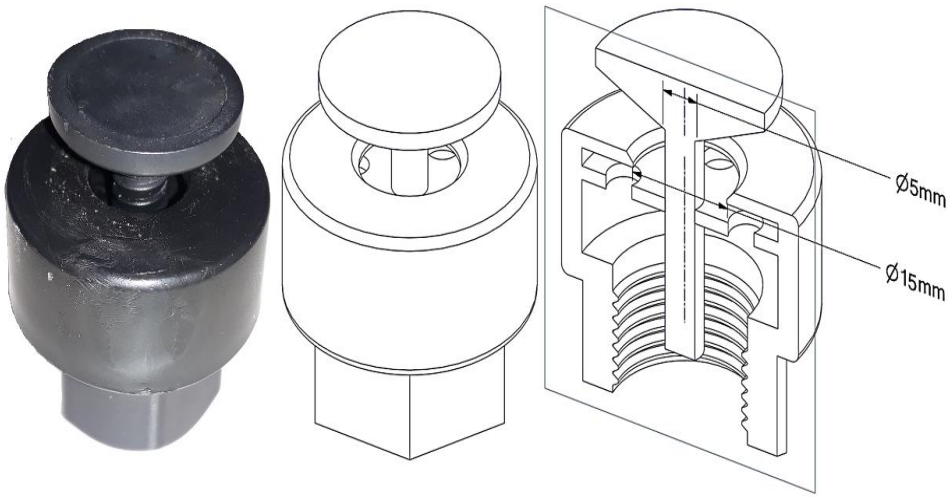

Figure IV.27: Type of nozzle used for the Mini-Center Pivot Systems studied.

The only variables in the proposed methodology for optimizing the design of a Mini-Centre Pivot System are the nozzle space and size (diameter). Nonetheless, parameters must be entered for the procedure's calculations. Table IV.4 lists the parameters that will be used in the subsequent equations.

Properties / Symbol	**Value**
Inlet flow rate (Q_{in}), m^3/h	23
Total length (L), m	60, 50 or 46
Pipe diameter (D), m	0.06
Pivot pressure (P_0), Pa	$1.25\ 10^5$
Nozzle's wetted diameter (Φ), m	4.6
Elevation difference (h_0), m	1.3
Kinematic viscosity at 25 °C (ϑ), m^2/s	$0.884\ 10^{-6}$
The density of the fluid (ρ), kg/m^3	10^3

Table IV.4: The characteristics of the Mini-Center Pivot Systems studied [80].

IV.3.1. DIFFERENT TRADITIONAL MINI-CENTRE PIVOTS SYSTEMS ADOPTED IN THE EL OUED REGION:

During our tour to the El-Oued farm areas, we observed two varieties of traditional Mini-Centre Pivot Systems, 50m and 60m in length, with major changes in nozzle spacing. Table IV.5 shows the results of our experiment using five pivots to show the difference in nozzle distances.

	Nozzle Spacing (m)				
Nozzle Number	MCPS 1 (60m)	MCPS 2 (60m)	MCPS 3 (50m)	MCPS 4 (50m)	MCPS 5 (50m)
1	3,5	3,5	3,2	3,5	3,6
2	8,0	8,0	6,5	6,9	6,8
3	12,3	12,4	9,8	10,2	10,0
4	16,4	16,7	13,3	13,4	13,1
5	20,3	20,9	16,6	16,5	16,4
6	24,0	24,8	20,0	19,5	19,5
7	27,5	28,7	23,5	22,4	22,7
8	30,9	32,3	26,3	25,2	25,9
9	34,0	35,4	28,9	27,9	29,1
10	36,9	38,4	31,4	30,4	32,3
11	39,6	41,2	34,9	32,7	34,7
12	42,1	44,0	37,1	34,8	37,1
13	44,5	46,7	39,6	36,8	39,5
14	46,8	49,2	42,1	38,7	41,9
15	49,0	51,7	44,6	40,5	44,3
16	51,1	54,2	47,2	42,2	46,9
17	53,1	56,3	47,8	43,9	48,3
18	56,2	57,3		45,4	49,1
19	58,0	58,9		46,0	50,2
20	59,4	59,1		46,5	
21	60,0			47,0	
22	60,6				

Table IV.5: The nozzles' spaces of the specified Mini-Centre Pivot System.

To supply uniform water, the international standards require that the normalization factor of the Heermann and Hein uniformity coefficient (CUH) should be greater than 80% [35]. If the nozzle discharge along the system is not adequate, center pivots will not operate effectively.

IV.3.2. HETEROGENEITY OF WATER DISTRIBUTION THROUGHOUT THE TRADITIONAL MINI-CENTRE PIVOTS SYSTEMS ADOPTED IN THE EL OUED REGION:

The circular irrigated area indicated by the distance x from the fixed axis in these devices is directly proportional to the square of this distance of the circle's area (if the circle's distance is raised x times, the area will be elevated to x^2 times the original area). The majority of the circle areas, however, are on the lateral pipe's outer end. Figure IV.28 illustrates the heterogeneity of water distribution throughout the lateral pipe of the 46-meter-long Mini-Centre Pivot System, with 808 collectors placed uniformly 3 meters in all directions over the entire field, using the real (original) nozzle sizes and spaces.

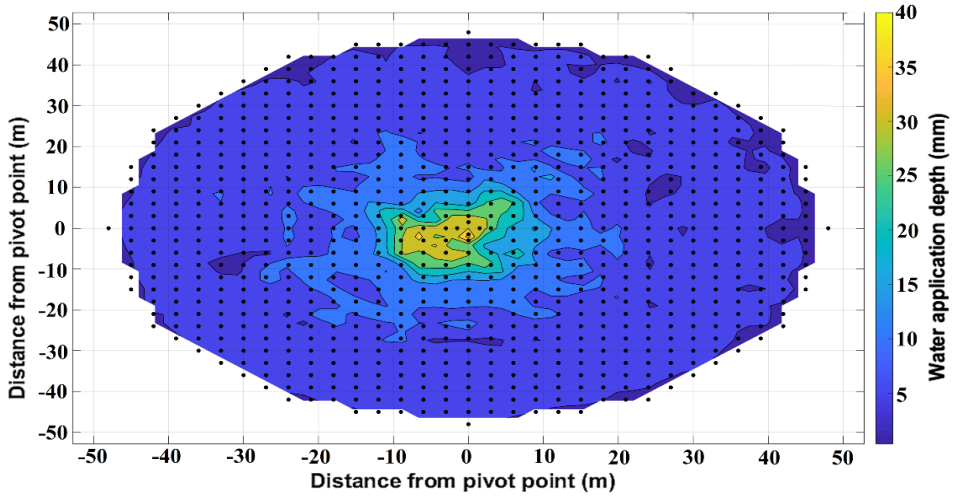

Figure IV.28: The heterogeneity of water distribution along with the mini-center pivot system 46m in the actual nozzles distribution [80].

In this conventional system, all of the nozzles are the same size (diameter), but the nozzles furthest from the pivot point cover a wider area (a larger portion of the field). Furthermore, whenever it moves away from the pivot point, the depth of water application diminishes which reduces the uniformity of water distribution significantly. Consequently, significant efforts should be taken to provide an acceptable flow rate and the most uniform distribution of water along with the system. As a result, defining the nozzle space and size of the conventional Mini-Centre Pivot System is a critical factor for the use and popularity of this methodology.

IV.4. MEASURING INSTRUMENTS AND TOOLS:

The experimental test's goal was to identify an international standard process for data collection from a system that would still allow a calculation of the uniformity of water distribution in the field from Mini-Centre Pivot Systems 60, 50, and 46 m in length. The goal was to collect a variety of pressure and flow measurements from nozzles along with the MCPS, calculate total flow and pivot point pressure, and utilize this data to validate the proposed model's output. The pressure and discharge readings from all nozzles along the lateral, on the other hand, would be adequate to confirm the system's performance in terms of water distribution along with the center pivot system.

The nozzles are near the ground because the water application system is 1.5 m above the soil surface. Installing a pressure gauge (as illustrated in Annex 1) in the water flow to each nozzle was expected to enable the selection of the appropriate nozzle pressure, in which the nozzle pressure range does not exceed 2/3 of the pressure gauge's working pressure.

Volume flow measurement and a stopwatch could be used to calculate the flow rate. Therefore, we used this method since we were unable to obtain and configure digital flow meters. The same method should be used to verify the input flow and pressure at the pivot point.

Wind velocity data, for example, has not been as easily gathered as intended. A minimum of two people are required on-site, while three can be more effective. The wind speed factor can make spraying ineffective, worse, or heterogeneous. However, the anemometers, often known as wind speed gauges (see Annex 1), are instruments used to measure the speed, direction, and strength of the wind.

It is valuable to monitor and predict wind speed in spraying systems such as center-pivot irrigation systems by using online software and weather stations.

To reduce measurement error, [64] suggested that the collectors used in the tests be as large as possible, i.e., identical and shaped in such a way that water does not splash in or out. The collector's lip must be symmetrical and free of depressions. Each collector has a height of 150 mm, which is more than twice the maximum depth of the water collected during the test. Each collector has an 85 mm diameter, which is at least half the height as depicted in Annex 1.

IV.5. EXPERIMENTAL SETUP AND TEST PROCEDURES:

A typical method for testing the irrigation uniformity of center pivot systems is the catch can test. The collectors were 150 mm in height with an 85 mm opening diameter. These collectors were fixed on the crop without supports and were consistently spaced 3 m apart along a radial straight line. With graduated test tubes, the volumes were measured as required. The Mini-Centre Pivot Systems as a whole were subjected to the catch can test. The catch cans were placed along a radial line that was far enough away from the pipeline for the system to attain functioning conditions before reaching the test site. By dividing the applied water volume by the collector's cross-sectional area, the applied water depth was calculated. At the pivot pipe, a pressure gauge was used to measure the system's operating pressure. The entire field was quite flat, and the slope in the test zones was about nil. Wind speed and direction were measured using an anemometer. Figure IV.29 shows a schematic representation of the experimental testing.

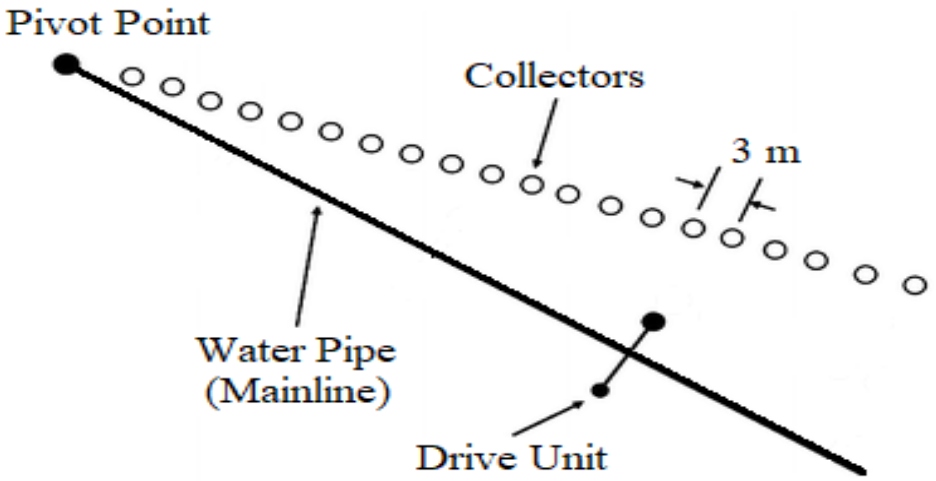

Figure IV.29: A schematic representation of the experimental testing.

Meanwhile, the average wind speed was set at < 3 m s^{-1}, which is considered acceptable according to [81]. The CUH was calculated experimentally for the pivots 60, 50, and 46 m in length for both the actual (original) nozzle configuration (i.e. before optimization) and the optimized configuration by applying the proposed model. The water application uniformity tests were conducted on the Mini-Centre Pivots Systems according to the ISO 11545 [64] standards. Before choosing the model for all possible Mini-Centre Pivots Systems, a comparison between the experimental and analytical calculations should be implemented.

IV.6. A HYDRAULIC COMPARISON BETWEEN CENTER PIVOT IRRIGATION SYSTEMS TRADITIONAL AND MODERN:

The Center pivot irrigation system plays a major role in many agricultural practices throughout Algeria especially in the south of the country, as many farming regions do not receive consistent and adequate rainfall. The objective of this section is to realize a hydraulic comparison between the traditional and modern (Type ANABIB) irrigation pivot systems. This comparison is based on the evolution of hydraulic parameters like pressure, flow, and length between the sprinklers (nozzles) to obtain a homogeneous distribution of water over the entire irrigated area. Center Pivot irrigation has an important agricultural component in Algeria, especially in the South (El Oued, Ouargla, Meniaa, Adrar, etc.). However, farmers, who don't have the scientific expertise to develop and improve the performance of their equipment, taking into account the weather conditions of desert areas, as well as the sizing of the pumping system, often use this irrigation technique. Farmers in El Oued deal with the traditional Mini-Centre Pivot System and do not accept the modern type ANABIB with suitable normalization factor because of its high cost. Therefore, it the necessity to improve the hydraulic performance of the traditional Mini-Centre Pivot System until it has a high normalization factor and good uniformity of

irrigation. However, in well-designed devices, we can get a good hydraulic efficiency which is often more than 85%.

IV.6.1. MODERN PIVOT IRRIGATION SYSTEM STUDIED:

Center pivots are mechanical irrigation systems that automatically revolve in a field to apply irrigation water through sprinklers, divers main components make up a center pivot. Each part is responsible for the movement, control, or structure of the machine. The modern center pivot system is located in the region named El Hadjira, Ouargla to irrigate barley. This system is named 160 EL and it is electrically powered by using a public power source. The 160 EL modern pivot system is made up of six drive units each one is powered by 0.74 KW. The system constitutes of some spans connected and rotating about a central fixed point or pivot point. These spans have 52 meters in length and around 3.7 meters in height (see Figure IV.30). Each span is propelled by a small electric motor. For a typical 312-meter-long system, the rotation or speed is 123 m/h. The rate of water supply to the system is depended on the pump rate and the design of the system. However, the water application rate increases along the pivot span as it digresses outwards from the center.

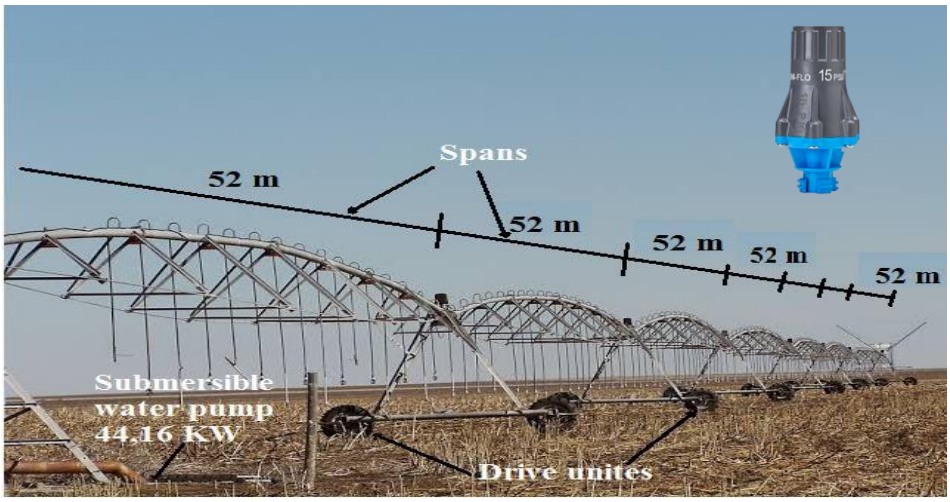

Figure IV.30: The modern pivot irrigation system studied.

The ANABIB pivot systems are suitable to irrigate most crops and have been developed to irrigate barley in the south of Algeria, Adrar and Ouargla are the best towns equipped with this kind of irrigation system. Table IV.6 highlights the main characteristics of the 160 EL system used in El Hadjira.

Parameters	Characteristics
Radius watered, y beyond the edges	312 m
Area watered in a full circle	32.96 ha
Kind of Span	52 m
Tube diameter	160 mm
Height of construction	3,7 m
medium height of sprinklers compared to the land	1,3 m
Watering capacity	0,93 à 1.39 l/s/ha (soit 8 à 12 mm/j)
Total water consumption	69,6 m^3/h - 104,4 m^3/h
Hour of service during a day	24/24h
Max speed drive unite	123 m/h
Minimum time of rotation	12 h 10 min
Pluviometer mini. of rotation	4-6 mm
Feed pressure admission pivot	1,7-1 ,8 bar
Pressure sprinkler at last connection	1,2 bar
Pressure exercised on the land	13 N/cm^2
Voltage	380 v
Generator power required	10,5 kVA
Absorbed power of the public network	7,2 kVA

Table IV.6: The nozzles' spaces of the specified Mini-Centre Pivot System [82].

The cups are buried 1/3 of their height. The medium wind speed is 10 Km/h considered suitable (less than 3.5 m/s [83]). We put a collector every two (02) meters separately in two lines for traditional pivot and every twelve (12) meters separately in two lines too for modern ANABIB pivot. The choice of two lines is to avoid the measurement errors and the effect of the wind on the results, furthermore, to validate the different results and to discover the anomalous values.

IV.6.2. PLUVIOMETRY EVALUATION:

A schematic representation of water collected along the systems studied is shown in Figure IV.31. For the traditional Mini-Centre Pivot System, the depth of water is high at the few selected points (near the pivot point) but it decreases greatly at the major selected points farthest from the pivot point. While for the modern 160 EL pivot system, just a 5% variation of pluviometry between the pivot point and the distance of 300 m from the pivot point could be considered convergent and therefore gave a uniform distribution of water along with the system.

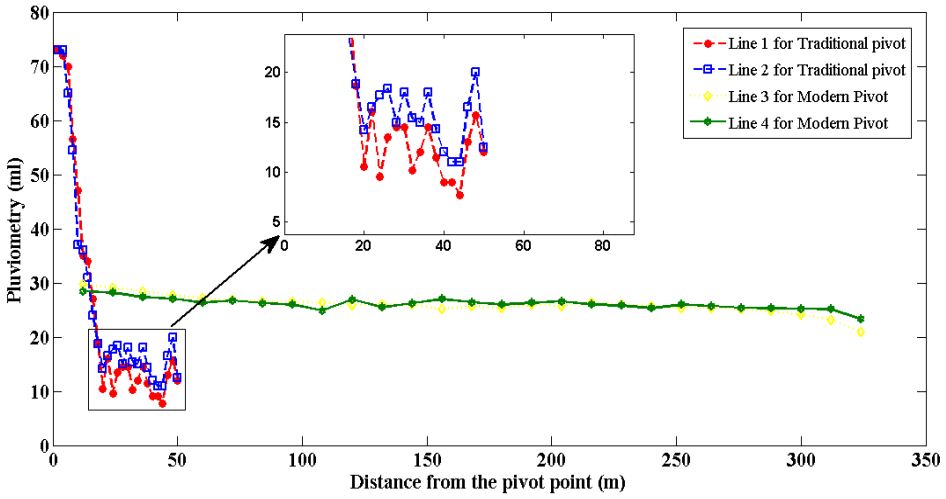

Figure IV.31: The pluviometry recordings of the investigated systems.

