UNIVERSIDADE FEDERAL DE LAVRAS

FIDEL LUÍS RODRIGUES TAMBO

MOVIMENTAÇÃO DISCRETA DAS TORRES DE UM PIVÔ CENTRAL E SUA APLICAÇÃO DE ÁGUA

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Prof. Dr. Luiz Antonio Lima
Orientador

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MOVIMENTAÇÃO DISCRETA DAS TORRES DE UM PIVÔ CENTRAL E SUA APLICAÇÃO DE ÁGUA

DISCRETE MOVEMENT OF A CENTER PIVOT TOWERS AND ITS WATER APPLICATION

Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Recursos Hídricos, área de concentração em Recursos Hídricos em Sistemas Agrícolas, para a obtenção do título de Doutor.

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Prof. Dr. Michael Silveira Thebaldi	UFLA
Prof. Dr. Adriano Valentim Diotto	UFLA
Prof. Dr. José Alves Junqueira Junior	IFSUDESTEMG
Prof. Dr. Lucas Alves da Silva	UFLA

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Este trabalho é dedicado

à minha família, a meus pais e irmão, em particular.

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A Deus todo Ele altíssimo e misericordioso, por tudo que sou.

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RESUMO GERAL

O movimento do pivô central é citado como sendo um dos fatores que pode afetar na uniformidade de aplicação de água, razão pela qual, neste trabalho, estudou-se a movimentação das torres de um pivô central e sua aplicação de água. Para o desenvolvimento da pesquisa, foram instalados três receptores de sinal GNSS, em três torres móveis de um pivô central, a fim de georreferenciar as posições exatas, de cada torre móvel, durante a operação do pivô central em intervalos de tempo de 3 s. Com os dados coletados pelos GNSS, foram ajustados modelos matemáticos que permitiram calcular a posição das torres por unidade de tempo ao longo do seu percurso. Esses modelos foram utilizados para desenvolver um programa computacional que possibilitou efetuar simulação de movimento das torres e determinar a efeito de ângulo de desalinhamento entre torres sobre a distribuição de lâminas e coeficiente de uniformidade. Foram também posicionados coletores, em cada vão do pivô central, em três formas de amostragem: radial, circular e malhada, com o objetivo de comparar as uniformidades de irrigação obtidas em função da forma de amostragem das lâminas. Os modelos matemáticos ajustados mostraram ser eficientes para determinar a posição das torres por unidade de tempo. Constatou-se que os tempos de parada e de movimentação das torres afetaram a distribuição de lâminas aplicadas e uniformidade de irrigação; foi observada maior variabilidade de lâminas e coeficientes de uniformidade de irrigação à medida que se aumentou o ângulo de desalinhamento entre torres. Quanto às amostragens de lâminas, a disposição de coletores radial foi estatisticamente diferente das disposições circular e malhada. Pôde-se verificar que a disposição radial apresenta maior variabilidade de lâminas, porque detecta problemas que ocorrem entre lances de emissores, além disso, a largura amostral de lâminas no sentido de movimentação das torres é curta; para disposição circular detecta problemas causados pelas irregularidades do terreno na direção de movimento do pivô, porém a largura amostral na direção de raio do pivô central é curta, fato que faz com que a sobreposição de lâminas ocorra somente na direção de movimentação do pivô central; já a disposição malhada apresentou menor variabilidade, porque os coletores são mais concentrados, o que possibilita maior sobreposição de lâminas tanto na direção do raio assim como no sentido de movimento do pivô central. Além disso, possibilitou detectar problemas causados pelo vento independentemente da sua direção.

Palavras-chave: Irrigação por aspersão. Desempenho de sistema de irrigação. Lâmina de água aplicada. Uniformidade de irrigação.