IV.6.3. EVALUATION OF PRESSURE DISTRIBUTION ALONG THE LATERAL PIPE:

In the center pivot system, the nozzle produces the desired pattern at a certain pressure and wind speed. Frequently, the new designs of center pivot systems install individual sprinkler pressure regulators to assume "identical" sprinklers operating at identical pressures, but in reality, the pressure may not be constant over the field. The resulting variation of discharge among sprinklers increases the overall variability of water application. [84] Estimated the loss of uniformity due to pressure variation in a typical situation to be about 8%. The length of a lateral characterizes this significant effect.

For the traditional Mini-Centre Pivot System, the pressure is decreasing from the pressure admission of the pivot to 0.8 bar at 25 meters from the pivot point as shown in Figure IV.32, after this distance, the pressure is practically taking a stable value. Whereas we observe for the modern ANABIB pivot system the pressure is gradually decreased and approaches to get a straight line in shape. However, all the measured pressure values are suitable for the pressure required by this kind of sprinkler (103.4 KPa). Therefore, for the modern pivot system slight variations of pressure may be present but do not affects negatively the performance of the system. An example of adding up emitter discharge variability due to pressure and manufacturing can be found in [85].

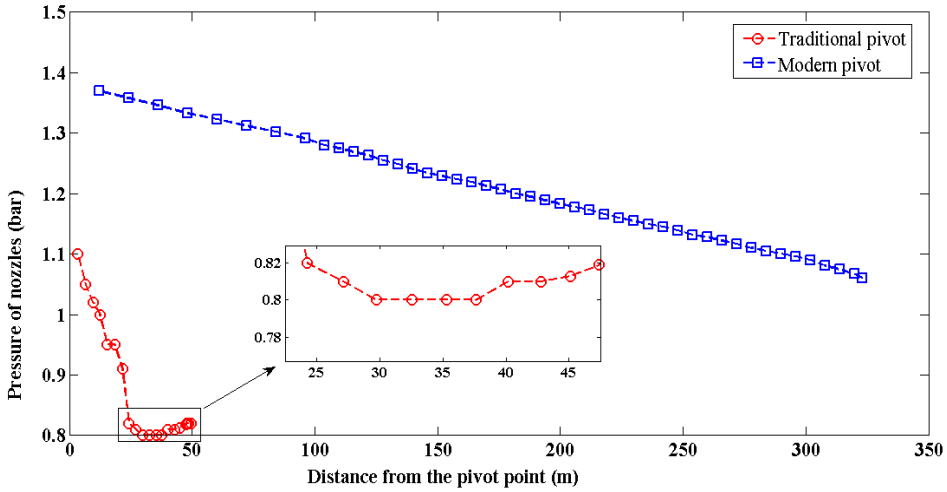

Figure IV.32: Indicates the pressure distribution along the lateral of the investigated systems.

IV.6.4. EVALUATION OF FLOW DISTRIBUTION ALONG THE LATERAL PIPE:

In center pivot systems, the effect of sprinkler discharge on the uniformity of irrigation, which will be almost completely optimized, deserves a special mention. Figure IV.33 indicates that the flow rate of water delivered by each sprinkler decreases as the distance of the nozzle increases starting with the nozzle next to the pivot point and terminating with the nozzle farthest from the pivot point. However, for the traditional center pivot system, a huge decrease is observed according to Figure IV.33, whereas a small variation of discharge among sprinklers is observed for the modern center pivot ANABIB system. Perhaps center-pivot systems are particularly sensitive to sprinkler discharge.

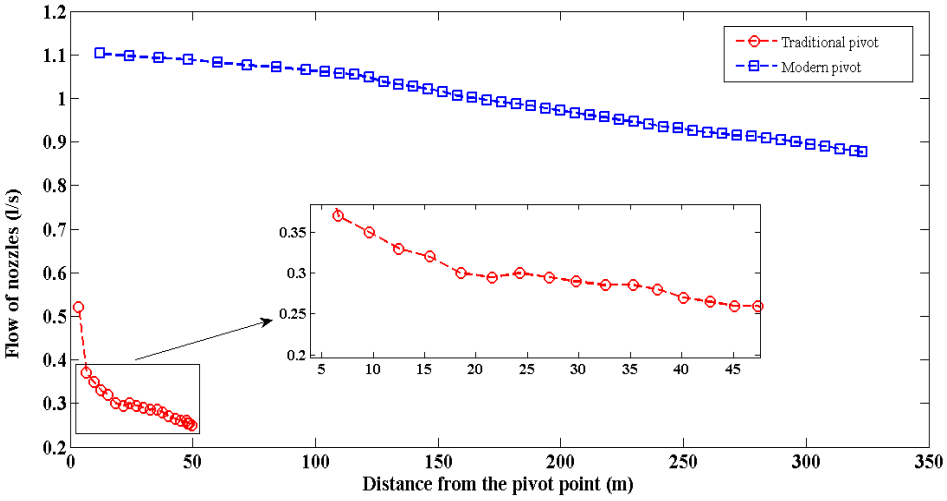

Figure IV.33: The flow rate distribution along with the investigated systems.

IV.6.5. THE UNIFORMITY COEFFICIENT OF THE INVESTIGATED SYSTEMS:

Uniform irrigation is difficult. It is also intuitively clear that the cost of irrigation as a function of uniformity must increase more rapidly at higher uniformity levels. However, at the low-uniformity end

of the scale, the crop's production is likely to respond more strongly to improved uniformity, and as uniformity approaches perfection, the crop's productivity will approach a finite limit.

In this study, the uniformity coefficient of Heermann and Hein CUH is selected to evaluate the uniformity of water distribution. The repeatability test of CUH for the two studied systems is indicated in Figure IV.34.

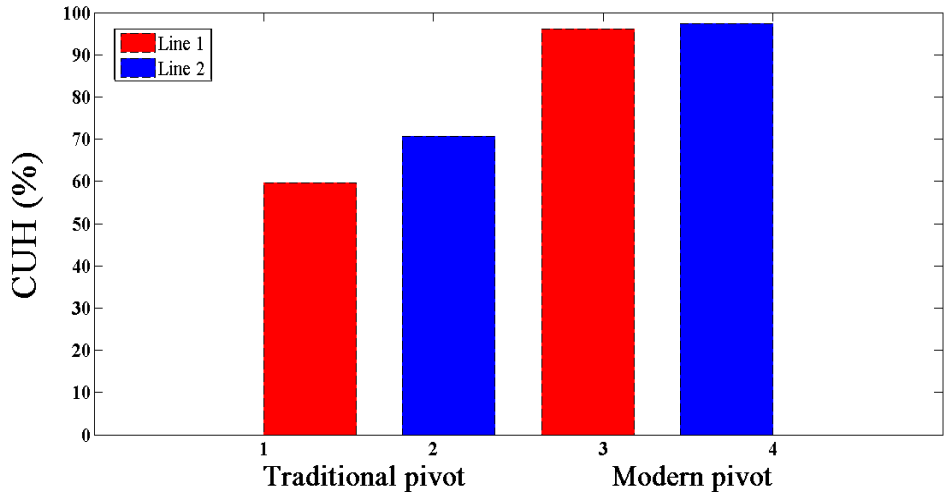

Figure IV.34: Histogram indicates the uniformity coefficients of the two systems studied.

For better comprehension, the difference values of CUH (between the two irrigation systems studied) may be used to develop irrigation strategies, which lead to acceptably high uniformities even under specific parameters. Improved uniformity of low-uniformity irrigation systems may mean minimizing the cost of irrigation (less expensive supply water).

The results of the work showed that the CUH values of the traditional system commonly used by farmers were **59.58%** and **70.76%**. These values give us the possibility to improve the uniformity of irrigation of the traditional Mini-Centre Pivots Systems (No uniform irrigation systems) by the predominant effect of the sprinkler's distances and sizes to get an acceptable value of normalization factor (over 85%). On the other hand, the ANABIB system gives **95.98%** and **97.28%** of CUH, which tend to consider suitable values.

The international standards stipulate that the normalization factor of the CUH should be more than 80% to provide uniform water [35]. Therefore, center pivots cannot operate properly if the nozzle’s discharge and space along the system are not appropriate.

IV.7. THEORETICAL SPRINKLER-SPACING CONFIGURATIONS FOR CENTER PIVOT IRRIGATION SYSTEMS TRADITIONAL AND MODERN:

Irrigation's objective is to provide the most uniform water pattern available. The absence of homogeneous irrigation results in three distinct areas: over-irrigated, under-irrigated, and adequately

irrigated. It might regard both over-and under-irrigated areas to be an economic loss because the first creates a loss of water under the roots, while the latter affects the amount and quality of the produce. Uniformity is always questioned in most mass-production processes and from many sources. High uniformity results in more uniform production, but irregularity might cause some areas to receive more or less water than they require, therefore it is considered an economic loss in terms of quantity or quality.

The goal of this part is to provide a mathematical procedure for calculating the best spacing between neighboring sprinklers. As a result, the quantity and quality of crops produced by any center pivot irrigation system are improved without requiring a significant investment. Nevertheless, the sprinkler position of three types of center pivot irrigation systems was modified. The first and second are artisanal devices made by craftsmen in El Oued, and the third is a modern center pivot installed in a region known as El Hadjira Ouargla. Both systems are investigated in the south of Algeria.

IV.7.1. THE CONFIGURATIONS PROCEDURE:

Optimal spacing between neighboring sprinklers is regarded as one of the most successful and cost-effective methods of improving the homogeneity of water in center pivot irrigation systems. This research uses integrated equations derived from data collection and specific data, mostly from topographic conditions, to provide homogeneous water distribution using a new theoretical sprinkler position around the center pivot. The study's strategy is represented in Figure IV.35.

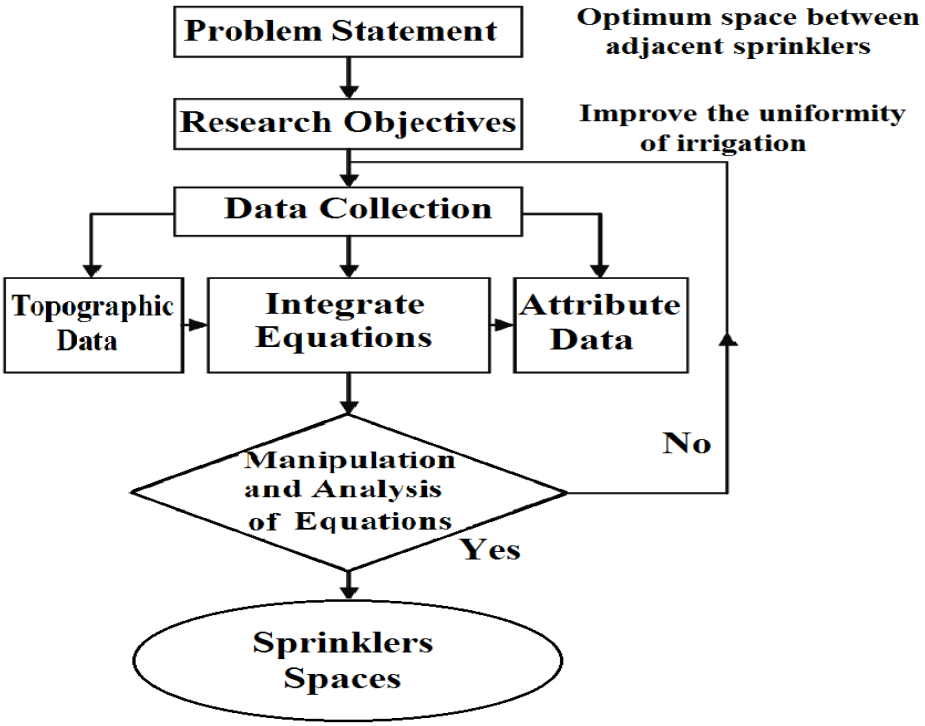

Figure IV.35: Highlighted the configurations procedure flowchart used in the investigation.

IV.7.2. SECTION FLOW RATE, q_{RI}:

For infinity of nozzles, the section flow rate (*qri*) corresponds to a distance *r* equal to the integral of flow rate on an interval [*r*, *R*] and measures the amount of volume that passes through an area (*P* * *A*) per time (*T*), where the section *A= 2 r dr*, as shown in Figure IV.36. Equation IV.23 represents the section flow rate.

$$qr_i = 2\pi(\frac{P}{T}) \int_r^R r dr = \pi R^2 (\frac{P}{T}) [1 - (r_i^2/R^2)] \quad \text{(IV.23)}$$

in which:

qr_i is the section flow rate corresponding to a distance *r* in the center pivot from the pivot point [m^3/h]

P is the water applied per revolution [m]

T is the system revolution time [h].

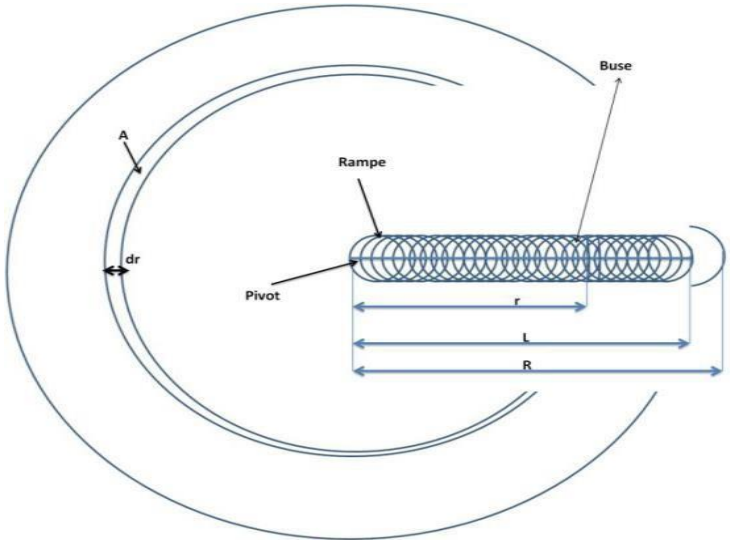

Figure IV.36: The section flow rate in the center pivot irrigation system.

At the pivot point, *r* = 0 therefore, Equation IV.24 becomes:

$$qr_0 = \pi R^2(\frac{P}{T}) \quad \text{(IV.24)}$$

From Equations IV.23 and IV.24, Equation IV.25 represents as follows:

$$qr_i = qr_0[1 - \left(\frac{r_i^2}{R^2}\right)] \quad \text{(IV.25)}$$

Moreover, Equation IV.26 becomes as follows:

$$qr_i = qr_{i-1} - q_i \quad \text{(IV.26)}$$

For example: $qr_1 = Q_0 - q_i$ (see Figure IV.37).

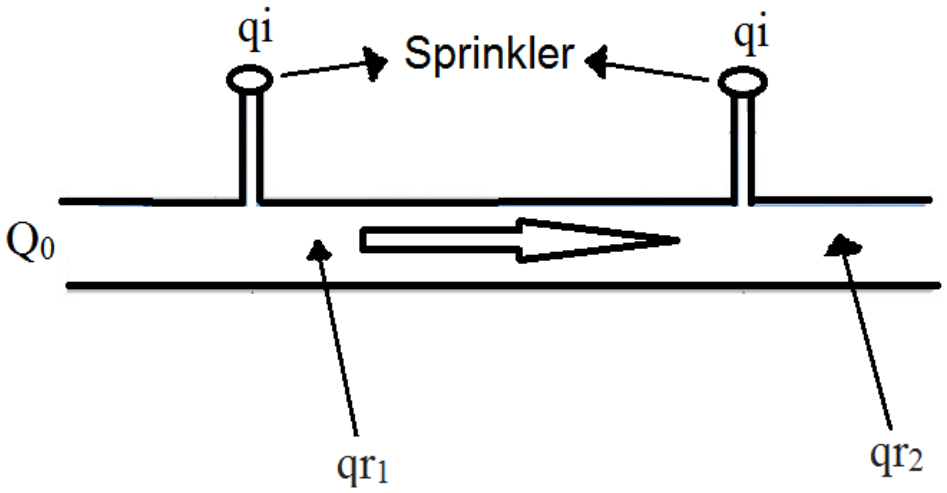

Figure IV.37: The section flow rate of distance *r* in the center pivot system.

By simplifying Equation IV.25, we obtain Equation IV.27.

$$r_i = \mathrm{R}\sqrt{[1 - (\frac{qr_i}{qr_0})]} \qquad [\mathrm{m}] \qquad \text{(IV.27)}$$

in which:

r_i is the radius that corresponds to the flow rate qr_i in the center pivot.

Finally, the sprinkler position (X_i) is calculated by Equation IV.28 as follows:

$$X_i = r_{i-1} + [(r_i - r_{i-1}) / 2] \qquad [\mathrm{m}] \qquad \text{(IV.28)}$$

in which:

X_i is the better sprinkler's position.

Noted that in the pivot point $r_0 = 0$ and if calculated $\Delta X_i > \Delta X_{max}$, it must take $\Delta X_i = \Delta X_{max}$ until it becomes less than ΔX_{max}. Then we should take the different values of calculated X_i.

IV.7.3. THE CONFIGURATION SOLUTION IN EXAMPLE 1:

From the pivot point to the end of the lateral, the sprinkler with a diameter of 13 mm is spontaneously positioned along with the system. The sprinkler-watered surface area is 4.3m, and factor *C* is 1.04. As a result, the intervals between sprinklers with wind speeds up to 1.8 m/s are indicated in Table IV.7 before and after the calculation research. Due to the loss of pressure in the pipes and valves, the distances between sprinklers should not spontaneously The Herman and Hein uniformity coefficient, which equals 59.58 % in the actual nozzles distribution (Note that the international standards, which stipulate the normalization factor, are over 80 % [35]), elucidates that sprinklers would be impossible

to provide uniform water coverage with this design. Figure IV.38 shows a comparison of overlap between actual and modified sprinkler distribution for the center pivot 50m.

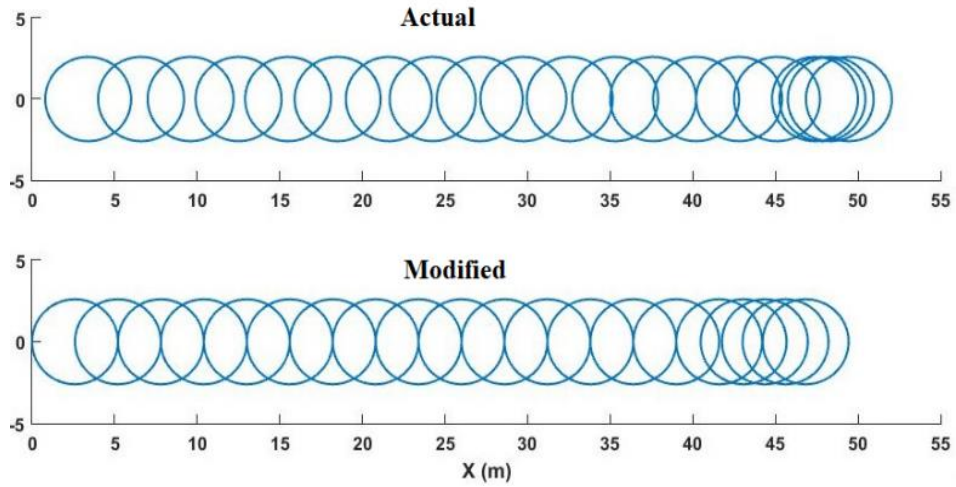

Figure IV.38: A comparison of actual and modified sprinkler distribution spacing for a center pivot of 50m [86].

The discharge decreases in direct proportion to the distance between nozzles or sprinklers along the lateral in the actual distribution. The wetted diameter is the distance on which water is thrown from the nozzle. According to the theoretical methodology provided by the study, the distance between neighboring sprinklers along the lateral is inversely proportional to the radial distance from the pivot (see Figure IV.38). The sprinklers are positioned about 2.6 meters apart near the pivot point and then reduce to about 1.2 meters towards the moving or outer end of the lateral. This theoretical technique offers a CUH value that is acceptable (93%).

IV.7.4. THE CONFIGURATION SOLUTION IN EXAMPLE 2:

Using the same conventional system as in the previous example, farmers attempted to develop the system by varying the length of the center-pivot irrigation system (60 m) and, of course, the spacing between sprinklers, based on their knowledge gained through repeated tests over many years. The identical sprinkler (ΔX_{max}=2.6m and C=1.04) was utilized, and the wind speed reached 1.8 m/s. Table IV.7 shows the findings before and after the calculation.

The radial distance from the pivot is inversely proportional to the actual and calculated sprinkler spacing along the lateral (see Figure IV.39). For the actual distribution, the sprinklers are spaced about 4m apart near the pivot, then decrease to about 1m at the moving or outer end of the lateral, and for the modified design, the sprinklers are spaced about 2.6 m apart near the pivot, then decrease to about 1.2 m at the outer end of the lateral.

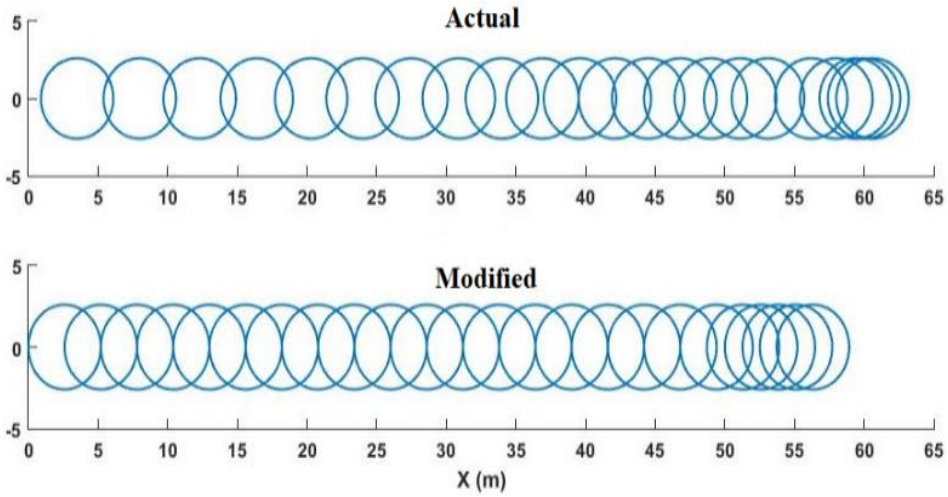

Figure IV.39: A comparison of actual and modified sprinkler distribution spacing of the 60-m-long center pivot system [86].

Farmers are well conscious of the importance of spacing between sprinklers in achieving a uniform water distribution throughout the center-pivot irrigation system, but they have not yet created a solution for their sprinkler distribution. However, the actual case computed Heermann and Hein uniformity coefficient is 64.34 % (less than 80%). It is important to note that in this conventional system, the inlet flow rate is higher ($2.7 \leq q_i \leq 3$ m^3\h), but the maximum space between sprinklers is small ($\Delta X_{max} \leq$ 2.6m), indicating that farmers are using low-quality sprinklers.

IV.7.5. THE CONFIGURATION SOLUTION IN EXAMPLE 3:

Factor *C* is 1.7 for a typical 312-meter-long system (ANABIB 160 EL type), while the average wind speed at El Hadjira, in which the system is installed, is about 3.5 m/s. The major characteristics of the ANABIB 160 EL system installed in El Hadjira are summarized in Table IV.6. The type of sprinkler employed in this study is the Nelson R3000, which has the following features: The operating pressure is 1.4 bar, the nozzle is 14 mm in diameter, and the throw diameter is 12 meters for a mounting height of 1.8 meters.

Sprinkler spacing along the lateral is inversely proportional to the radial distance from the pivot in both the actual and modified sprinkler distributions. Sprinkler spacing begins near the pivot with sprinklers spaced about 12 meters apart, then decreases to about 3 meters at the moving or outer end of the lateral (see Figure IV.40).

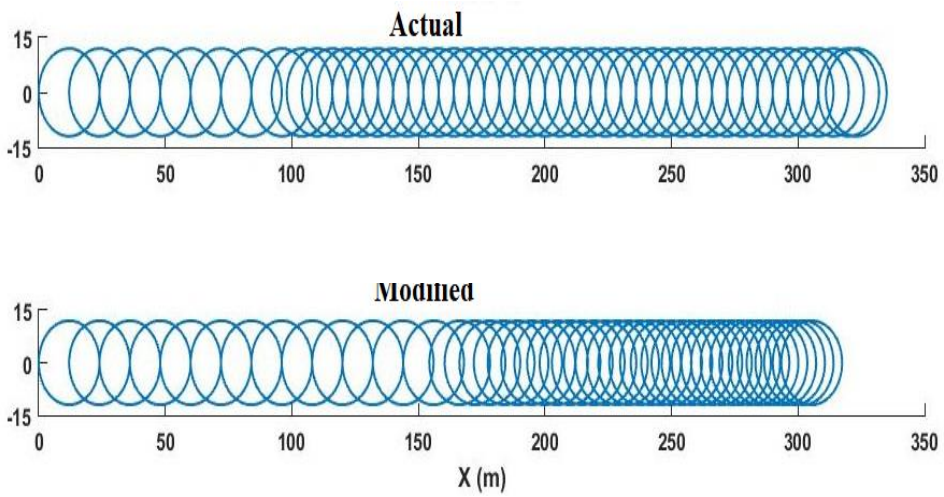

Figure IV.40: A comparison of sprinkler spacing between the original and modified distributions for the center pivot 160EL model [86].

This system's Heermann and Hein uniformity coefficients reached acceptable values of 91 % (more than 80%), indicating little spatial variability (uniform irrigation) around the system. This system also requires a lower sprinkler inlet flow rate ($0.71 \leq q_i \leq 1.6$ m^3\h), but only with enough space among sprinklers (ΔX_{max}=12m). The new design's CUH coefficient is 82 %, resulting in a uniform sprinkler discharge with just minor discharge variations.

Table IV.7 shows the findings before and after the sprinkler spacing calculation for the three systems investigated.

	Nozzle Spacing (m)								
	Pivot 50m		Pivot 60m		Pivot 324m				
N°	X_i act	X_i mod	X_i act	X_i mod	X_i act	X_i mod	**N°**	X_i act	X_i mod
S1	3	2,6	3,5	2,6	12	12	**S25**	200	224
S2	7	5	8,0	5	24	24	**S26**	206	229
S3	10	8	12,3	8	36	36	**S27**	212	233
S4	13	10	16,4	10	48	48	**S28**	218	237
S5	16	13	20,3	13	60	60	**S29**	224	242
S6	19	16	24,0	16	72	72	**S30**	230	246
S7	22	18	27,5	18	84	84	**S31**	236	250
S8	24	21	30,9	21	96	96	**S32**	242	254
S9	27	23	34,0	23	104	108	**S33**	248	258
S10	30	26	36,9	26	110	120	**S34**	254	262
S11	33	29	39,6	29	116	132	**S35**	260	266
S12	35	31	42,1	31	122	144	**S36**	266	270
S13	38	34	44,5	34	128	156	**S37**	272	274
S14	40	36	46,8	36	134	166	**S38**	278	277
S15	43	39	49,0	39	140	172	**S39**	284	281
S16	45	42	51,1	42	146	178	**S40**	290	285

S17	47	43	53,1	44	152	184	**S41**	296	288
S18	48	44	56,2	47	158	189	**S42**	302	292
S19	48	46	58,0	49	164	195	**S43**	308	295
S20	49	47	59,4	51	170	200	**S44**	314	299
S21			60,0	53	176	205	**S45**	320	302
S22			60,6	54	182	210	**S46**	323	305
S23				55	188	215			
S24				56	194	219			

Table IV.7: A Comparison between the actual and modified spacing in three investigated systems.

Figure IV.41 shows the test repeatability of the CUH coefficient for the three systems in three different scenarios: experimental based on ISO standardizations [64], actual, and modified design based on theoretical calculations.

The irrigation quality in the three center-pivot irrigation systems must be evaluated using the histogram below. Due to the ignoring of the wind velocity effect in the first and second examples, the theoretical CUH values for the actual design are 10% higher than the experimental. Furthermore, when compared to the actual design using theoretical calculations, the adjusted sprinkler spacing configuration (new design) provides a significant enhancement in CUH value. In the third example, the experimentally determined value of CUH is about 91 %. Moreover, there is a little difference in uniformity coefficient using theoretical calculation between the actual and modified designs (72 % and 82 %, respectively), which is due to the use of professional sprinklers distribution of actual design with the appropriate theoretical technique.

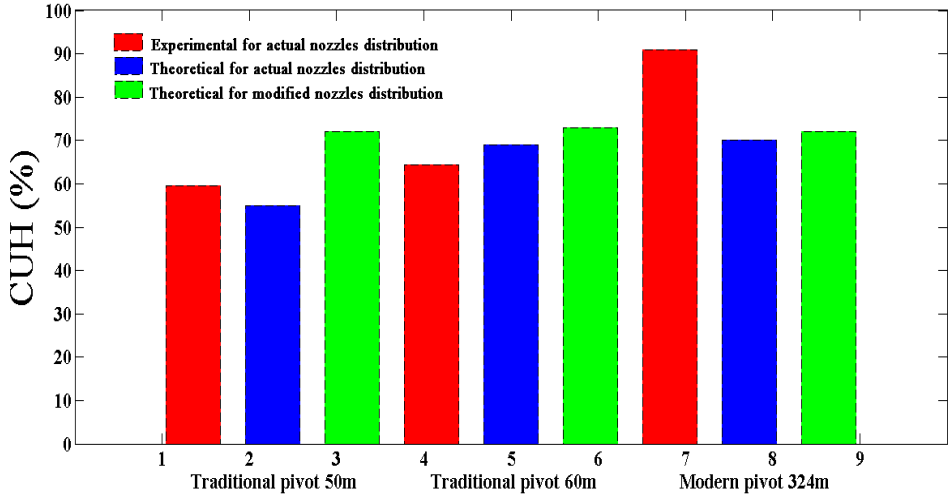

Figure IV.41: The uniformity coefficients of the three investigated systems [86].

The obtained results from the theoretical calculation are comparable to recent scientific research that used a calculation procedure to improve the homogeneity of water distribution in irrigation areas without significant investment. The majority of references specify that the minimum coefficient of

uniformity should not be less than 80% [35].

IV.8. CONCLUSION:

Center pivots have the potential to be uniform and efficient, but they must be properly designed, installed, and maintained to achieve that potential. The study area and system characteristics for investigated center pivot systems were presented in this chapter. We also present procedures for selecting sprinkler spaces and evaluate sprinkler flow, pressure and pluviometry of the three investigated systems to can help the systems to operate efficiently.

CHAPTER V.

RESULTS AND DISCUSSION

V.1. INTRODUCTION:

It is not novel to look for the optimum nozzle space and diameter for center-pivot irrigation systems. Engineering principles of thumb like the loss of pressure not to exceed 20% (a field-scale criterion) and the coefficient of uniformity of more than 80% (a local-scale criterion) are examples of intuitive optimization [53]. Because the efficiency factors, such as the dimension and size of the nozzle, are not consider by several studies which, attempted to optimize the design and operation of center pivot irrigation systems, in this chapter of the work we search on these two factors on the role of enhancing the irrigation uniformity.

V.2. OPTIMAL CONFIGURATION OF THE NOZZLES SIZES (DIAMETERS):

V.2.1. OPTIMIZATION PROBLEM FORMULATION:

The GA optimization model is used in this research to make design improvements to a Mini-Centre Pivot System depending on nozzle sizing. The MATLAB genetic algorithm toolbox [70] resolves the above-mentioned optimization problem for discrete or dependent variables. To specify the sprinkler size at each known position under the Mini-Centre Pivot System, it is important to model sprinkler discharge to calculate the quantity of water flowing at this position and to obtain the maximum uniformity of water distribution.

Since real-world problem resolution necessitates rapid convergence, the effective GA approach was employed to create a globally optimal solution. The model's structure, on the other hand, is dependent on the design's possible range of variables. However, because the initial solution should be chosen for optimized population convergence, the design's initial random population variable is generated. The iterative search process commences before the requirements for the stoppage are satisfied. All the unfavorable variables in a suboptimal solution that fail to reach one of the requirements of restriction are gradually changed by newly created random variables during this cycle (see Figure V.42). The GA optimization approach was employed in this process to concentrate on improving optimization efficiency for large populations. As a result, the maximum generating number is set to 100. The starting population consists of 100 individuals who use the rank scaling method. In this concept, the crossover operation is utilized to distribute stochastic uniform selection and mutation of the default constraint. Figure V.42 shows a schematic representation of the important steps employed for the investigated genetic algorithm optimization technique along with a Mini-Centre Pivot System.

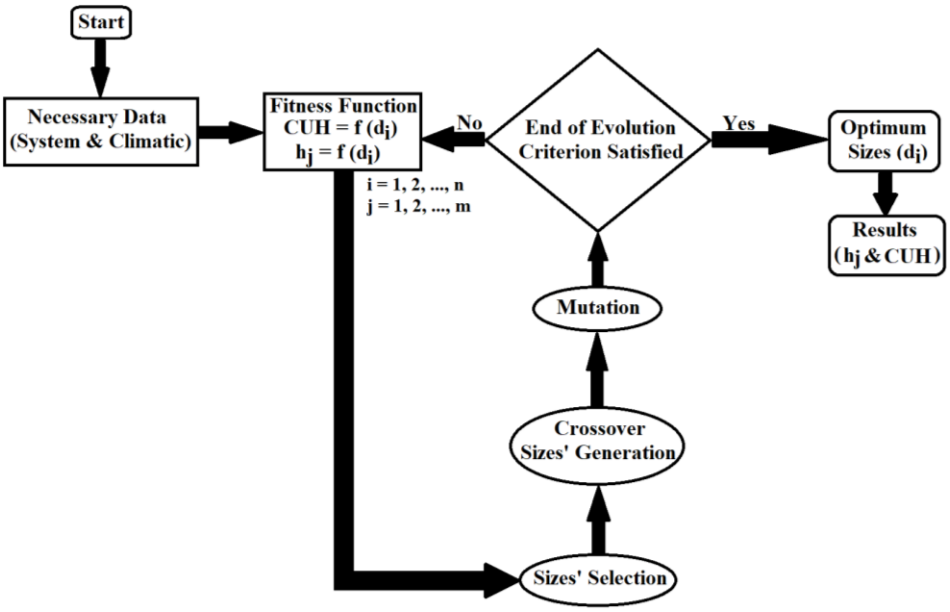

Figure V.42: The major steps of the genetic algorithm optimization technique that were investigated. Uniformity coefficients Heermann and Hein CUH.

The objective function is stable after 100 generations and achieves its maximum values when the termination condition is satisfied. In the evolutionary process, the best individual is chosen based on the value of each individual's fitness function for each generation. The goal of this improvement technique is to determine the best nozzle size, which satisfies every one of the mentioned nonlinear restrictions to maximize the uniformity coefficient of a Mini-Centre Pivot System 60, 50, and 46 m in length with single upstream pressure and flow rate. As a result, the nozzle size symbolizes the decision variable.

This research has presented a practical and necessary technique for improving the hydraulic efficiency in Mini-Centre Pivot Systems with lengths of 60, 50, and 46 meters. Improvement, on the other hand, necessitates both time and money. Because of the nonlinear limitation (constraint), all the nozzle size variable improvement actions are achievable. The modified formula of Heermann and Hein is utilized as the objective function in this methodology, nonlinear restriction conditions are frequently used, nozzle size variables are declared, and the GA is used to solve the optimization problems that exist.

To get the right optimized model, a nozzle sizing equation is needed. Equation V.29 is the main goal of an optimized mathematical model for the problem addressed in this study:

$$\text{Find } d_i = \{d_1, d_2, d_3, \dots, d_n\} \tag{V.29}$$

in which:

d - nozzle diameter.

The most successful criterion for optimization in center pivots irrigation systems is to maximize the uniformity of water distribution. On this basis, the hydraulics parameters are often optimized. Equations

V.30 and V.31 provide the formulation of fitness function for the studied mathematical models to predict nozzle diameter as a function of needed flow and pressure.

$$Minimize\ -p(d)\ such\ as\ d \in S \subset R^n \tag{V.30}$$

$$p(d) = CUH = 100\left[1 - \frac{\sum_{j=1}^{m} 3(j)|h_j - h_{moy}|}{\sum_{j=1}^{m} 3(j)h_j}\right] \qquad (j = 1, 2, 3\ldots, m) \tag{V.31}$$

in which:

m - the number of collectors.

Determining the nozzle diameter is one of the significant factors in the hydraulic design of center pivots. A GA technique was used to obtain an accurate, optimized model for sizing nozzles along with the pivot for the best design. The required volume of collected water is expressed in this model by specifying a measured cup volume (m^3), a collector's cross-sectional area (m^2), and a difference among the increased circular surfaces (m^2). As a result, Equation V.32 represents a volume of received water in the j^{th} collector:

$$h_j = \frac{S_{coll}}{\pi(l_i^2 - l_{i-1}^2)} h_i \qquad (i = 1, 2, 3\ldots, n) \tag{V.32}$$

Equation V.33 is used to calculate the volume of water collected:

$$h_i = \frac{\pi^2}{16\,K^2\,\rho g}\, d_i^4\, [2\ 10^2(P_0 - P_i - 0.074\ l_i) + v_0^2 + 2gh] \tag{V.33}$$

The formula for calculating the average weight volume of water collected by the nozzles is given in Equation V.34:

$$h_{moy} = \frac{\sum_{j=1}^{m} 3(j)\ h_j}{\sum_{j=1}^{m} 3(j)} \tag{V.34}$$

in which:

l - nozzle distance from the pivot point

S_{coll} - the surface of the collector

n - number of nozzles.