GENERAL ABSTRACT

The movement of the center pivot is referred as one factor that can affect its water application uniformity, reason for carrying out this research. Therefore, three GNSS satellite signal receivers were installed on three mobile towers of a center pivot to acquire georeferenced positions of each tower during equipment operation, every 3 seconds interval. With the collected data, mathematical models were fitted, to turn possible to calculate tower position versus time along its route. These models were used to develop a computer program to simulate the towers movement and determine the effect of the misalignment angle between spans on water depth distribution and uniformity coefficient. Collectors were positioned under each span, in three sampling forms: radial, circular and at regular mesh, with objective to compare irrigation uniformities obtained due to these different water depths sampling patterns. The fitted mathematical models proved to be efficient to determine tower position per unit of time. It was verified that the towers' stoppage and movement times affected the distribution of applied depths and irrigation uniformity; greater variability of water depths and irrigation uniformity coefficients were observed as the misalignment angle between towers increased. As for water sampling, the arrangement of radial collectors was statistically different from the circular and mesh. It was possible to verify that the radial arrangement presents greater water depth variability, as it detects problems that occur between sets of emitters; in addition, the width of the sampling area along the towers direction movement is short; circular pattern can detects problems caused by terrain irregularities in the system's movement direction, but the width of sampling area at the direction of radius is also short, a fact that causes the overlapping of water depths to occur only at direction of movement; the mesh arrangement, on the other hand, showed less variability because the collectors are more concentrated, which allows greater water depth overlapping, both along the direction of radius as well as at the movement direction. In addition, this sampling pattern made it possible to detect problems caused by the wind regardless its direction.

Keywords: Irrigation systems performance. Sprinkler irrigation. Applied water depth. Irrigation uniformity.

SUMÁRIO

PRIMEIRA PARTE

1 INTRODUÇÃO GERAL

Mesmo sendo responsável pelo incremento de produtividade e qualidade da produção agrícola, o consumo de água pela agricultura irrigada é tema de ampla discussão no âmbito da gestão de recursos hídricos. Sendo assim, deve-se buscar, na ótica da irrigação tecnificada, desempenho dos sistemas compatíveis com os anseios de órgãos ambientais e da sociedade em geral. Desta forma, qualquer sistema de irrigação deve aplicar água ao solo, o mais uniformemente possível, pois garante-se o crescimento uniforme das culturas, economia no uso de água e requisitos para se ter um bom desempenho técnico e econômico (FREITAS et al., 2018; NASCIMENTO et al., 2017).

Entre os diversos fatores que podem afetar a uniformidade de aplicação, em um sistema de irrigação, para o caso de pivôs centrais, há particularidades relacionadas ao movimento discreto das torres do equipamento, como a velocidade de deslocamento, o tempo da parada das torres e alinhamento da linha lateral (RAJAN et al., 2015; LI et al., 2016; MOHAMED et al., 2021). Em pivôs centrais, em que as torres se movem de forma descontínua, acionadas por meio de sensores mecânicos, que são posicionados no topo de cada torre móvel, maior tempo de parada das torres pode afetar não somente o desempenho do sistema, mas também pode contribuir à ocorrência do escoamento superficial, principalmente quando a irrigação ocorre em solos com problemas de selamento superficial ou mesmo com baixa capacidade de infiltração (RODRIGUES et al., 2001; KING e BJORNEBERG 2011; AL-BAAJ e LEWIS 2019; MOHAMED et al. 2021).

No que diz respeito ao alinhamento, para pivôs Centrais, em que o movimento das torres se dá de forma descontínua, quando o desalinhamento entre vãos é grande, ou seja, maior que 5º, aumenta-se o tempo de parada das torres móveis, fazendo com que os emissores apliquem mais água no mesmo local, o que pode dificultar o manejo de irrigação, pois é necessário determinar o tempo exato, para suprir adequadamente a demanda hídrica da cultura na área irrigada, além de aplicação de produtos químicos por meio de água de irrigação (MOHAMED et al., 2021), além de levar a uma baixa uniformidade de irrigação.

Sendo assim, pode-se afirmar que o movimento discreto das torres é um fenômeno importante relacionado ao desempenho do sistema, mas é difícil de se estabelecer uma associação clara, quando o estudo é realizado diretamente no campo, em razão da ocorrência de fatores que podem atuar, simultaneamente, sobre o pivô central, tais como velocidade do vento, radiação solar, umidade relativa do ar, temperatura, pressão de serviço do emissor e relevo do terreno (HANSON e WALLENDER, 1986).

Diversos autores como Hanson e Wallender (1986), Le Gat e Molle (2000), Clark et al. (2003) e Sayyadi et al. (2012) pontuam que o movimento discreto das torres do pivô tem certa influência sobre sua uniformidade irrigação. Os autores procuraram apresentar indícios sobre essa teoria, ao desenvolverem modelos matemáticos, para simular o movimento das torres do pivô central e aplicação de água, no entanto resultados anteriores não foram totalmente conclusivos pelo fato desses modelos desconsiderarem o efeito do vento.

Assim tem-se que, para ser estabelecida situação de ausência de ventos, pressão de serviço desejada, de definição do ângulo de desalinhamento entre vãos e, além disso, para controle do tempo de parada, simulação computacional é uma ferramenta extremamente útil para este estudo, além do facto de elas garantirem a agilidade, precisão e segurança dos resultados obtidos (OUAZAA et al., 2015; MOHAMED et al., 2021).

Outro fato que deve ser questionado é a forma de amostragem das lâminas, em estudos que buscam avaliar a uniformidade de irrigação de um pivô central, visto que, geralmente, os coletores são posicionados no sentido radial, conforme a recomendação de ASAE S436.1 (1996) e ABNT NBR 14244 (1998), no entanto o pivô central se movimenta no sentido circular. Desta forma, pode-se destacar que, em sistemas de irrigação por aspersão, o posicionamento dos coletores é um fator relevante que pode contribuir no resultado da avaliação e influenciar na tomada de decisões técnicas referentes ao manejo da irrigação.

Yan et al. (2010), Ouazaa et al. (2015), Ouazaa et al. (2015) e Mohamed et al. (2021) citam que, para o sistema de irrigação por pivô central, a disposição radial pode não mostrar o comportamento das lâminas aplicadas no sentido de movimentação do equipamento. A lateral móvel passa por cima da linha de coletores por curto período que não é suficiente, para detectar problemas que podem ocorrer, ao longo do percurso do equipamento, na direção de movimentação, causado por diversos fatores, como irregularidade topográfica do terreno, parada da torres e diferença de velocidades entre torres adjacentes.

Portanto propõe-se como principal objetivo deste trabalho estudar a movimentação discreta das torres de um pivô central e sua aplicação de água. O estudo compreende a análise da dependência da uniformidade observada do sistema de pivô central, em função da forma de amostragem das lâminas aplicadas; análise do movimento discreto das torres do equipamento, por meio de observações no campo e simulações computacionais; e, por fim, estudar a dependência entre uniformidade de aplicação de água e o movimento das torres de um pivô central.

Sua característica inovadora está no fato de se terem aplicado técnicas de georreferenciamento, para determinar os ângulos de desalinhamento horizontal, tempo de parada das torres, velocidade das torres móveis e de se terem utilizado modelos matemáticos que descrevem a movimentação de cada torre móvel, espacialmente e, por se ter desenvolvido uma planilha eletrônica que possibilite simular o movimento do pivô central com o controle de diversas outras variáveis (velocidade do vento, temperatura, umidade relativa do ar, pressão de serviço dos emissores e topografia do terreno), que podem afetar as avaliações em campo, além do fato de aplicar séries de Fourier para análise do comportamento de distribuição das lâminas.

Os resultados do estudo servirão de base a questionamentos e atualizações na norma, além de servirem não só para tomada de decisão de produtores, mas também de Engenheiros e Técnicos, na escolha da forma de amostragem das lâminas, em função do problema que se pretende detectar, ao se avaliar a uniformidade de um pivô central, além de disponibilizar uma ferramenta computacional desenvolvida em visual basic, que pode ser utilizada, para testar diversos cenários de operação de sistemas de pivô central, de forma simples e auxiliar na tomada de decisões técnicas relativas à movimentação de torres do pivô central.

1.1 Objetivos

1.1.1 Objetivo geral

Estudar a movimentação discreta das torres de um pivô central e sua aplicação de água.

1.1.2 Objetivos específicos

a) Avaliar a dependência entre a uniformidade de aplicação de água de um pivô central e o padrão de amostragem das lâminas;
b) Analisar o movimento discreto das torres do pivô central por meio de observações no campo e simulações computacionais; e
c) Estudar a dependência entre uniformidade de aplicação de água e o movimento das torres de um pivô central.

2 REFERENCIAL TEÓRICO

2.1 Sistema de irrigação por pivô central

A irrigação pode ser entendida como sendo a aplicação artificial de água ao solo, em quantidades adequadas, visando proporcionar a umidade adequada ao desenvolvimento normal das plantas nele cultivadas, a fim de suprir a falta ou a má distribuição das chuvas (VICENTE et al., 2015; MARTINS et al., 2016; SOUZA et al., 2020). Basicamente, a irrigação está dividida em três métodos e, por sua vez, a irrigação pode ser aplicada por diversos sistemas de irrigação (LOPES et al., 2017). Os autores supracitados afirmam que se define como método de irrigação a forma que a água é conduzida até as plantas e, como sistema de irrigação, a estrutura hidráulica que conduz e aplica a água. De acordo com Lopes et al. (2017), os métodos de irrigação estão divididos em irrigação por superfície (que compõe os sistemas de irrigação por sulco, inundação e faixa), irrigação por aspersão (que compõe os sistemas por aspersão convencional, aspersão em malha, por pivô central e autopropelido) e irrigação localizada (que compõe sistemas de gotejamento e microaspersão).