While developing the GA optimization model, the following nonlinear inequality constraints (V.35) are used: the diameter of every nozzle should be between 5 and 15 mm, and the diameter increases, as the nozzle gets further away from the pivot point.

$$\begin{cases} 5 \leq d_i \leq 15\ mm, \\ d_i > d_{i-1} \end{cases} \quad \text{(V.35)}$$

V.2.2. RESULTS AND VALIDATION:

V.2.2.1. OPTIMISATION RESULTS:

Figure V.43 represents the optimum solutions for every nozzle diameter of the Mini-Centre Pivot Systems 60, 50, and 46 m in length after 100 generations. The adjusted formula of CUH rises as the nozzle diameter increases, commencing with the nozzle closest to the pivot point and finishing with the nozzle farthest from the pivot point, according to the optimization findings. Figures V.43, 44, and 45 show the results of the optimizations. These findings are presented in a summary format to provide a clear overview of the obtained results from every optimization.

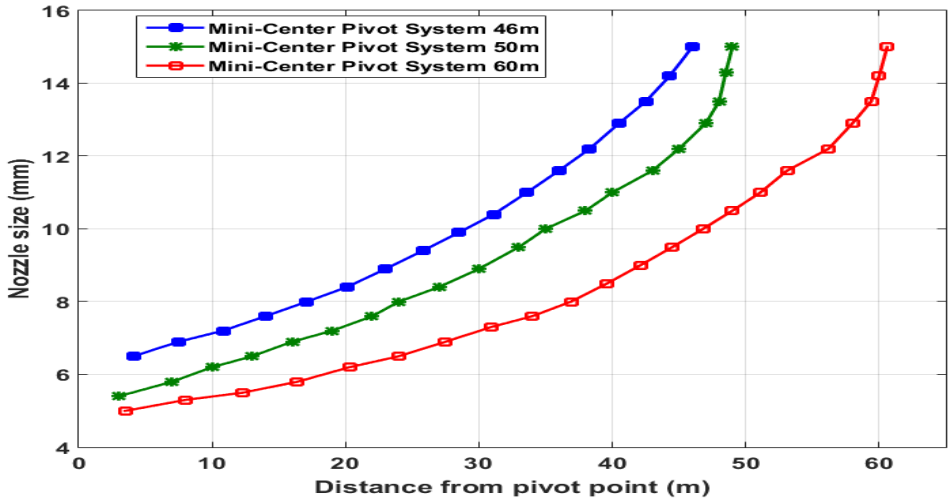

Figure V.43: Optimum nozzle sizes of the Mini-Centre Pivot Systems investigated.

Figure V.43 shows the results of the optimized model, which is a collection of nozzle sizes from the three studied Mini-Centre Pivot Systems. It indicates that the improved distributions are so much preferable to the original or actual distributions (as expected). It also indicates as recommended by [23] that the increasing impact nozzle diameters for the optimized distribution fit the water application rate better than the actual distribution.

For higher water uniformities, the diameters of the actual nozzles should be changed for all studied distributions in which the difference between the nozzles is an order of diameter larger still, beginning with the nozzle closest to the pivot point and finishing with the nozzle furthest from the pivot point. If all the parameters that affect the system are correctly identified, an appropriate model can be created which will give the optimum nozzle sizes. To improve the overall performance of a center pivots irrigation system, the appropriate model should be applied.

In hydraulic engineering, modeling a measured catch can volumes to estimate the performance of a center-pivot irrigation system is a complex task. The difference between achieved and

original performance is frequently the main objective. The coefficient of uniformity can be considered as the efficiency of the latter type, where the perfect uniformity is the potential. Nevertheless, according to the definition of Seginer [53], uniformity is not the only main goal of irrigation. If water is applied uniformly but excessively, it creates water loss by deep percolation. Moreover, if too little water is applied uniformly, the crop will suffer. Both scenarios are unacceptable, and an effective improvement method for irrigation efficiency should identify them. This principle was further shown by [86], which stated that the efficiency should be dependent on both the applied mean depth and the uniformity. The measured catch can volumes are compared with the volumes predicted by the suggested model in Figure V.44 for each system studied.

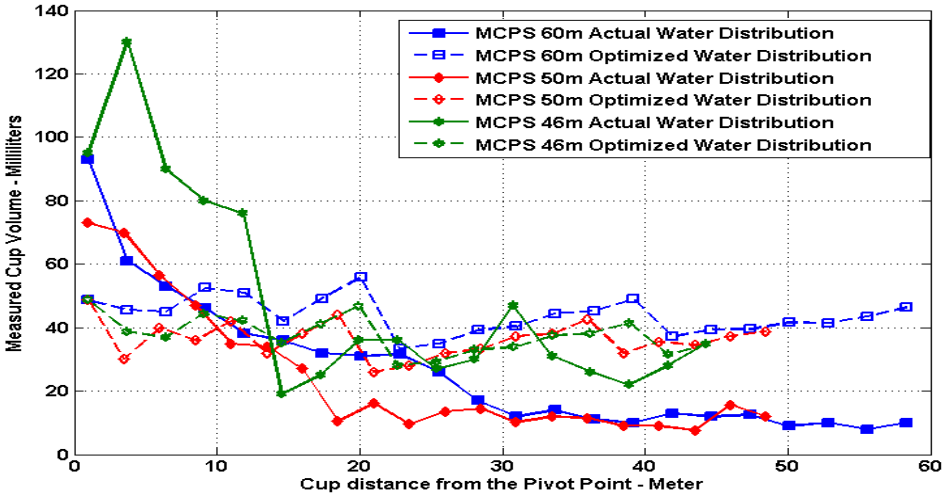

Figure V.44: The sampling and evaluation criteria for the irrigation efficiency of the investigated Mini-Centre Pivot Systems [80].

Figure V.44 illustrates the evaluation criteria for irrigation efficiency. The real and optimized water distributions of the Mini-Centre Pivots Systems examined are shown in this figure. The real distributions show the heterogeneity of water along the lateral pipe for each system, as well as their insufficient flow discharges. The quantity of water received in catch cans decreases significantly, as you get closer to the pivot point, to about 15 meters. After that, the unsuitable volumes of water received gradually decrease until the pivot's end. The uniformity of water distribution is reduced because of the decrease in the catch can volumes along the lateral pipe, and the crop production suffers as a result. The nozzle sizing of the Mini-Centre Pivot Systems showed a little decrease in volumes of catch cans along the lateral pipe of the systems using the improving procedure offered by this research, resulting in a sufficient average volume of water collected in all catch cans. As a result, an adequate flow supply by each nozzle provides a uniform water distribution throughout the system at all distances from the pivot point. As a result, the water application uniformity along the examined Mini-Centre Pivot Systems is improved.

Based on Figure V.44, as well as on conclusions of Howell [47], it is clear that the size of the nozzles distribution function presented by the study can effectively improve the uniformity irrigation of center pivot irrigation systems. Because there is no significant difference in the measured catch can volumes along with the investigated systems for the optimized nozzle distributions against the original nozzle distributions. The final solution (optimum nozzle diameters) for a particular center-pivot irrigation system is determined by its hydraulic and geometrical specifications.

V.2.2.2. THE EXPERIMENTAL VALIDATION:

The enhancement involves the determination of appropriate sizes of individual nozzles, properly positioned, to create uniform water distribution over the whole field. It would be useful to compare the Heermann and Hein uniformity coefficient (CUH) of an investigated system in actual (real) nozzles distribution (experimentally and analytically), and optimized nozzles distribution (analytically) for the sake of simplicity of validating the present problem.

The nozzle diameters were calculated with the pressure at every outlet in the actual nozzle distribution of the investigated Mini-Centre Pivot Systems (before optimization). The size of these nozzles is the same, about 13mm. Furthermore, because pressure regulators are not utilized in these conventional systems, the experimentally recorded pressure at every nozzle outlet during operation is input into the model as a vector in place of pressure regulators. The experimental measurements of CUH for the 60 m, 50 m, and 46 m Mini-Centre Pivot Systems, respectively, were 64.34 %, 59.58 %, and 69.92 %. As a result, unless the nozzles' size configuration along the lateral pipe is modified, the original design delivers water with a CUH < 80%.

The findings of the experiments, which analytically determined the CUH for the existing systems in original and optimized nozzles distribution by the model, are then compared with the CUH measured experimentally before the optimization. The comparison of these results is shown in Figure V.45.

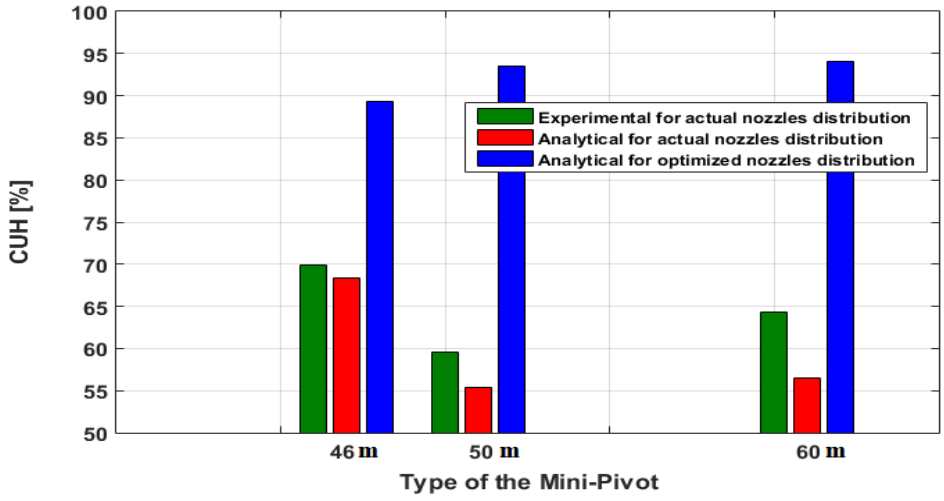

Figure V.45: Comparison between the experimental and analytical Heermann and Hein uniformity coefficient (CUH) [80].

V.2.3. DISCUSSION:

In the El Oued region in southern Algeria, the traditional Mini-Centre Pivot System is widely utilized for irrigating crops, and its use is increasing quickly. However, the procedure for sizing nozzles of a Mini-Centre Pivot System utilizing a GA demonstrated that the difference between the measured CUH experimentally and by the model is acceptable if the operating conditions and system characteristics are adequately specified (For the 60, 50, and 46 m Mini-Centre Pivot Systems, the differences were 7.86%, 4.17%, and 1.62%, respectively). For the actual nozzle diameters of each studied system, there is no significant difference between the experimental and modeled CUH, as shown in Figure V.45. However, when the system parameters are well identified and the operating conditions are well determined, these findings automatically refer that the result of the provided methodology is valid.

The procedure has a remarkable feature, which is the ability to estimate the experimental uniformity of water distribution based on the calculation by applying the proposed methodology to a Mini-Centre Pivot System. This happens as a result, of rounding in the methodology's CUH calculation.

In three optimized scenarios of the investigated Mini-Centre Pivot Systems, the CUH of the sized nozzles where the pressure regulator was utilized is significantly greater than in actual (original) nozzles distribution. Based on the proposed methodology, the uniformity of irrigation improves by more than **32%** on average [80]. As a result, utilizing the provided methodology for nozzle sizing ensures that this kind of irrigation device obtains a sufficient increase in efficiency. A further feature of the optimization methodology is the ability to estimate the CUH with or without pressure regulators when the pressure of each nozzle is measured experimentally and then inserted as a vector into the model. As discovered by [87], the CUH could be utilized in the future to improve the irrigation efficiency of a center pivot equipped with fixed sprinklers (FSPS) by switching the FSPS to rotating sprinklers (RSPS).

The presented methodology allows a design optimization in both project deployments and improvement of existing systems in the field. Furthermore, although the proposed technology necessitates well-defined operating conditions and characteristics of a Mini-Centre Pivot System, this optimized design offers nozzle sizes, which improve irrigation uniformity, resulting in a significant increase in both yield and higher quality of agricultural products when compared to the actual (original) nozzle distribution of the same system.

Much research in recent years has focused on improving the design and operation of sprinkle irrigation systems (including moving systems like center pivots), with an emphasis on uniformity. Nevertheless, despite the slightly different uniformity problems they set out to resolve and the variations in strategy, the various methods have generally the same objective. Perhaps the effective way to improve irrigation uniformity is to begin by writing the fundamental objective function of the hydraulic problem and then create a few constraints to control the decision variables, similar to how the presented methodology

worked for choosing the optimum sizes of nozzles to improve the hydraulic design of center pivot irrigation systems.

V.3. OPTIMAL CONFIGURATION OF THE NOZZLES POSITIONS (SPACES):

On a wide scale, a center pivot systems water distribution uniformity plays a critical role in defining the system's performance and crop quality. In recent years, selecting spaces of sprinklers for a variable spacing package of center pivot system take an increased interest in the optimization design of these systems. In addition, it is quite difficult in the center pivot system to determine sprinkler spaces precisely when all the sprinklers have the same size. For these reasons, the spacing between the sprinklers should be decreased with the distance from the pivot point to account for the change in the area irrigated. Furthermore, the wetted radius should be similar for the entire system. This research offers a new methodology for determining the optimum nozzle spaces of the most common irrigation method in El Oued, southern Algeria to distribute water uniformly for the entire system. It also shows the big influence of the optimized nozzles spaces provided by the study on the performance of MCPS.

V.3.1. OPTIMIZATION PROBLEM FORMULATION:

The genetic algorithms technique solves complicated problems of optimization and conceptual design in diverse domains like biology, engineering, and computer science, as shown by some research [88, 89]. To enhance water application uniformity, a process for design optimization based on nozzle sizing and comparisons with real sizes of the same Mini-Centre Pivot System was established previously [80]. The goal of this section is to develop a model that can be used for a Mini-Centre Pivot System (MCPS) to find the appropriate nozzle space at any point along the lateral pipe while maximizing irrigation uniformity. To accomplish this, a genetic algorithm GA was employed to optimize the coefficient of uniformity under the MCPS when the design parameters were entered and combined with the modified formula of Heermann and Hein. The optimization is conducted on water distribution modeling and Heermann and Hein uniformity coefficient CUH calculations for three existing MCPS with lengths of 60, 50, and 46 meters. The essential steps of the researched GA optimization approach are shown in Figure V.46.

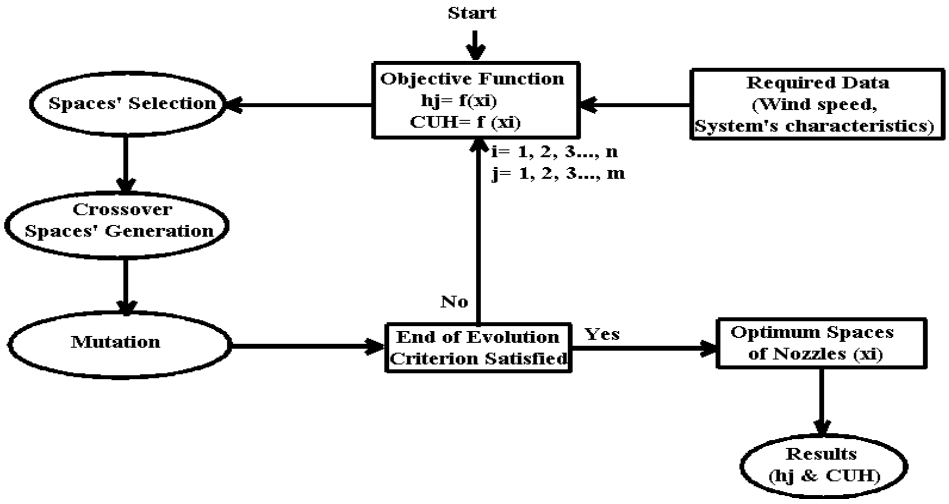

Figure V.46: Flowchart of the optimization process applied in the study.

The GA is used to solve optimization problems, and the modified formula of Heermann and Hein is used as the objective function. Nonlinear constraint conditions are often used, the pressure regulator is even used and the nozzle space variables are assumed. The goal of the optimization is to maximize CUH by identifying the appropriate nozzle spaces, which satisfy all of the nonlinear constraints.

As mentioned in Equation V.36, the fundamental purpose of the optimization problem is to determine the optimal spaces of nozzles where CUH is maximized.

$$\text{Find} \quad X_i = \{X_1, X_2, X_3, \dots, X_n\} \tag{V.36}$$

in which:

X is the space of the nozzle.

Equations V.37 and V.38 are used to define the fitness function:

$$Minimize \ -p(X) \ such \ as: X \in S \subset R^n \tag{V.37}$$

$$p(X) = CUH = 100\left[1 - \frac{\sum_{j=1}^{m} 3(j)|h_j - h_{moy}|}{\sum_{j=1}^{m} 3(j)\, h_j}\right] \tag{V.38}$$

Equation V.39 calculates h_{moy} as follows:

$$h_{moy} = \frac{\sum_{j=1}^{m} 3(j)\, h_j}{\sum_{j=1}^{m} 3(j)} \tag{V.39}$$

Among the most difficult aspects in the hydraulic design of a center-pivot system is determining the ideal nozzle spacing. Under the MCPS, however, a GA technique was employed to solve the problem of calculating the optimal volume of water sprayed by a specific nozzle. This model shows the estimated volume of collected water by specifying the nozzle mass (mm), collector surface (m^2), and the difference

between the increases in the circular area (m). Equation V.40 is used to calculate the volume of water collected in the j^{th} collector.

$$Q_{in} = \sum_i^n Q_{out} \quad \text{(V.40)}$$

where

Q_{in} is the inlet flow rate,

n is the number of the nozzle, (i=1, 2, 3…, n)

Q_{out} is the outlet flow rate.

Nozzle flow rates can be precisely determined as a function of operating pressure by empirically measuring flow levels. However, the orifice flow is empirically characterized by the function of the nozzle flow. Equation V.41 can be used to calculate the nozzle discharge at a specific position along with an MCPS:

$$q_i = \mathrm{K} * (P_i)^x \quad \text{(V.41)}$$

where

q_i is the nozzle's flow rate,

K is a factor, which characterizes the dimensions of the orifice,

x is the orifice exponent that characterizes the regime of flow.

By graphing q against P_{nozzle} on a log-log graph, the coefficients K and x are found. The intercept at P_{nozzle} = 1.0 is K and the slope of the straight line is x. The nozzle discharge indicator was specified as for laminar flow, x = 1.0, for turbulent flow x = 0.5, and x = 0 for compensated flow.

The volume of water received in the j^{th} collector, h_j, should be calculated to enable the estimated MCPS application efficiency. The volume of water collected can then be calculated using Equations V.42 and V.43.

$$h_j = \frac{S_{coll}}{\pi(l_i^2 - l_{i-1}^2)} h_i \quad \text{(V.42)}$$

where

l is a distance from the pivot point (m), $l_i = 2(X_i + X_{i-1} + X_{i-2} + X_{i-3} + \cdots)$.

$$h_i = \frac{\pi^2}{16\,K^2\,\rho g}\, d_i^4 \left[2\,10^2\left(P_0 - P_i - \Delta P_{i(l+s)}\right) + v_0^2 + 2gh\right] \quad \text{(V.43)}$$

in which:

S_{coll} is the surface of the collector (m^2)

d is the nozzle's diameter (m)

ρ is the density of the fluid (kg/m^3)

g is the acceleration of gravity (m/s^2)

h is the elevation difference between the pivot point and the position of the last nozzle (m) which can be positive or negative

P_0 is the pivot pressure (Pa)

v_0 is water inlet velocity at the pivot point (m/s)

P_i is the nozzle's outlet pressure (Pa)

$\Delta P_{i(l+s)}$ is the total head loss of pressure (Pa).

The total pressure loss in the MCPS is defined in Equation V.44 as follows:

$$\Delta P_{i(l+s)} = \Delta P_{i_l} + \Delta P_{i_s} \quad \text{(V.44)}$$

in which:

ΔP_{i_l} is the linear pressure loss,

ΔP_{i_s} is the nozzle's pressure loss.

Much of the literature has offered equations for computing the pressure head loss along with a center-pivot irrigation system in various formats. However, in so many center-pivot calculations, losses are minimal and ignored in fittings, nozzles, and valves along the sides (minor losses). Therefore, orifice losses were considered negligible in this study since $\Delta P_{i_s} << \Delta P_{i_l}$ and ΔP_{i_l} was calculated using the Darcy–Weisbach equation.

The nonlinear constraint requirements are as follows: the space among any adjacent nozzles must be between 60% of the nozzle's wetted diameter and R (the whole length of the pivot in meters), and the spacing of the nozzles should increase toward the outer portion from the pivot point, as shown in Equation V.45.

$$\begin{cases} 60\%\, W_d \le X_i \le R \\ X_{i+1} > X_i \\ X_{i+2} - X_{i+1} < X_{i+1} - X_i \end{cases} \quad \text{(V.45)}$$

in which

W_d is the nozzle's wetted diameter (m).

V.3.2. RESULTS AND DISCUSSION:

The Heermann and Hein uniformity coefficient CUH was calculated based on the international standard for determining water distribution uniformity ISO [64] to evaluate existing MCPS performance for real (actual) nozzle configurations. The experimental measurements of CUH for the Mini-Centre Pivot Systems 60 m, 50 m, and 46 m in length, on the other hand, were 64.34 %, 59.58 %, and 69.92 %, respectively. In regards to these measurements, the water distribution along the studied systems was not uniform since CUH was less than 80% [35]. In reality, water heterogeneity was observed in the studied systems, with an over-irrigated area near the pivot point and an under-irrigated area on the outer portion. For the original (actual) nozzle arrangement, the heterogeneity of water distribution across the lateral pipe of the 46-m-long MCPS was evaluated using 808 collectors equally spaced 3 m in all directions over the whole field [80]. Figure V.47 depicts the major findings from each field test, including the volume of each catch can along with the systems that were evaluated.

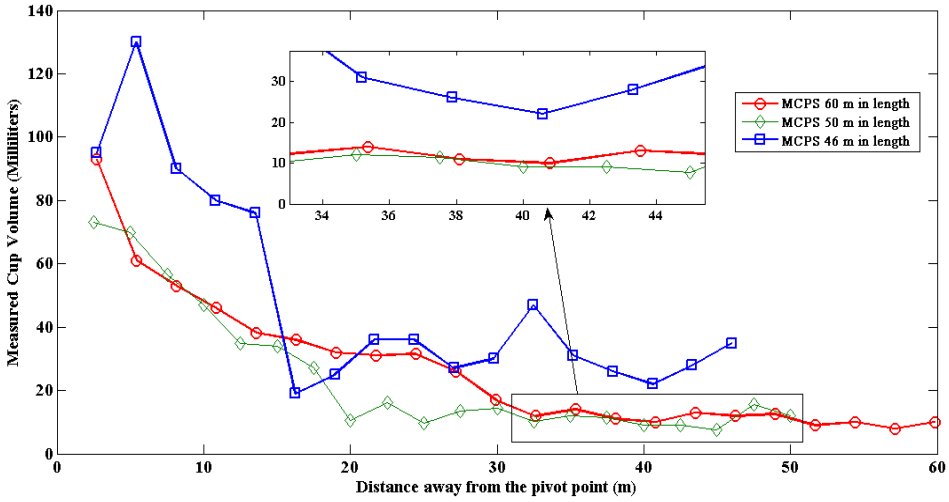

Figure V.47: The measured catch can volumes along each individual tested system [90].

Figure V.47 shows how the measured volume decreases as it moves away from the pivot point which reduces the water application uniformity dramatically. Consequently, great efforts should be taken to ensure an appropriate nozzle flow rate that enables a water distribution uniformity as high as possible. The significant decrease in observed volumes happens when the nozzle distance attains the system's second half (the outer portion of a system). These sections cover a larger portion of the field and have the smallest application rates, which might be inefficient for the performance of an MCPS since each unit length of lateral covers a large area. Furthermore, when the position of the nozzles improves, the water distribution will be highly uniform.

V.3.2.1. OPTIMIZATION RESULTS:

Many applications in precision agriculture, particularly center-pivot irrigation systems, require improvement design. However, utilizing Heermann and Hein's modified formula maximization by GA, three optimization nozzles spaces of the existing MCPS 60, 50, and 46 m in length were conducted. The above-mentioned optimization problem is solved by using the GA with the MATLAB genetic algorithm toolbox [91]. Based on the possible range of design variables, a random initial population of design variables is generated. The repeated search process is then carried out until the stoppage constraints are satisfied. If any individual fails to meet one of the constraint conditions during this cycle, the penalty function method will eliminate them from the succeeding evolution process. The generating number limit is set to 100. Default constraint mutation and crossover dispersed stochastic uniform selection are used. The optimized nozzles spaces result are compared with the actual nozzles spaces of MCPS evaluated for optimization design in Table V.8. Once the termination condition is reached, the fitness value is constant after 100 generations and reaches its maximum value.

	MCPS 60 m in length		**MCPS 50 m in length**		**MCPS 46 m in length**	
Distance from pivot point	Actual distance (m)	Model distance (m)	Actual distance (m)	Model distance (m)	Actual distance (m)	Model distance (m)
$\mathbf{X_1}$	3.50	6.23	3.00	4.45	4.05	4.31
$\mathbf{X_2}$	8.00	11.84	7.00	8.45	7.45	8.20
$\mathbf{X_3}$	12.30	17.16	10.00	12.25	10.75	11.89
$\mathbf{X_4}$	16.40	22.22	13.00	15.86	13.95	15.39
$\mathbf{X_5}$	20.30	25.36	16.00	19.11	17.05	18.55
$\mathbf{X_6}$	24.00	28.34	19.00	22.20	20.05	21.54
$\mathbf{X_7}$	27.50	31.18	22.00	25.14	22.95	24.39
$\mathbf{X_8}$	30.90	33.87	24.00	27.92	25.75	27.09
$\mathbf{X_9}$	34.00	36.43	27.00	30.57	28.45	29.66
$\mathbf{X_{10}}$	36.90	38.86	30.00	33.09	31.05	32.10
$\mathbf{X_{11}}$	39.60	41.16	33.00	35.48	33.55	34.42
$\mathbf{X_{12}}$	42.10	43.36	35.00	37.75	35.95	36.62
$\mathbf{X_{13}}$	44.50	45.44	38.00	39.90	38.25	38.72
$\mathbf{X_{14}}$	46.80	47.42	40.00	41.83	40.45	40.70
$\mathbf{X_{15}}$	49.00	49.30	43.00	43.65	42.45	42.59
$\mathbf{X_{16}}$	51.10	51.08	45.00	45.09	44.25	44.39
$\mathbf{X_{17}}$	53.10	52.78	47.00	46.46	45.97	46.00
$\mathbf{X_{18}}$	56.20	54.39	48.00	47.77		
$\mathbf{X_{19}}$	58.00	55.92	48.50	48.96		
$\mathbf{X_{20}}$	59.40	57.37	49.00	50.00		
$\mathbf{X_{21}}$	60.00	58.76				
$\mathbf{X_{22}}$	60.60	60.00				

Table V.8: A Comparison between the model spaces with the real spaces of MCPS evaluated.

The key findings from each MCPS, including the actual nozzles spaces and optimized nozzles spaces, are listed in Table V.8. As recommended by Bremond and Molle [92], the model spacing provides for at least 100% overlaps between all nozzles (every nozzle space is staggered by nearly a half of the wetted diameter).

The proposed changes aim to minimize the differences among catch cans volumes along with the center pivot irrigation system. Figure V.48 shows the estimated volume of water received under the MCPS at specific points as calculated by the model.

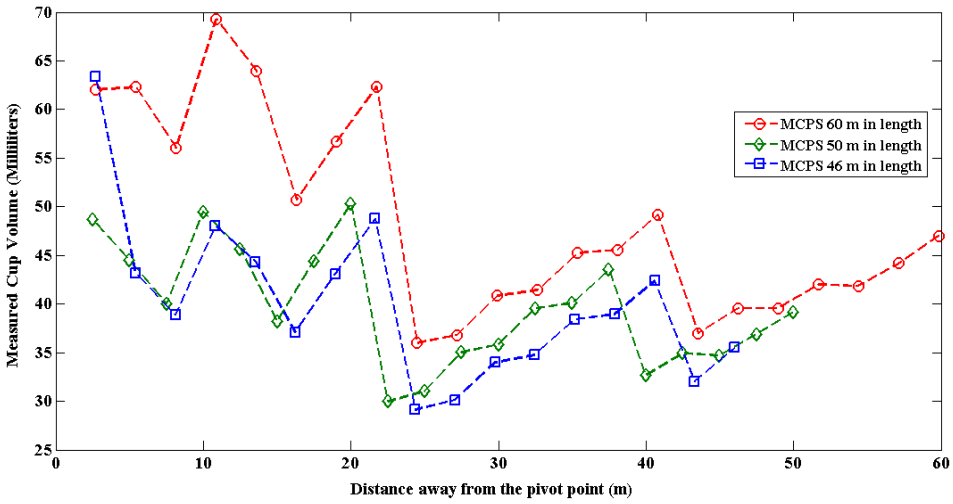

Figure V.48: The catch can volumes at specific points under the MCPS evaluated as calculated by the model [90].

Figure V.48 shows three examples of water distribution along with the studied MCPS as estimated by the model. As the nozzle spacing increases, the values of measured catch can volumes converge, and the range of variation along the lateral pipe is acceptable (about 50 ml). As a result, the average of catch can volumes calculated by the model is appropriate for different nozzle spaces. The appropriate values of volumes suggested that the model's nozzle spaces were accurately defined. Because of the nozzle space improvements, the water distribution under the studied systems with spacing optimization will be highly uniform to the actual configuration.

V.3.2.2. DISCUSSION:

In the following discussion, a CUH comparison of each MCPS's original and optimized nozzle distribution is presented. In general, there is a rapid decrease in the catch cans volumes in the actual nozzles distribution, notably from the middle to the end (the outer portion from the pivot point is more important because they cover more area). Water distribution uniformity lowers and crop productivity reduces when the volume of catch cans along the lateral pipe decreases. Conversely, along the lateral pipe, the optimized nozzle distribution results from a gradual decrease in the catch can

volumes. Therefore, the water distribution uniformity throughout the system is improved. Consequently, the optimization method improves the CUH of a center pivot system significantly. The computed CUH of the MCPS studied is shown in Table V.9 for diverse spacing configurations (actual and improved by the model).

Type of Mini-Center Pivot System	**CUH values**	
	Original spaces of nozzles	Model spaces of nozzles
MCPS 60 m in length	64.34%	88.12%
MCPS 50 m in length	59.58%	89.57%
MCPS 46 m in length	69.92%	87.88%

Table V.9: Evolution of CUH in the studied systems by a function of improved nozzle spacing.

Table V.9 shows a considerable increase in the efficiency of the systems studied, the significant enhancement in CUH between the optimized and actual nozzle spaces is linked to a reduction in differences between a catch can volumes on the optimized nozzle spaces along the system evaluated. Furthermore, the inlet of the nozzle may be connected with a pressure regulator to keep the nozzle of MCPS at an adequate and constant pressure value, although the nozzles of the majority of MCPS found in the El Oued region are not linked with a pressure regulator. The model, on the other hand, can calculate CUH with and without pressure regulators, in which the pressure of each nozzle is calculated experimentally and then inserted into the model as a vector.

According to the results of the previous investigation, model spaces showed better system performance than actual nozzle spaces in the MCPS evaluated. Furthermore, a model was developed to assist in the selection of optimal nozzle spaces for new center pivot systems and the enhancement of spacing configurations for existing systems. To ensure high water distribution uniformity and, as a result, higher crop quality along with the center pivot irrigation system, the fixed spray plate nozzle with a large interval of diameter should be changed into a rotating spray plate nozzle, as indicated by Jiao, et al. [28].

V.3.3. MODEL VALIDATION:

To validate the proposed model's performance, a modern center-pivot irrigation system with a length of 312.5 m was chosen. The reason for this selection is that a specialist national company constructed it, and Nelson Irrigation Corporation, which was specified as a part of this system design, manufactured the sprinklers, and determined the suitable sprinklers chart of this system. The experimental tests were carried out after one month of sprinklers renovation and the calculation of performance indicator CUH of this center pivot sprinkler was performed considering the central pivot pluviometry as a part (the first two spans). However, when the test conditions and equipment were based on ISO [64] and the average

wind speed was acceptable (less than 3.5 m/s [83]), the CUH calculated experimentally was 89.83 %. This value indicates that water is uniformly distributed throughout the irrigated area. The major characteristics of the system utilized for the validation test are highlighted in Figure V.49.

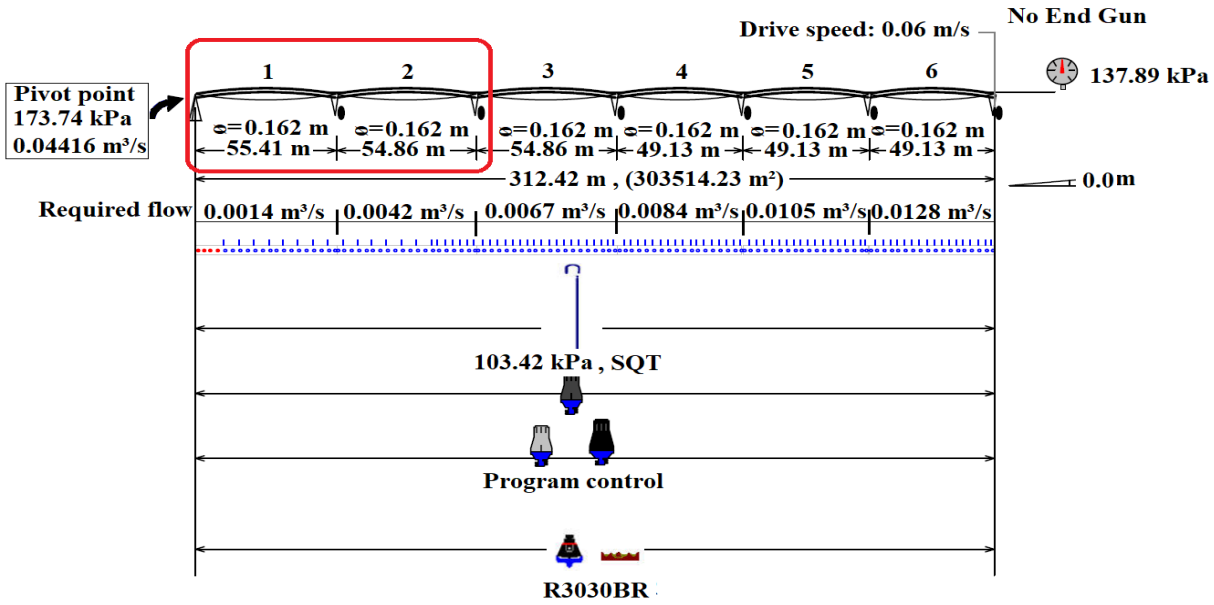

Figure V.49: Basic characteristics of the system employed for model validation.

When all of the characteristics of the chosen system are well declared, the proposed model calculates a CUH of 86.68 %. As a result, the experimentally determined CUH value was very near to the proposed model's CUH value for a similar type of center pivot system. Although the measuring methods were different (theoretical and experimental), there was no significant difference (3.15%) in the uniformity coefficient with the chosen system. This difference returns to the errors in the experimental measurement, as well as the no optimal experimental conditions, such as those considered in the theoretical procedure. This shows that the proposed model has a considerable impact in which the model can be used to estimate the experimental value of CUH for every center pivot system. In addition, when the optimization varied only by the nozzles' spaces, the optimum spaces of nozzles determined by maximization of generation for CUH utilizing GA were compared to the real nozzles distribution of the same selected system. Figure V.50 shows the comparison between the actual and optimized nozzles spaces of the selected system.

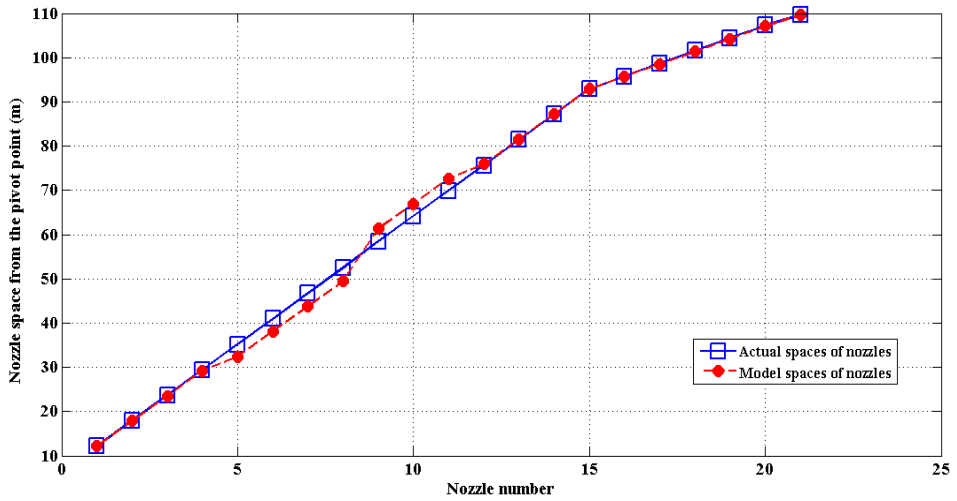

Figure V.50: A comparison between the actual and optimized nozzles spaces of the selected system [90].

Figure V.50 shows the proposed model's accuracy in determining nozzle spaces. Furthermore, this study demonstrates that the enhancement design by nozzle space can improve both the quantity and quality of agricultural products by enhancing irrigation uniformity. As a result, the study's optimization procedure has an impact on the uniformity of irrigation, which has a significant impact on crop productivity.