A irrigação por superfície é o método de irrigação, no qual a condução de água até qualquer ponto de infiltração, dentro da parcela a ser irrigada, é feita diretamente sobre a superfície do solo exigindo, portanto áreas sistematizadas com declividade, em geral, de 0 a 2% de acordo com tipo de solo (BERNARDO et al., 2019). A irrigação localizada aplica água diretamente na região radicular, em pequenas intensidades (baixa vazão) e alta frequência (turno de rega pequeno), mantendo esse solo com umidade próxima da capacidade de campo (VENTURA et al., 2017). Corrêa et al. (2019) citam que, na irrigação por aspersão, a água é aspergida sobre as plantas, simulando uma chuva intensa e uniforme - o sistema pode ser fixo ou móvel, com movimentação manual ou mecânica. Entre os sistemas que compõem o método de irrigação por aspersão, destaca-se o pivô central, que, recentemente, também, tem sido utilizado, em aplicações localizadas, originalmente designadas como *mobile drip irrigation* (irrigação localizada móvel), como apresentado por Oker et al. (2019) e Kisekka et al. (2020).

O pivô central é um sistema de movimentação circular, acionado, na maioria dos casos, por energia elétrica, constituído por uma linha lateral móvel, que irriga uma área circular, por meio da rotação da linha lateral de aspersão em torno de um ponto fixo denominado "ponto do pivô" (FRIZZONE et al., 2018). O movimento das torres também pode ser feito por bombeamento de óleo hidráulico como nos pivôs fabricados pela T-L Irrigation.

De acordo com Silveira et al. (2013), destacam-se como principais vantagens do pivô central a economia de mão de obra e possibilidade de manejo da irrigação de diferentes culturas sob um mesmo equipamento; e como principais desvantagens a alta intensidade de aplicação de água, na extremidade de linha do pivô, o que pode gerar escoamento superficial e erosão hídrica, além do fato de perder 21,5% da área irrigada quando um círculo é inserido numa área quadrada.

2.1.1 Principais constituintes e funcionamento de um pivô central

O suprimento de água para o ponto do pivô é feito por meio de uma adutora enterrada. Uma tubulação vertical (tubo de subida), com curvas nas extremidades, faz a ligação entre a adutora e a lateral móvel (AGUIAR NETTO e BASTOS, 2013). Os autores supracitados afirmam que a lateral móvel é sustentada, acima da superfície do solo, por estruturas triangulares (torres móveis) dotadas de um mecanismo de propulsão (moto-redutor) e rodas. O movimento de rotação da lateral móvel, em torno do tubo de subida, é feito, por meio de uma junta localizada, na base da curva, que faz a união entre o tubo de subida e a lateral móvel (MARTINS et al., 2016. SOUZA et al., 2020).

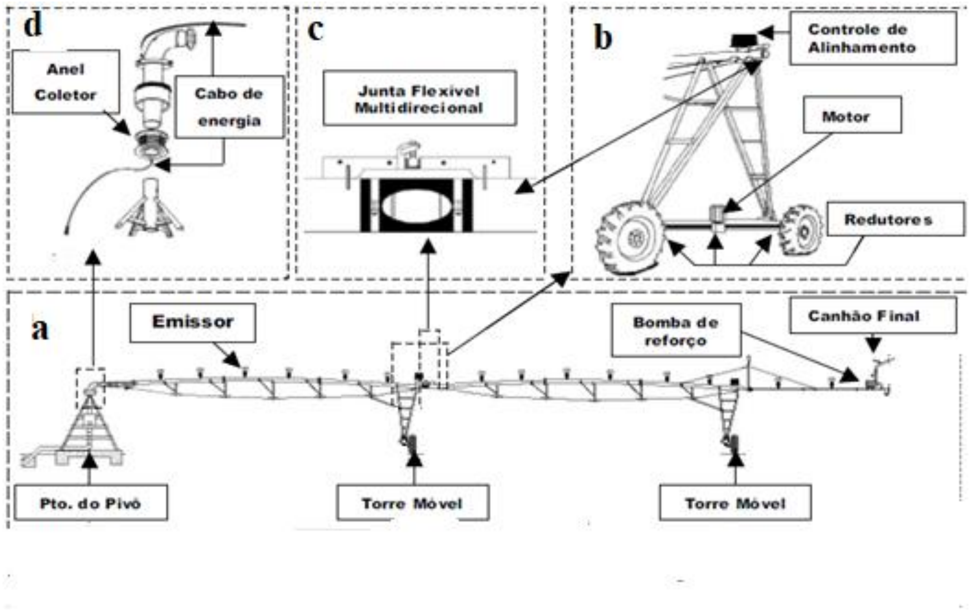
No espaço entre torres, denominado vão, a tubulação lateral é sustentada por uma estrutura dotada de treliças e tirantes. A parte da lateral móvel que se estende além da última torre é denominada lance em balanço. Em alguns pivôs, na extremidade do lance em balanço, é comum a instalação de um aspersor de alcance maior, geralmente um aspersor do tipo canhão hidráulico, que pode requerer a instalação de uma bomba de reforço, no final da lateral, para elevar a pressão da água aplicada pelo canhão final (BERNARDO et al., 2019).