For the existing MCPS 60, 50, and 46 m in length, 22, 20, and 17 variables are determined, respectively. Moreover, this research provides significant insights into the impact of nozzle spacing optimization on MCPS efficiency. One of the main study's advantages is that it contains experimental tests to confirm the accuracy of the proposed model. The proposed model for design optimization based on nozzle space would contribute to enhancing the system's efficiency while also increasing the quantity and quality of agricultural products. The model can improve CUH values by more than **17%**.

V.4. CONCLUSION:

Under variable operating and meteorological conditions, a model for assessing the uniformity of irrigation for a center-pivot irrigation system has been proposed. The modelled Heermann and Hein's uniformity coefficient (CUH) values were validated with the CUH values calculated experimentally and no significant difference in the uniformity coefficient values was obtained indicating an excellent agreement between the modelled and experimental results.

The performance of the model was tested for optimization nozzles sizes using a conventional Mini-Center Pivot Systems and for optimization nozzles spaces using a modern center-pivot irrigation system with a length of 312.5 m. All validation tests, however, provided acceptable results. The proposed model's usefulness was clarified by evaluating three different conventional Mini-Center Pivot Systems

with 60, 50, and 46m of length installed in El Oued, southern Algeria before selecting the model for all available center-pivot irrigation systems.

It was illustrated that the nozzles configuration of existing systems is designed at a lower level of uniformity for the conventional investigated systems. The influence of the proposed methodology for optimizing design based on nozzle space and size (diameter) was explored and according to the findings, a detailed analysis should be considered of all interacting hydraulic parameters, operating conditions, environmental factors, and pivot specifications is required for enhancing the system's efficiency therefore inevitably increasing the quantity and quality of agricultural products.

GENERAL CONCLUSION

GENERAL CONCLUSION

To effectively evaluate the system's performance in a particular environment, a comprehensive strategy for optimizing the irrigation uniformity of a center-pivot irrigation system is required. As a consequence, a model for assessing the water distribution of a center-pivot system that depends on nozzle sizing and dimensioning has been developed, taking into account the system's specifications and operational conditions to achieve the necessary irrigation uniformity. The water distribution under a pivot system was investigated for different Mini-Center Pivot Systems with lengths of 60, 50, and 46m installed in El Oued, southern Algeria, using the developed model for optimizing the recommended uniformity to determine the optimal nozzle sizes and spaces. A procedure showing the validation method was presented with a case study to prove the effectiveness of the suggested model.

The proposed uniformity assessment model needs input weather data (wind velocity), specifications of the system (total length, TDH, pivot pressure, nozzle height), and fluid characteristics (kinematic viscosity, fluid density) to predict the maximum values of Heermann and Hein uniformity coefficient (CUH) depending on nozzle diameters (or spaces). The model's findings were validated using experimental measurements obtained from the test field in El Oued, southern Algeria, and an excellent agreement was observed (no significant difference between the experimental and modelled CUH values).

A calculation methodology using theoretical equations to observe circles overlap due to sprinklers spray was presented considering factors influencing the uniformity of irrigation such as wind speed, rate of flow, pressure, and dimensions of the system (chapter IV). The results of this theoretical methodology showed a substantial improvement in CUH values between the actual and modified design, according to notable variation in sprinkler arrangements of the traditional pivot systems. For the modern pivot system, no major improvement was observed because the sprinklers arrangement is based on the sprinkler chart which, was delivered by the sprinkler manufacturer.

The uniformity of a conventional Mini-Centre Pivot System has been accurately evaluated for a given area. A variety of interrelated factors (wind velocity, hydraulic parameters, system characteristics such as inlet flow rate and operating pressure, and system efficiency) as well as sprinkler variables (diameter, space from the pivot point, type, wetted diameter, elevation height, and application pattern shape) was incorporated in the suggested model. The suggested approach has a lot of potential for increasing the performance of the system and, as a result, increasing the quantity and quality of agricultural products. The study's most interesting finding is that applying a genetic algorithm for design optimization based on nozzle size enhances water application uniformity by more than 19% in terms of the CUH, whilst using nozzle space would help to improve CUH values by more than 17%.

The work performed in this thesis enables advancements in sprinkler arrangement, which is available for further improvements in the performance of the center pivot system. Completion and calibration of this optimized model will enable us in the future, the verification of the obtained results when using another uniformity coefficient such as the Distribution Uniformity, which may be used in a wide range of applications. In addition, this optimized model may integrate other compatible optimizing procedures to minimize the cost and enhance the performance of the system based on different factors such as reducing the inlet flow rate and evaluating different types of sprinklers. Future work must focus well on studying the effectiveness of various types of algorithms used in optimization methods to improve the performance of the center pivot system.

PERSPECTIVE AND RECOMMENDATIONS

Many factors, like the potential to augment water application rate, are constrained by the high initial cost and energy consumption, resulting in financial obstacles when improving the performance of a center-pivot irrigation system. As a result, strategies for sizing and dimensioning nozzles of existing or new systems under specific conditions should be very advantageous to cope with the challenge and should be a reliable uniformity enhancement strategy for use in sprinkler irrigation methods.

More reliable equipment such as the use of a water flow meter and a recording rain gauge that incorporates an apparatus for continually recording the depth of water using pluviometry data represented graphically (pluviography) should be used in assessing the uniformity under the center-pivot irrigation system. The pluviography can limit physical work, and time (movement between measuring devices), and allow the observation of other phenomena which could give significant information.

The system must be designed with a high level of efficiency in consideration, to keep the total application water within the desired uniformity limits (more than 85 %). The nozzle discharge should be tested individually and stationary to make these tests compared to each other and directly transportable to the case of the system in motion. However, such detailed tests are necessary to push further the analysis to improve the quality of crops as a function of nozzles spacing. Moreover, low-pressure nozzles should be often chosen to reduce the TDH at the minimum level possible.

The wind speed decreases during the night, especially in desert areas. This can strongly affect the irrigation process day and night. Therefore, it is advisable to water a given area at night when the previous irrigation was done during the day and vice versa, which, generally improve the coefficient of uniformity. In addition, it should utilize a filter that allows the fluid to pass through but keeps the solid particles to ensure regular clean water is sprayed through every nozzle in which solid particles in a liquid are removed.

The performance of a center-pivot system can be assessed for each year of historical weather data, or only one simulation may be performed by giving expected climatic variables based on previous data analysis. The model does not currently include data treatment for predicting climatic variables using probability distributions. Induction of such models, on the other hand, should enhance the developed model's performance or facility of use, and hence adaptation. As a result, more work in this field might be performed to ensure effective models that predict the concerned climate variables based on historical data analysis.

REFERENCES

REFERENCES

[1] A. O. Rebai, T. Hartani, M. N. Chabaca, and M. Kuper, "Une innovation incrémentielle: la conception et la diffusion d'un pivot d'irrigation artisanal dans le Souf (Sahara algérien)," *Cahiers Agricultures,* vol. 26, no. 3, p. 35005, 2017.

[2] G. Baiamonte, G. Provenzano, M. Iovino, and M. Elfahl, "Hydraulic Design of the Center-Pivot Irrigation System for Gradually Decreasing Sprinkler Spacing," *Journal of Irrigation and Drainage Engineering,* vol. 147, no. 7, p. 04021027, 2021.

[3] M. Valín, M. Cameira, P. Teodoro, and L. Pereira, "DEPIVOT: A model for center-pivot design and evaluation," *Computers and electronics in agriculture,* vol. 87, pp. 159-170, 2012.

[4] J. Roupec, "Advanced genetic algorithms for engineering design problems," *Engineering Mechanics,* vol. 17, no. 5-6, pp. 407-417, 2011.

[5] T. Zhang, Y. Liu, Y. Rao, X. Li, and Q. Zhao, "Optimal design of building environment with hybrid genetic algorithm, artificial neural network, multivariate regression analysis and fuzzy logic controller," *Building and Environment,* vol. 175, p. 106810, 2020.

[6] J. Ferdyn-Grygierek and K. Grygierek, "Multi-variable optimization of building thermal design using genetic algorithms," *Energies,* vol. 10, no. 10, p. 1570, 2017.

[7] H. Leyva, J. Bojórquez, E. Bojórquez, A. Reyes-Salazar, J. Carrillo, and F. López-Almansa, "Multi-objective seismic design of BRBs-reinforced concrete buildings using genetic algorithms," *Structural and Multidisciplinary Optimization,* pp. 1-16, 2021.

[8] Q. Tu, X. Wang, and H. Li, "Optimization of sprinkler irrigation machine based on Genetic Algorithms," in *2012 Dallas, Texas, July 29-August 1, 2012*, 2012: American Society of Agricultural and Biological Engineers, p. 1.

[9] R. Delirhasannia, A. Sadraddini, A. Nazemi, D. Farsadizadeh, and E. Playán, "Dynamic model for water application using centre pivot irrigation," *Biosystems engineering,* vol. 105, no. 4, pp. 476-485, 2010.

[10] W. R. Walker, *Guidelines for designing and evaluating surface irrigation systems*. Rome: Food and Agriculture Organization of the United Nations (in English), 1989.

[11] J. K. a. D. M. Richard G. Allen, P. Clarence Prestwich, CAIS, CID, USDA-NRCS, P. Wendell E Dorsett, and I. r. Valmont Industries, Eds. *Center Pivot Design*, 2nd Edition ed. 6540 Arlington Boulevard Falls Church, VA 22042-6638703.536.7080: Irrigation Association, September 2011, p. 311.

[12] W. Splinter, "Address to a meeting of the Society of Automotive Engineers," *Irrigation Journal,* vol. 29, no. 5, p. 42, 1979.

[13] B. Boman *et al.*, "Efficiencies of Florida agricultural irrigation systems," *Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, Univ. of Florida, Gainesville, FL*, 1991.

[14] M. Al-Jamal, S. Ball, and T. Sammis, "Comparison of sprinkler, trickle and furrow irrigation efficiencies for onion production," *Agricultural water management*, vol. 46, no. 3, pp. 253-266, 2001.

[15] A. Hamdy, "Water use efficiency in irrigated agriculture: an analytical review," *Water use efficiency and water productivity: WASAMED project*, pp. 9-19, 2007.

[16] S. Rad *et al.*, "Sustainable water resources using corner pivot lateral, a novel sprinkler irrigation system layout for small scale farms," *Applied Sciences*, vol. 8, no. 12, p. 2601, 2018.

[17] "Center Pivot Irrigation Systems Market Analysis Report 2016-2023," 2016. [Online]. Available: http://www.decisiondatabases.com/contact/download-sample-10234

[18] R. J. Edling, "Variation of center pivot operation with field slope," *Transactions of the ASAE*, vol. 22, no. 5, pp. 1039-1043, 1979.

[19] S.-T. Chu, "Pumping energy reduction by modified cost analysis," *Journal of the Irrigation and Drainage Division*, vol. 106, no. 2, pp. 149-154, 1980.

[20] D. L. Martin, W. L. Kranz, T. Smith, S. Irmak, C. A. Burr, and R. E. Yoder, *Center pivot irrigation handbook*. University of Nebraska-Lincoln, Extension, 2017.

[21] J. D. Valiantzas and N. Dercas, "Economic design of center-pivot sprinkler laterals," *Journal of irrigation and drainage engineering*, vol. 130, no. 6, pp. 491-498, 2004.

[22] J. D. Valiantzas and N. Dercas, "Hydraulic analysis of multidiameter center-pivot sprinkler laterals," *Journal of irrigation and drainage engineering*, vol. 131, no. 2, pp. 137-146, 2005.

[23] S. T. Chu, "Center Pivot Irrigation Design," *Agricultural Experiment Station Technical Bulletins*, vol. 61, 1980, doi: http://openprairie.sdstate.edu/agexperimentsta_tb/61.

[24] S. T. a. A. Petersen, *SPRINKLER SYSTEM DESIGN*. British Columbia, Ministry of Agriculture, 2014.

[25] I. Seginer, "Water distribution from medium pressure sprinklers," *Journal of the Irrigation and Drainage Division*, vol. 89, no. 2, pp. 13-30, 1963.

[26] NELSON, *water application solutions for CENTER PIVOT IRRIGATION* (sprinkler technology). Copyright © 2005 Nelson Irrigation Corporation.

[27] D. C. Kincaid, "APPLICATION RATES FROM CENTER PIVOT IRRIGATION WITH CURRENT SPRINKLER TYPES," *Applied Engineering in Agriculture*, vol. 21, no. 4, pp. 605-610, 2005, doi: https://doi.org/10.13031/2013.18570.

[28] J. Jiao, Y. Wang, L. Han, and D. Su, "Comparison of Water Distribution Characteristics for Two Kinds of Sprinklers Used for Center Pivot Irrigation Systems," *Applied Sciences*, vol. 7, no. 4, p. 421, 2017. [Online]. Available: https://www.mdpi.com/2076-3417/7/4/421.

[29] H. Yan, H. Jin, and Y. Qian, "Characterizing center pivot irrigation with fixed spray plate sprinklers," *Science China Technological Sciences*, vol. 53, no. 5, pp. 1398-1405, 2010.

[30] D. L. Martin, W. L. Kranz, A. L. Thompson, and H. Liang, "Selecting sprinkler packages for center pivots," *Transactions of the ASABE*, vol. 55, no. 2, pp. 513-523, 2012.

[31] B. A. King and D. C. Kincaid, "Optimal performance from center pivot sprinkler systems," 1997.

[32] H. Yan, P. Yao, Y. Zhu, and P. Yu, "Nozzle configuration and software for center pivot irrigation system," *Nongye Jixie Xuebao= Transactions of the Chinese Society for Agricultural Machinery*, vol. 42, no. 6, pp. 84-88, 2011.

[33] H. Al-Sayim and A. Saeed, "A software tool for appropriate design of center pivot irrigation system," *Sudan Journal of Agricultural Research (Sudan)*, 2011.

[34] M. D. Dukes and C. Perry, "Uniformity testing of variable-rate center pivot irrigation control systems," *Precision Agriculture*, vol. 7, no. 3, p. 205, 2006.

[35] R. D. Bliesner and J. Keller, *Sprinkle and trickle irrigation*. New York, N.Y.: Van Nostrand Reinhold (in English), 1990.

[36] R. Von Bernuth, "Nozzling considerations for center pivots with end guns," *Transactions of the ASAE*, vol. 26, no. 2, pp. 419-0422, 1983.

[37] G. Prado, A. Colombo, and A. C. Barreto, "Water distribution model for center pivot end gun sprinklers," *Revista Brasileira de Engenharia Agrícola e Ambiental*, vol. 23, no. 7, pp. 477-483, 2019.

[38] J. a. R. Shae, "Center Pivot Irrigation Design," *Washington, DC: Natural Resources Conservation Service (NRCS)*, 2009. [Online]. Available: http://irrigationtoolbox.com/Powerpoints/Chapter2/CenterPivotIrrigationDesign.ppt.

[39] J. A. Genovia *et al.*, "WATER ABSORPTION OF SOIL APPARATUS."

[40] L. D. Baver, W. H. Gardner, and W. R. Gardner, *Soil physics* (no. 04; S592. 3, B38 1972.). Wiley New York, 1972.

[41] A. M. M. Amer, "Drainable and water-filled pores as related to water storage and conductivity in agricultural soils of the Nile Delta," *Internationale Vereinigung für theoretische und angewandte Limnologie: Verhandlungen*, vol. 28, no. 4, pp. 1912-1919, 2002.

[42] D. DeFrancesco and R. Baker, "Landscape Watering by the Numbers," ed: Np: Park & Co, 2008.

[43] H. J. Schenk and R. B. Jackson, "The global biogeography of roots," *Ecological monographs*, vol. 72, no. 3, pp. 311-328, 2002.

[44] C. Brouwer and M. Heibloem, *Irrigation water management: irrigation water needs* (Training manual, no. Training manual no. 3). 00100 Rome, Italy: Food and Agriculture Organization of the United Nations, 1986.

[45] P. Ed Butts, CPI, "IRRIGATION FUNDAMENTALS Part 7, Sprinkler Systems, Center Pivots, and Linears," *Water Well Journal WWJ,* vol. 73, No.11, no. ENGINEERING YOUR BUSINESS, November 2019.

[46] V. Buono Silva Baptista, A. Colombo, B. D. Barbosa, L. A. Alvarenga, and A. Valentim Diotto, "Pressure Distribution on Center Pivot Lateral Lines: Analytical Models Compared to EPANET 2.0," *Journal of Irrigation and Drainage Engineering*, vol. 146, no. 8, p. 04020025, 2020.

[47] T. Howell, "Water loss comparison of sprinkler packages," in *15th annual Central Plains Irrigation Conference and Exposition proceedings, February 4-5, 2003, Colby, Kansas*, 2003: Colorado State University. Libraries.

[48] O. E. Turgut, M. Asker, and M. T. Coban, "A review of non iterative friction factor correlations for the calculation of pressure drop in pipes," *Bitlis Eren University Journal of Science and Technology,* vol. 4, no. 1, pp. 1-8, 2014.

[49] T. F. Scherer, W. Kranz, D. Pfost, H. Werner, J. Wright, and C.D. Yonts, L. Miller, Ed. *Sprinkler Irrigation Systems. MWPS-30*, First Edition ed. 1999, p. 250.

[50] M. E. Jensen, "Design and operation of farm irrigation systems," American Society of agricultural engineers, 1980.

[51] Y. Fukui, K. Nakanishi, and S. Okamura, "Computer evaluation of sprinkler irrigation uniformity," *Irrigation Science*, vol. 2, no. 1, pp. 23-32, 1980.

[52] D. Heermann, G. Buchleiter, and K. Stahl, "Effect of application pattern shape on center pivot irrigation uniformity," in *Irrigation Technical Conf. Proceedings*, 1999, pp. 69-76.

[53] I. Seginer, "Spatial water distribution in sprinkle irrigation," in *Advances in irrigation*, vol. 4: Elsevier, 1987, pp. 119-168.

[54] L. Lianhao, Z. Xinyue, Q. Xiaodong, and L. Guiming, "Analysis of the decrease of center pivot sprinkling system uniformity and its impact on maize yield," *International Journal of Agricultural and Biological Engineering*, vol. 9, no. 5, pp. 108-119, 2016.

[55] M. Omary, C. Camp, and E. Sadler, "Center pivot irrigation system modification to provide variable water application depths," *Applied Engineering in Agriculture,* vol. 13, no. 2, pp. 235-239, 1997.

[56] M. W. Bittinger and R. A. Longenbaugh, "Theoretical Distribution of Water from A Moving Irrigation Sprinkler," *Transactions of the ASAE,* vol. 5, no. 1, pp. 26-0030, 1962, doi: https://doi.org/10.13031/2013.40926.

[57] D. F. Heermann and P. R. Hein, "Performance Characteristics of Self-Propelled Center-Pivot Sprinkler Irrigation System," *Transactions of the ASAE*, vol. 11, no. 1, pp. 11-0015, 1968, doi: https://doi.org/10.13031/2013.39320.

[58] I. Seginer, "A note on the economic significance of uniform water application," *Irrigation Science*, vol. 1, no. 1, pp. 19-25, 1978/08/01 1978, doi: 10.1007/BF00269004.

[59] D. Chen and W. W. Wallender, "Economic Sprinkler Selection, Spacing, and Orientation," *Transactions of the ASAE*, vol. 27, no. 3, pp. 737-0743, 1984, doi: https://doi.org/10.13031/2013.32863.

[60] R. Chen, H. Li, J. Wang, and C. Chen, "Effects of Plate Structure and Nozzle Diameter on Hydraulic Performance of Fixed Spray Plate Sprinklers at Low Working Pressures," *Transactions of the ASABE*, vol. 64, no. 1, pp. 231-242, 2021, doi: https://doi.org/10.13031/trans.13958.

[61] J. E. Christiansen, "Irrigation by sprinkling," (in English), 1942. [Online]. Available: http://catalog.hathitrust.org/api/volumes/oclc/13311662.html.

[62] L. New and G. Fipps, "Center Pivot Irrigation," 01/01 1976.

[63] S. Lecina, R. W. Hill, and J. B. Barker, "Irrigation uniformity under different socio-economic conditions: evaluation of centre pivots in Aragon (Spain) and Utah (USA)," *Irrigation and Drainage*, vol. 65, no. 4, pp. 549-558, 2016, doi: https://doi.org/10.1002/ird.2031.

[64] *— Agricultural irrigation equipment — Centre-pivot and moving lateral irrigation machines with sprayer or sprinkler nozzles — Determination of uniformity of water distribution*, I. 11545, 2009. [Online]. Available: https://www.iso.org/standard/45543.html

[65] B. King, R. Dungan, and D. Bjorneberg, "Evaluation of center pivot sprinkler wind drift and evaporation loss," in *2012 Dallas, Texas, July 29-August 1, 2012*, 2012: American Society of Agricultural and Biological Engineers, p. 1.

[66] D. L. Martin, D. C. Kincaid, and W. M. Lyle, "Chapter 16. Design and Operation of Sprinkler Systems," pp. 557-631, 2007, doi: https://doi.org/10.13031/2013.23699.

[67] X.-S. Yang, "Chapter 1 - Introduction to Algorithms," in *Nature-Inspired Optimization Algorithms (Second Edition)*, X.-S. Yang Ed.: Academic Press, 2021, pp. 1-22.

[68] Z. Michalewicz, *Genetic algorithms+ data structures= evolution programs*. Springer Science & Business Media, 2013.

[69] A. Zhigljavsky and A. Zilinskas, *Stochastic global optimization*. Springer Science & Business Media, 2007.

[70] M. Saraswat and A. Sharma, "Genetic Algorithm for optimization using MATLAB," *International Journal of Advanced Research in Computer Science*, vol. 4, no. 3, pp. 155-159, 2013.

[71] A. El-Zahaby, A. EL-Nashar, and B. Abd EL-Rahman, "OPTIMIZATION OF DEVELOPED IRRIGATION SYSTEM NETWORK USING GENETIC ALGORITHMS.(Dept. M.(Power))," *Bulletin of the Faculty of Engineering. Mansoura University*, vol. 39, no. 1, pp. 8-22, 2020.

[72] N. Canpolat, *Optimization of seasonal irrigation scheduling by genetic algorithms*. Oregon State University, 1997.

[73] M. Moradi-Jalal, S. I. Rodin, and M. A. Mariño, "Use of genetic algorithm in optimization of irrigation pumping stations," *Journal of irrigation and drainage engineering*, vol. 130, no. 5, pp. 357-365, 2004.

[74] S. Yuan, B. Hu, X. Wang, X. Zhu, and Q. Tu, "Optimum configuration and performance experiment of sprinkler-drip dual-purpose irrigation machine," *Transactions of the Chinese Society of Agricultural Engineering*, vol. 30, no. 3, pp. 56-62, 2014.

[75] M. S. Pais, J. C. Ferreira, M. B. Teixeira, K. Yamanaka, and G. A. Carrijo, "Cost optimization of a localized irrigation system using genetic algorithms," in *International Conference on Intelligent Data Engineering and Automated Learning*, 2010: Springer, pp. 29-36.

[76] A. O. de Albuquerque *et al.*, "Deep semantic segmentation of center pivot irrigation systems from remotely sensed data," *Remote Sensing*, vol. 12, no. 13, p. 2159, 2020.

[77] L. Hassan-Esfahani, A. Torres-Rua, and M. McKee, "Assessment of optimal irrigation water allocation for pressurized irrigation system using water balance approach, learning machines, and remotely sensed data," *Agricultural Water Management*, vol. 153, pp. 42-50, 2015/05/01/ 2015, doi: https://doi.org/10.1016/j.agwat.2015.02.005.

[78] M. Á. Pardo, A. J. Riquelme, A. Jodar-Abellan, and J. Melgarejo, "Water and energy demand management in pressurized irrigation networks," *Water*, vol. 12, no. 7, p. 1878, 2020.

[79] L. Hassan Esfahani and M. McKee, "Optimal irrigation water allocation for a center pivot using remotely sensed data," in *AGU Fall Meeting Abstracts*, 2013, vol. 2013, pp. H41Q-04.

[80] M. S. Hadji, A. Guerrah, and A. Atia, "IRRIGATION UNIFORMITY OPTIMISATION OF A MINI-CENTRE PIVOT SYSTEM," *Engenharia Agrícola*, vol. 41, pp. 526-535, 2021.

[81] C. O. Robles Rovelo, N. Zapata Ruiz, J. Burguete Tolosa, J. R. Félix Félix, and B. Latorre, "Characterization and simulation of a low-pressure rotator spray plate sprinkler used in center pivot irrigation systems," *Water*, vol. 11, no. 8, p. 1684, 2019.

[82] L. ZELLA, *L'IRRIGATION PAR ASPERSION*, OPU 5430 ed. 2017, p. 144.

[83] A. Phocaides, *Handbook on pressurized irrigation techniques*. Food & Agriculture Org., 2007.

[84] R. Hill and J. Keller, "Irrigation system selection for maximum crop profit," *Transactions of the ASAE*, vol. 23, no. 2, pp. 366-0372, 1980.

[85] I. Amir and I. Seginer, "Emitter Uniformity as an economic factor Trickle System Design," *Transactions of the ASAE*, vol. 28, no. 3, pp. 826-0831, 1985.

[86] H. M. Salah, G. Ayoub, A. Abdelmalek, and M. Khaled, "Theoretical Sprinkler-Spacing Configurations in Center Pivot Irrigation System," *Water and Energy International,* vol. 62, no. 9, pp. 54-59, 2019.

[87] Y. Li, X. Hui, H. Yan, and D. Chen, "Effects of Travel Speed and Collector on Evaluation of the Water Application Uniformity of a Center Pivot Irrigation System," *Water,* vol. 12, no. 7, p. 1916, 2020.

[88] D. W. Coit, "Genetic algorithms and engineering design," *The Engineering Economist,* vol. 43, no. 4, p. 379, 1998.

[89] M. Olivero, D. Pasquale, A. Ghidoni, and S. Rebay, "Three-dimensional turbulent optimization of vaned diffusers for centrifugal compressors based on metamodel-assisted genetic algorithms," *Optimization and Engineering,* vol. 15, no. 4, pp. 973-992, 2014.

[90] H. M. Salah, A. Guerrah, and A. Atia, "Optimal Sprinkler Spacing for a Mini Center Pivot System," *Journal of Irrigation and Drainage Engineering,* vol. 148, no. 11, p. 04022042, 2022, doi: doi:10.1061/(ASCE)IR.1943-4774.0001715.

[91] M. Saraswat, "Genetic Algorithm for optimization using MATLAB," *International Journal of Advanced Research in Computer Science,* vol. 4, no. 3, 2013.

[92] B. Bremond and B. Molle, "Characterization of rainfall under center pivot: influence of measuring procedure," *Journal of irrigation and drainage engineering,* vol. 121, no. 5, pp. 347-353, 1995.

ANNEXES

ANNEXE A

MEASUREMENT TOOLS

THE WATER PRESSURE GAUGE

A pressure gauge measures water pressure and tests water flow in water systems. Too much water pressure damages plumbing pipes and appliances. However, the measurement of pressure in key points of a network is of major importance for water system operators. The pressure gauge should be installed in easily accessible places so that it is convenient to read and to maintain in proper working condition. The most common pressure gauge used in water supply and distribution services is highlighted in Figure A.1.

Figure A.1: Displays the water pressure gauge, with a range of 0 to 30 PSI.

A pressure gauge is a mechanical instrument designed to measure the internal pressure and/or vacuum of a vessel or system. The pressure gauges are offered in a variety of styles, sizes, and wetted part materials to meet the demands of standard and special applications. Most of the pressure gauges are constructed with a bourdon tube sensing element. When the sensing element is subjected to pressure, it flexes and the resulting motion is transmitted as a measurement through a mechanical movement to the dial face pointer. Figure A.2 shows the principle pressure gauge parts.

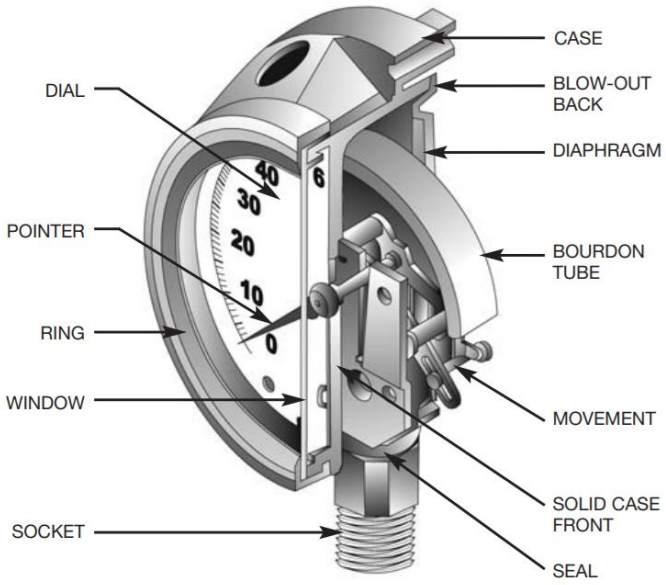

Figure A.2: Shows the water pressure gauge parts.

Under normal operating conditions, only the tube and socket assembly (Wetted Parts) of a pressure gauge will contact with the fluid being measured (Pressure Medium). The selection of the assembly will be determined by the composition of the medium. A bronze or brass bourdon tube and brass socket assembly usually satisfy air, gas, steam, water, and other non-corrosive media. Stainless steel or Monel wetted parts are used when the medium contains corrosive elements or when high operating pressures or temperatures will be encountered. A diaphragm seal is recommended for highly corrosive media or that which may solidify or deposit solids within the tube and socket assembly of the gauge.

The socket connection provides an entrance port for the process medium as well as a means to mount the gauge to a pipeline or vessel. Male connections can be provided with NPT, BSPT, or other thread styles, in sizes from 1/8" through 1/2". A high-pressure, 9/16" LHT connection is also available. The mounting location indicates where the connection protrudes from the case.

The accuracy of a pressure gauge is expressed as a percentage (plus or minus) of the maximum scale range. Please refer to Pressure Gauge Standard ASME B40.100.

The maximum operating pressure of the application should not exceed 75% of the measurement range selected. Therefore, the specified range should be twice the normal operating point of the gauge to avoid damage to the gauge internals. A wide variety of measurement ranges is available, from 30" Hg vacuum through 20,000-psi pressure. Frequently, ranges are indelibly presented in black figures and markings upon a white dial face.

Pressure gauge selection will be influenced by the environmental conditions under which the gauge is expected to perform. Condensation or waterproofing concerns can be addressed through the use of hermetically sealed or weatherproofed gauges. Case construction should be considered when selecting a gauge to be used in conditions of extreme or sustained heat or cold, or where the atmospheric environment may contain corrosive elements.

Liquid filling (glycerin, silicone, or other fills) can prolong the life of a pressure gauge by minimizing wear on the gauge internal resulting from vibration or oscillation. The liquid filling also acts as a permanent lubricant for the moving parts of the instrument.

WIND VELOCITY AND ANEMOMETER

Wind speed is classified into instantaneous and average types. The average wind speed is the average of the instantaneous wind speed over ten minutes. However, wind speed fluctuates continuously, and measured values of instantaneous wind speed are affected by anemometer response characteristics. Defined below are some basic terms and units used in wind measurement, with a focus on those related to response characteristics that affect anemometer performance.

Several different units are used to indicate wind speed, including meters per second (m/s), kilometers per hour (km/h), miles per hour (mph), feet per second (ft/s), and knots (kt). In synoptic reports, the average wind speed measured over 10 minutes is reported every 0.5 meters per second (m/s) or in knots (kt). The wind is described in terms of the direction from which it blows and is given as compass point expressions graduated into 8 or 16 directions clockwise from true north (Figure A.3).

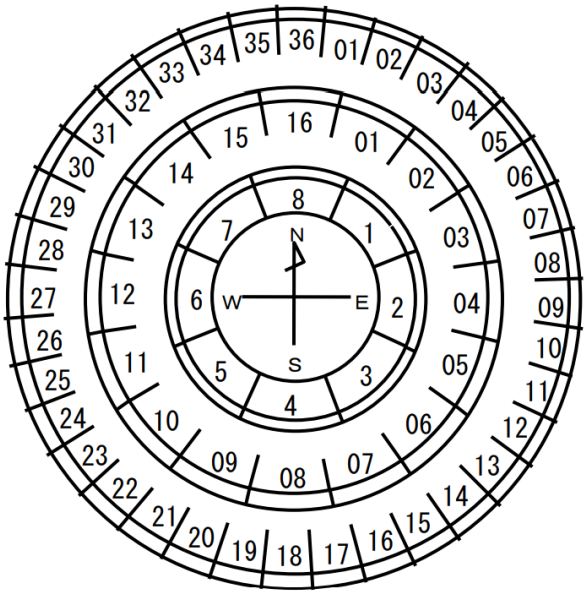

Figure A.3: Shows the wind-direction scale.

An anemometer is a device for measuring wind speed and is a common weather station instrument. The term is derived from the Greek word anemos, meaning wind. Leon Battista Alberti gave the first known description of an anemometer around 1450. Anemometers can be divided into two classes: those that measure the wind's speed, and those that measure the wind's pressure, but as there is a close connection between the pressure and the speed, an anemometer is designed for one will give information about both (see Figure A.4).

The most commonly used anemometer is the cup-type and the different types of anemometers are indicated as follows:

Cup anemometers, windmill anemometers, Hot-wire anemometers, Laser Doppler anemometers, sonic anemometers, and Ping-pong ball anemometers are wind speed anemometers.

Plate anemometers and tube anemometers are wind pressure anemometers.

Figure A.4: Displays a digital indicator wind speed gauge.

Meteorologists, to study whether conditions, mostly use this instrument. The physicists also this device to know the direction of airflow. It is generally called a meteorological instrument or wind speed meter. Worldwide researchers, physicists, meteorologists, and educational institutions use this instrument to measure the speed, velocity, direction, and pressure of the wind.

The anemometer working principle is simple and there no change since 1846. It works on the principle of converting mechanical energy into electrical energy as the tachometer does. Therefore, a tachometer converts the mechanical energy into corresponding electrical pulses to monitor the speed of the motor

digitally. In the same way, the digital type is also an electromechanical device that works on the same principle.

THE CATCH CAN TEST

A catch cans test is only one of the tests we perform when we conduct a water audit. Many Superintendents and Grounds Managers have the misconception that a water audit consists solely of performing a catch-can test. Some think an inventory audit is part of a water audit. An audit can include many elements and is subjective so it is important to understand what specific services an auditor is offering. If you are looking only for the catch can tests then have a specific reason for that service only? A catch-can test can serve several purposes including:

- ✓ Establishment of a Heermann and Hein uniformity coefficient (CUH) baseline for future comparison or budgeting upgrades
- ✓ Comparison of old conversions and sprinklers compared to completely new conversions or sprinklers
- ✓ Comparison of different manufacturers' sprinklers
- ✓ Comparison of different nozzles and sprinkler pressure settings
- ✓ Develop run times and irrigation schedules
- ✓ Compare system performance in different areas of the golf course.

All collectors used for a test shall be identical and shaped such that water does not splash in or out. The lip of the collector shall be symmetric and without depressions. The height of each collector shall be at least twice the maximum depth of the water collected during the test, but not less than 150 mm. It shall have a circular opening with sharp edges free from deformities. The diameter shall be at least half the height, but shall not be less than 85 mm. To minimize measurement error, it is recommended that testers use collectors that are as large as practicable. Figure A.5 shows the type of collectors used for the experimental tests.

Figure A.5: Highlights the collector utilized to determine water distribution in the Mini-Centre Pivot Systems tested.

ANNEXE B

THE DETAILS OF THE CURVES

Table B.1 correspond to the Figure IV.31 that shows the pluviometry recordings of the investigated systems.

Traditional Pivot			**ANABIB Pivot**		
X	Plyviometry line 1	Plyviometry line 2	**X**	Plyviometry line 1	Plyviometry line 2
2	73	73	**12**	29,7	28,4
4	72	73	**24**	29	28,2
6	70	65	**36**	28,4	27,3
8	56,5	54,5	**48**	27,7	27,1
10	47	37	**60**	27,2	26,3
12	35	36	**72**	26,8	26,7
14	34	31	**84**	26,5	26,2
16	27	24	**96**	26,5	26
18	18,7	18,8	**108**	26,4	24,9
20	10,5	14,2	**120**	25,9	26,9
22	16,1	16,5	**132**	26,1	25,5
24	9,5	17,7	**144**	26	26,2
26	13,5	18,4	**156**	25,1	27
28	14,5	15	**168**	25,6	26,4
30	14,5	18	**180**	25,3	26
32	10,2	15,4	**192**	26	26,3
34	12	15	**204**	25,7	26,6
36	14,5	18	**216**	26,4	26
38	11,5	14,3	**228**	26	25,8
40	9	12	**240**	25,6	25,3
42	9	11	**252**	25,4	26
44	7,7	11	**264**	25,4	25,7
46	13	16,5	**276**	25,1	25,4
48	15,7	20	**288**	24,8	25,3
50	12	12,5	**300**	24,1	25,2
			312	23,2	25,1
			324	21	23,3

Table B.2 correspond to the Figure IV.32, which indicates the pressure distribution along the lateral of the investigated systems.