Em razão dos esforços criados pela rotação da lateral e pelo bombeamento de água por intermédio dessa tubulação, para manter o tubo de subida, em uma posição fixa, é erguida uma armação metálica denominada torre fixa sobre uma base de concreto. No ponto do pivô, está localizado o painel de controle, que contém os mecanismos que permitem o controle da operação do pivô. Nos pontos de união entre vãos consecutivos sobre as torres móveis existe uma articulação com mangote flexível que permite desvios entre vãos quando as torres estão em movimento ou quando ocorrem variações topográficas do terreno (MARTINS et al., 2016; FRIZZONE et al., 2018).

Na parte superior das torres, exceto na última, existe um mecanismo que é sensível ao desalinhamento horizontal entre o vão da própria torre e o vão sucessivo. Os pivôs centrais são constituídos também de sensores que detectam o tempo transcorrido desde o último deslocamento da última torre, impedindo que a lateral móvel permaneça parada no mesmo ponto, por longo período, caso ocorra uma falha no sistema de propulsão da última torre (FRIZZONE et al., 2018).

Possuem também sensores de pressão que, quando detectam vazamentos no sistema, na eventualidade de uma falha no bombeamento, interrompem o seu deslocamento, esses sensores são conhecidos como pressostatos. Além disso, possuem também sensores de posicionamento da linha lateral, que são utilizados, para acionar mecanismos, que possibilitam a irrigação de áreas não circulares (FRIZZONE et al., 2018). Na Figura 1, estão apresentados os principais constituintes de um equipamento pivô central.

Figura 1 - (a) vista lateral de um pivô central de duas torres; (b) detalhe de uma torre móvel; (c) detalhe de uma junta móvel de união utilizada nas torres; (d) detalhe da parte superior do tubo de subida



Fonte: Adaptado de Frizzone et al. (2018).

2.1.2 Movimento das torres de um pivô central

Os principais componentes, para a movimentação das torres do pivô, é o conjunto moto-redutor que é instalado em cada torre móvel (Figura 1c). O moto-redutor é composto de um rotor, eixos de entrada e saída e engrenagens. No eixo de saída, existe um sistema de engrenagens que transmite o movimento para as caixas redutoras por um eixo cardan. Os motores elétricos, desenvolvidos e fabricados especialmente para essa aplicação, são submetidos a paradas frequentes e a variações amplas de temperatura. Possuem, portanto um dispositivo termossensível que os protege contracorrentes elétricas excessivas e contra um aquecimento elevado (AGUIAR NETTO e BASTOS, 2013; BERNARDO et al., 2019).

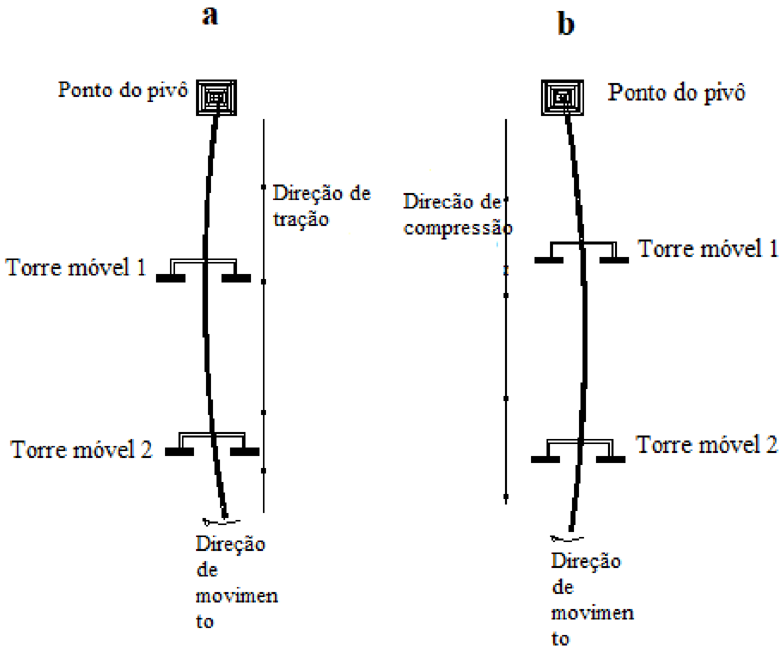
O movimento do pivô inicia-se, na última torre, que propaga uma reação em cadeia, a começar da penúltima torre até a primeira. Ou seja, no momento em que, no painel de controle, é dado o comando, para o início da movimentação da lateral do pivô, as torres encontram-se alinhadas e apenas o mecanismo de propulsão da última torre é acionado, assim, o deslocamento da última torre provoca o ângulo de desalinhamento horizontal entre o último e penúltimo vão. Esse ângulo de desalinhamento entre vãos é causado, porque, enquanto a última torre se move, a torre anterior encontra-se parada. Assim, quando o desalinhamento entre vãos excede um certo ângulo (aproximadamente 5º), um dispositivo mecânico-elétrico acionará o mecanismo de propulsão do motor da penúltima torre que se movimenta corrigindo rapidamente o desalinhamento. Quando o desalinhamento entre vãos é reduzido, esse mecanismo desativa a propulsão da torre (AGUIAR NETTO e BASTOS, 2013; BERNARDO et al., 2019).

Em consequência do deslocamento da penúltima torre, um novo desalinhamento é sentido pela caixa de controle da torre anterior, acionando o movimento dessa torre. Desta forma, o deslocamento da última torre gera um desalinhamento em cascata que se propaga até a primeira torre móvel, resultando no movimento de toda a lateral. De acordo com Ouazaa et al. (2015) e Mohamed et al. (2021), a interrupção frequente do movimento das torres pode resultar na variação da lâmina de água aplicada. Esse fenômeno impede que o conjunto pivô central também seja utilizado, para aplicar defensivos, já que, neste caso, a variação do volume aplicado pode trazer danos às plantas (AGUIAR NETTO e BASTOS, 2013; BERNARDO et al., 2019).

2.1.3 Alinhamento de um pivô central

O alinhamento das torres de um pivô central é um fator de extrema importância na operação do sistema, pois um pivô central desalinhado desenvolve tensões muito altas que podem causar danos estruturais, reduzindo a vida útil esperada dos motorredutores e da caixa de engrenagens. Quando a lateral do pivô central se desalinha, formando um arco contra o sentido de movimentação (Figura 2a), ocorrem forças de tração extremas, puxando a lateral do pivô, quando em operação, o que pode causar danos estruturais; já quando o desalinhamento é um arco no sentido de movimento do pivô central (Figura 2b), causa uma compressão de todo o equipamento, os vãos são submetidos à força de compressão tendendo a perder sua resistência. Portanto o pivô central deve ser alinhado para operar em uma linha tão reta quanto possível.

Figura 2 – Esquema de representação do efeito de desalinhamento de linha lateral do pivô central.



Fonte: O autor (2022).

Ao se alinhar um pivô central, primeiramente, deve-se observar se a unidade de acionamento está funcionando ou não e ajustar o percentímetro entre 50 e 70%, em seguida, iniciar o pivô na direção para frente ou para trás. O "método de três torres" é recomendado por diversos fabricantes para determinar se uma torre está funcionando "à frente" ou "atrás". Com esse método, o alinhamento é iniciado, no final do pivô central, em que o operador deve simplesmente estar preocupado em usar as torres, em cada lado da torre em questão, para observar se está operando em linha. Consiste em alinhar uma torre central, em relação às outras duas torres (torre dianteira e traseira), a partir dos seus motorredutores, de tal forma que o motorredutor da torre móvel ligue e desligue seu movimento, em distâncias iguais, em relação aos motorredutores das torres mais próximas. A primeira torre móvel (localizada próximo ao ponto do pivô) é alinhada fazendo-se coincidir uma linha imaginária entre o seu motorredutor e tubo de subida vertical.