Traditional Pivot		**ANABIB Pivot**	
X	Pression en (bar)	**X**	Pression en (bar)
3,4	1,1	**12**	1,37
6,6	1,05	**24**	1,358
9,6	1,02	**36**	1,346
12,5	1	**48**	1,333
15,5	0,95	**60**	1,323
18,5	0,95	**72**	1,312
21,6	0,91	**84**	1,302
24,25	0,82	**96**	1,291
27,1	0,81	**104**	1,28
29,75	0,8	**110**	1,275
32,55	0,8	**116**	1,269
35,3	0,8	**122**	1,263
37,6	0,8	**128**	1,255
40,2	0,81	**134**	1,249
42,8	0,81	**140**	1,241
45,1	0,813	**146**	1,234
47,4	0,819	**152**	1,229
47,85	0,82	**158**	1,224
48,35	0,82	**164**	1,219
49,45	0,82	**170**	1,213
		176	1,207
		182	1,2
		188	1,195
		194	1,189
		200	1,183
		206	1,178
		212	1,173
		218	1,166
		224	1,16
		230	1,155
		236	1,15
		242	1,145
		248	1,139
		254	1,132
		260	1,128
		266	1,122
		272	1,117
		278	1,11
		284	1,105
		290	1,101
		296	1,096
		302	1,09
		308	1,081
		314	1,075
		320	1,067
		323	1,061

Table B.3 correspond to the Figure IV.33 that highlights the flow rate distribution along with the investigated systems.

Traditional Pivot		**ANABIB Pivot**	
X	Début en (L/S)	**X**	Début en (L/S)
3,4	0,52	**12**	1,103
6,6	0,37	**24**	1,097
9,6	0,35	**36**	1,093
12,5	0,33	**48**	1,089
15,5	0,32	**60**	1,082
18,5	0,3	**72**	1,076
21,6	0,295	**84**	1,071
24,25	0,3	**96**	1,065
27,1	0,295	**104**	1,061
29,75	0,29	**110**	1,058
32,55	0,285	**116**	1,054
35,3	0,285	**122**	1,048
37,6	0,28	**128**	1,037
40,2	0,27	**134**	1,032
42,8	0,265	**140**	1,027
45,1	0,26	**146**	1,021
47,4	0,26	**152**	1,015
47,85	0,255	**158**	1,006
48,35	0,255	**164**	1,001
49,45	0,25	**170**	0,996
		176	0,991
		182	0,988
		188	0,983
		194	0,977
		200	0,972
		206	0,966
		212	0,961
		218	0,957
		224	0,951
		230	0,946
		236	0,941
		242	0,935
		248	0,931
		254	0,926
		260	0,922
		266	0,919
		272	0,915
		278	0,913
		284	0,909
		290	0,905
		296	0,9
		302	0,894
		308	0,89
		314	0,884
		320	0,88
		323	0,876

Table B.4 correspond to the Figure V.43 that presents the optimum nozzle sizes of the Mini-Centre Pivot Systems investigated.

Nozzle Number	Pivot 60m		Pivot 50m		Pivot 46m	
	Xi Actual	Optimized Diameter	Xi Actual	Optimized Diameter	Xi Actual	Optimized Diameter
Noz.1	3,5	5,0	3,0	5,4	4,1	6,5
Noz.2	8	5,3	7,0	5,8	7,5	6,9
Noz.3	12,3	5,5	10,0	6,2	10,8	7,2
Noz.4	16,4	5,8	13,0	6,5	14,0	7,6
Noz.5	20,3	6,2	16,0	6,9	17,1	8,0
Noz.6	24	6,5	19,0	7,2	20,1	8,4
Noz.7	27,5	6,9	22,0	7,6	23,0	8,9
Noz.8	30,9	7,3	24,0	8,0	25,8	9,4
Noz.9	34	7,6	27,0	8,4	28,5	9,9
Noz.10	36,9	8,0	30,0	8,9	31,1	10,4
Noz.11	39,6	8,5	33,0	9,5	33,6	11,0
Noz.12	42,1	9,0	35,0	10,0	36,0	11,6
Noz.13	44,5	9,5	38,0	10,5	38,3	12,2
Noz.14	46,8	10,0	40,0	11,0	40,5	12,9
Noz.15	49	10,5	43,0	11,6	42,5	13,5
Noz.16	51,1	11,0	45,0	12,2	44,3	14,2
Noz.17	53,1	11,6	47,0	12,9	46,0	15,0
Noz.18	56,2	12,2	48,0	13,5		
Noz.19	58	12,9	48.5	14,3		
Noz.20	59,4	13,5	49,0	15,0		
Noz.21	60	14,2				
Noz.22	60,6	15,0				

Table B.5 correspond to the Figure V.44 that illustrates the sampling and evaluation criteria for the irrigation efficiency of the investigated Mini-Centre Pivot Systems.

Number of collector	Measured Cup Volume [Milliliters]					
	Pivot 60m		Pivot 50m		Pivot 46m	
	Actual	Optimized	Actual	Optimized	Actual	Optimized
1	93	48,7	73	48,7	95	48,7
2	61	45,6	70	30,0	130	38,8
3	53	45,0	56,5	40,0	90	36,9
4	46	52,5	47	36,0	80	44,3
5	38,2	50,9	35	42,0	76	42,1
6	36	42,0	34	32,0	19	35,1
7	32	49,1	27	38,0	25	41,2
8	31	55,9	10,5	44,0	36	46,9
9	31,5	33,4	16,1	26,0	36	28,1
10	26	34,9	9,5	28,0	27	29,3
11	17	39,2	13,5	32,0	30	33,0
12	12	40,4	14,5	33,3	47	33,9
13	14	44,4	10,2	37,3	31	37,4
14	11	45,3	12	38,0	26	38,1
15	10	49,0	11,5	42,7	22	41,4
16	13	37,1	9	32,0	28	31,4
17	12	39,4	9	35,5	35	34,8
18	12,5	39,5	7,7	34,5		
19	9	41,6	15,7	37,3		
20	10	41,5	12	38,8		
21	8	43,5				
22	10	46,3				

Table B.6 correspond to the Figure V.47, which shows the measured catch can volumes along each individual tested system for the actual (original) nozzles distribution.

	Pivot 60 m		Pivot 50 m		Pivot 46m	
Cup Number	**Cup Distance from the Pivot Point (m)**	**Experimental Measured Cup Volume**	**Cup Distance from the Pivot Point (m)**	**Experimental Measured Cup Volume**	**Cup Distance from the Pivot Point (m)**	**Experimental Measured Cup Volume**
1	2,7	93	2,5	73	2,7	95
2	5,5	61	5,0	70	5,4	130
3	8,2	53	7,5	56,5	8,1	90
4	11,0	46	10,0	47	10,8	80
5	13,7	38,2	12,5	35	13,5	76
6	16,5	36	15,0	34	16,2	19
7	19,2	32	17,5	27	18,9	25
8	22,0	31	20,0	10,5	21,6	36
9	24,8	31,5	22,5	16,1	24,4	36
10	27,5	26	25,0	9,5	27,1	27
11	30,3	17	27,5	13,5	29,8	30
12	33,0	12	30,0	14,5	32,5	47
13	35,8	14	32,5	10,2	35,2	31
14	38,6	11	35,0	12	37,9	26
15	41,3	10	37,5	11,5	40,6	22
16	44,1	13	40,0	9	43,3	28
17	46,8	12	42,5	9	46,0	35
18	49,6	12,5	45,0	7,7		
19	52,3	9	47,5	15,7		
20	55,1	10	50,0	12		
21	57,9	8				
22	60,6	10				

Table B.7 correspond to the Figure V.48, which depicts the catch can volumes at specific points under the MCPS evaluated as calculated by the model.

	Pivot 60 m		Pivot 50 m		Pivot 46m	
Cup Number	**Cup Distance from the Pivot Point (m)**	**Model Measured Cup Volume**	**Cup Distance from the Pivot Point (m)**	**Model Measured Cup Volume**	**Cup Distance from the Pivot Point (m)**	**Model Measured Cup Volume**
1	2,7	62,0	2,5	48,7	2,7	63,3
2	5,5	62,3	5,0	44,5	5,4	43,1
3	8,2	56,1	7,5	40,0	8,1	38,8
4	11,0	69,3	10,0	49,5	10,8	48,0
5	13,7	64,0	12,5	45,7	13,5	44,3
6	16,5	50,7	15,0	38,2	16,2	37,1
7	19,2	56,7	17,5	44,4	18,9	43,1
8	22,0	62,4	20,0	50,3	21,6	48,8
9	24,8	36,0	22,5	30,0	24,4	29,1
10	27,5	36,8	25,0	31,1	27,1	30,1
11	30,3	40,8	27,5	35,0	29,8	34,0
12	33,0	41,4	30,0	35,8	32,5	34,8
13	35,8	45,2	32,5	39,6	35,2	38,4
14	38,6	45,6	35,0	40,1	37,9	39,0
15	41,3	49,2	37,5	43,5	40,6	42,4
16	44,1	37,0	40,0	32,6	43,3	32,1
17	46,8	39,6	42,5	35,0	46,0	35,5
18	49,6	39,6	45,0	34,7		
19	52,3	42,0	47,5	36,9		
20	55,1	41,9	50,0	39,2		
21	57,9	44,2				
22	60,6	47,0				

Table B.8 correspond to the Figure V.50, which shows a comparison between the actual and optimized nozzles spaces of the system selected for validation.

Nozzle Number	Nelson Distance (m)	Program Distance (m)
X1	12,16	12,20
X2	17,92	17,86
X3	23,68	23,53
X4	29,44	29,19
X5	35,17	32,44
X6	40,93	38,10
X7	46,70	43,77
X8	52,46	49,43
X9	58,40	61,32
X10	64,16	66,99
X11	69,92	72,65
X12	75,65	75,90
X13	81,41	81,56
X14	87,17	87,23
X15	92,93	92,89
X16	95,80	95,72
X17	98,69	98,55
X18	101,56	101,39
X19	104,42	104,22
X20	107,32	107,05
X21	109,61	109,60

ANNEXE C

THE SCIENTIFIC PUBLICATIONS

ARTICLE 1: THEORETICAL SPRINKLER-SPACING CONFIGURATIONS IN CENTER PIVOT IRRIGATION (DECEMBER 2019)

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Theoretical Sprinkler-Spacing Configurations in Center Pivot Irrigation System

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Abstract

The objective of this article is to improve the spaces between neighbouring sprinklers that increase the quantity and quality of crops product provided by center pivot irrigation systems without a substantial investment. This study deals with three models of center pivot irrigation by changing its sprinkler's position; the first and the second are just an artisanal machines made by craftsmen in El Oued; and the third is a modern center pivot installed in a region named El Hadjira Ouargla, Both systems are examined in the southern of Algeria. Good uniformity gives more uniform production, but irregularity may water some places either more than enough or less than required, therefore it is considered as an economic loss in terms of quantity or quality. This research process was carried on the theoretical analysis of the various equations until obtaining optimum spaces between adjacent sprinklers therefore the optimum design of the nozzle plan of a center pivot system. The obtained result show good agreement between experimental and theoretical analysis of uniformity coefficient. It also depicts that Herman and Hein's uniformity coefficient has improved by changing of sprinkler-spacing configurations.

Top

Keywords

Center pivot irrigation, Nozzle, Sprinkler-spacing configurations, Theoretical analysis, Uniformity of irrigation.

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ARTICLE 2: IRRIGATION UNIFORMITY OPTIMISATION OF A MINI-CENTRE PIVOT SYSTEM (Sep. / Oct. 2021)

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IRRIGATION UNIFORMITY OPTIMISATION OF A MINI-CENTRE PIVOT SYSTEM

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KEYWORDS

genetic algorithm, mini-centre pivot, nozzle design, uniformity coefficient.

ABSTRACT

In El Oued, southern Algeria, the traditional Mini-Centre Pivot System (MCPS) is widely used for the irrigation of agricultural crops, and its use has been growing continuously. However, these systems have a constant nozzle diameter along the lateral pipe, which affects productivity directly, besides decreasing both the quantity and quality of agricultural products by irrigation heterogeneity. Therefore, optimising the design of the MCPS nozzles is linked strongly to the desired uniform irrigation. This study aims to determine the optimal configuration of nozzles for high irrigation uniformity. To achieve this goal, a genetic algorithm was used for maximising the uniformity of MCPS-mediated irrigation. The optimisation is carried out according to water distribution modelling, calculation of the Heermann and Hein uniformity coefficient (CUH), and existing nozzle diameters. To verify the accuracy of the proposed model, three existing MCPS (60 m, 50 m, and 46 m in length) are investigated experimentally. The developed code findings in terms of CUH are in agreement with those obtained by experimental tests. The analysis indicated that the nozzle diameter should vary from 5 to 15 mm along the lateral pipe. In these optimal conditions, the CUH was improved by 29.77%, 33.99%, and 19.36%, respectively, for the existing 60, 50, and 46 m irrigation systems. The most obvious findings to emerge from this study is that using a genetic algorithm to optimise the design based on the nozzle size improves water application uniformity by more than 19% in terms of the CUH.

INTRODUCTION

In a centre pivot irrigation system, the heterogeneity of water distribution or water delivery over the entire irrigated area is a challenge for improving the design of the system based on optimisation modelling. This optimisation is also necessary for many applications in precision agriculture. Furthermore, because irrigated agriculture is so important to the economy, there are long-term benefits to optimising irrigation uniformity and conserving water (Rogers et al., 2019). In recent studies, many researchers have used optimisation techniques for irrigation systems to investigate the hydraulic efficiency of these systems, as these models can consider the interaction between several parameters affecting an irrigation system, such as the atmospheric characteristics, the pump unit, the crop, and the geometry of the system.

The most commonly used irrigation method in El Oued, southern Algeria, is the traditional Mini-Centre Pivot System with more than 35,000 implementations, which represented approximately 40% of Algeria's national production of potatoes in 2015 (Rebai et al., 2017). Ben Charfi et al. (2021) created a mathematical model based on the ballistic principle on a daily and hourly basis. This model accurately estimates the water distribution pattern for one or more centre-pivot irrigation systems. The mode of spray application has a significant impact on the efficiency of sprinkler irrigation systems. Rajan et al. (2015) evaluated the features of spray application of 14 centre pivot irrigation systems located in the Texas High Plains, in the southern United States of America. These authors concluded that the centre pivots in the application of the low energy precision application (LEPA) type showed superior efficiency of

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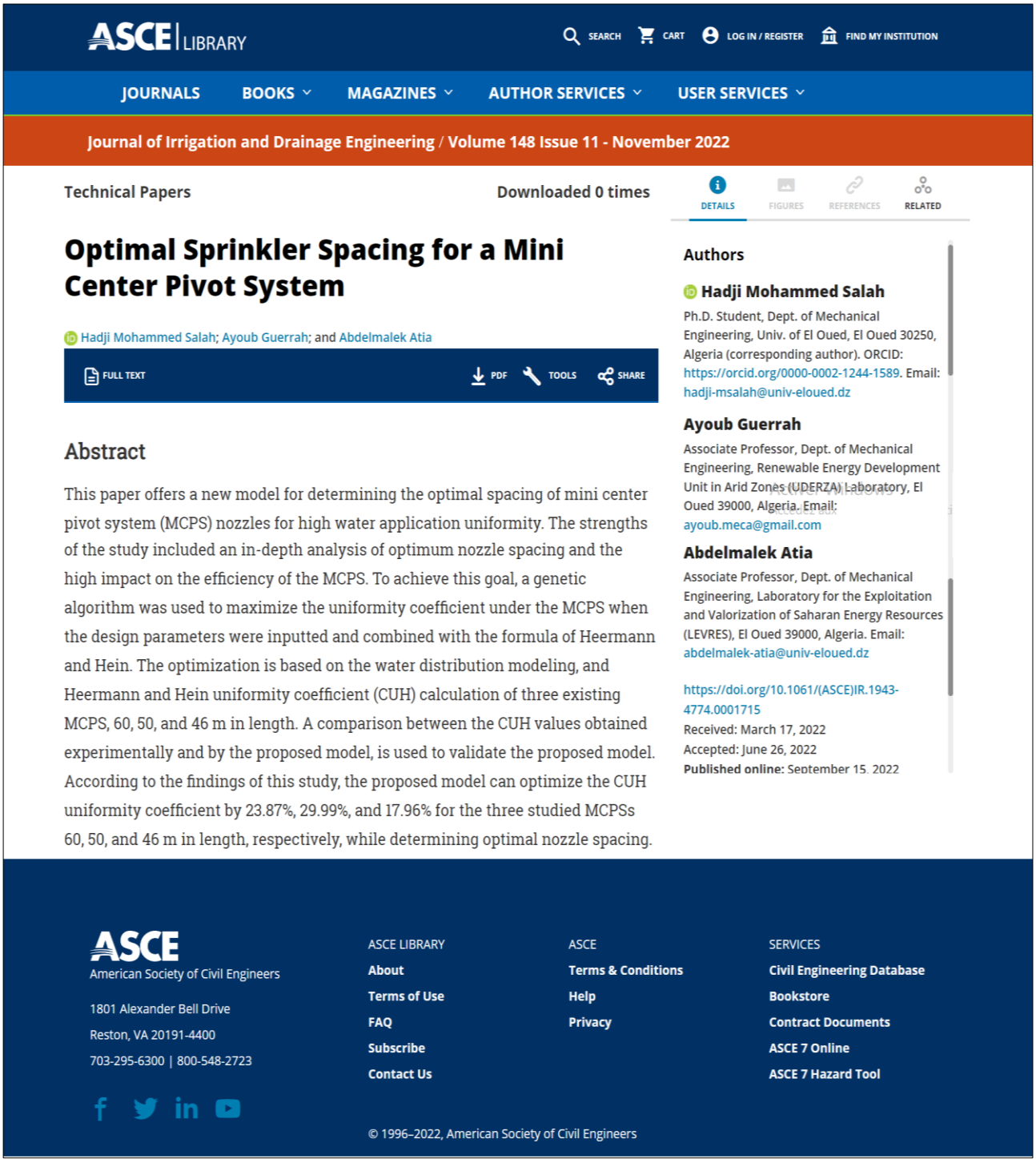
ARTICLE 3: OPTIMAL SPRINKLER SPACING FOR A MINI CENTER PIVOT SYSTEM (Submissions in Production)



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Optimal Sprinkler Spacing for a Mini Center Pivot System

Hadji Mohammed Salah; Ayoub Guerrah; and Abdelmalek Atia

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Abstract

This paper offers a new model for determining the optimal spacing of mini center pivot system (MCPS) nozzles for high water application uniformity. The strengths of the study included an in-depth analysis of optimum nozzle spacing and the high impact on the efficiency of the MCPS. To achieve this goal, a genetic algorithm was used to maximize the uniformity coefficient under the MCPS when the design parameters were inputted and combined with the formula of Heermann and Hein. The optimization is based on the water distribution modeling, and Heermann and Hein uniformity coefficient (CUH) calculation of three existing MCPS, 60, 50, and 46 m in length. A comparison between the CUH values obtained experimentally and by the proposed model, is used to validate the proposed model. According to the findings of this study, the proposed model can optimize the CUH uniformity coefficient by 23.87%, 29.99%, and 17.96% for the three studied MCPSs 60, 50, and 46 m in length, respectively, while determining optimal nozzle spacing.

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