2.2 Variáveis relativas à aplicação de água de um pivô central

Como qualquer outro sistema de irrigação, a lâmina bruta aplicada por pivô central é a razão entre o volume de água aplicado e a área na qual esse volume é aplicado, determinado pelo produto da vazão total do sistema e número de horas necessário para irrigar essa mesma área (AGUIAR NETTO e BASTOS, 2013). Sendo assim, se toda a área irrigada por um pivô central for considerada, o tempo necessário, para o equipamento completar um giro de 360º, é determinado pela Equação 1.

$$T_g = \frac{2.\pi.Rut}{Vut} \tag{1}$$

Em que:

Tg: tempo de giro em (horas);

Vut: velocidade média de deslocamento da última torre (m h-1); e

Rut: é o raio de giro da última torre (m).

Com os valores do tempo de giro (Tg, em horas), vazão total do sistema (Qt, em m^3 h^{-1}) e área total irrigada (A, em hectares), a lâmina bruta aplicada (Lb, em mm) é obtida por meio da Equação 2 (AGUIAR NETTO e BASTOS, 2013).

$$Lb = \frac{T_g \, . \, Qt}{10 \, . \, A} \tag{2}$$

O controle da lâmina bruta aplicada é feito, via controle do tempo de giro, por meio do dispositivo de controle percentual do tempo, o percentímetro, que determina o tempo de funcionamento do motor da última torre. Quando a regulagem do percentímetro é de 100%, o motor da última torre trabalha 100% do tempo e, consequentemente, o tempo de giro é mínimo. Sendo assim, em qualquer regulagem do dispositivo percentual de tempo (Pt em %), é possível obter a velocidade de última torre por meio da Equação 3:

$$Vut = \frac{Pt}{100} . Vut_{100} \tag{3}$$

Em que:

Vut_{100}: velocidade de última torre (m h^{-1}), para percentímetro a 100%; e

Pt: regulagem do percentímetro (%).

Pode-se também desenvolver expressões relacionando a lâmina bruta (Lb) e o tempo de giro (Tg), observados em uma dada regulagem do dispositivo percentual de tempo (Pt em %), com a lâmina bruta (Lb_{100}) ou tempo de giro (Tg_{100}), obtidos com dispositivo percentual de tempo regulado para um valor de 100%, por meio da Equação 4.

$$\frac{Pt}{100} = \frac{Lb_{100}}{Lb} = \frac{Tg_{100}}{Tg} = \frac{Vut}{Vut_{100}} \quad (4)$$

Como o movimento de pivô central é circular uniforme, considerando que todos os pontos de pivô central completam o giro, ao mesmo tempo, para calcular a velocidade angular das torres, pode ser utilizada a Equação 5. Já a velocidade de deslocamento tangencial, em relação ao ponto pivô, pode ser calculada pela Equação 6 (SILVA et al., 2015).

$$\omega = \frac{\theta}{T} \quad (5)$$

$$V_{rs} = \frac{2\pi \, . \, Rs}{T} \quad (6)$$

Em que:

ω: velocidade angular (rad h^{-1});

θ: trajetória percorrida pela torre móvel (rad);

T: período para percorrer essa trajetória, se se considerar a trajetória completa do pivô central a esse período para ser igual ao tempo de giro (h);

V_{rs}: velocidade de deslocamento em relação a distância “Rs” do ponto pivô (m h^{-1}); e

2π rs: perímetro de deslocamento correspondente à torre localizada a distância “Rs” do ponto do pivô (m).

O autor supracitado afirma que, para a estimativa do perímetro (2πrs), podem ser utilizados os valores adotados de lâmina bruta, tempo de giro, valores experimentais de vazão e largura do padrão molhado medido para cada bocal, aplicando-se Equação 7.

$$2\pi \, rs = \frac{\frac{q_b \, . \, Tg}{L_b}}{W_{rs}} \quad (7)$$

Em que

q_b: vazão média do bocal (L h^{-1});

L_b: lâmina bruta adotada (mm); e

W_{rs} : largura do padrão molhado do bocal na distância “Rs” do ponto do pivô (m).

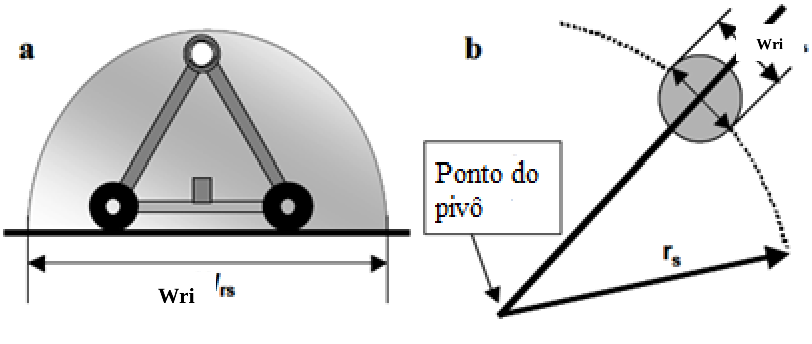
2.2.1 Perfil de distribuição de água

Diversos autores, como Kincaid et al. (1969); Dillon et al. (1972); Gilley (1984); Bernuth e Gilley (1985) citam que variações temporais do valor da taxa de aplicação de água em pivô central são analisadas, considerando-se que, durante o intervalo de tempo correspondente ao tempo de molhamento, o perfil de aplicação de água segue um modelo elíptico. Além disso, outros autores, como Luz e Heermann (2005); DeBoer (2001); Kincaid (2005), consideram que o perfil parabólico ou o padrão trapezoidal são mais adequados.

Smith et al. (2008) desenvolveram um modelo que consideraram que o perfil de distribuição de lâmina aplicada, ao longo da lateral, é igual ao somatório do padrão de aspersão na direção paralela à direção de deslocamento. Esse modelo considera lâminas de água obtidas de uma série de distâncias menores e, aproximadamente equidistantes, ao longo da lateral, iniciando a partir do curso do trajeto do lado externo da área molhada e finalizando perto do emissor. O padrão de aspersão é previsto como uma série de círculos concêntricos de raio (ri) que têm a taxa de aplicação (Ti) e cujo espaçamento corresponde ao espaçamento da lâmina medida (RIBEIRO, 2009).

A largura do padrão molhado (Wri) é medida perpendicularmente à linha lateral do pivô, da faixa que é irrigada simultaneamente pelo pivô (Figura 3). É função do raio molhado dos emissores nas imediações do ponto considerado. Nos equipamentos pivô central que apresentam emissores com vazão crescente, ao longo da linha lateral, a largura do padrão molhado tende a aumentar à medida que nos afastamos do ponto do pivô (SILVA et al., 2015).

Figura 3 - Largura do padrão molhado de um pivô central: (a) vista transversal; (b) vista superior.



Fonte: Adaptado de Frizzone et al. (2018).

Segundo Smith et al. (2008), a largura do padrão molhado, na distância percorrida pelo emissor, em um tempo de contribuição para a lâmina de água (L_1), é dada pela Equação 8.

$$W_{ri} = 2.\sqrt{r_0{}^2 - r_i{}^2} \quad (8)$$

Em que:

W_{ri}: largura do padrão molhado na distância ri ao bocal (m);

r_0: distância do coletor sem água ao bocal (m); e

r_i: distância do coletor com água ao bocal (m).

A taxa de aplicação de água, ao longo da tubulação lateral de um pivô, pode ser descrita em termos de taxa média, taxa máxima e taxa instantânea (SILVA et al., 2015). A taxa média é definida como a taxa de fluxo de água por unidade de área molhada do padrão molhado. Para Smith et al. (2008), a taxa média de aplicação de água, na largura do padrão molhado Wri, é dada pela Equação 9.

$$imed_{ri} = \frac{L_c}{W_{ri}} V_{rs} \quad (9)$$

Em que:

L_c: lâmina média de água coletada a distância ri do bocal (mm); e

V_{rs}: velocidade de deslocamento do bocal à distância rs (m h^{-1}).

A taxa máxima de aplicação é considerada como sendo o ponto acima do padrão de aplicação médio, a partir do padrão de sobreposição de aspersores, ao longo da lateral, que pode ser calculada por meio da Equação 10. A taxa de aplicação instantânea ocorre, para curtos períodos, pela concentração de pulverização de muitos jatos de aspersores.

$$imax = 8.\frac{L_b}{T_g}\frac{r_s}{W_{ri}} \quad (10)$$

Em que:

imax: valor máximo da taxa real de aplicação de água em cada distância do ponto do pivô (mm h^{-1}); e

r_s: distância radial ao ponto do pivô (m).

2.3 Avaliação do desempenho de um sistema de irrigação por pivô central

Na avaliação de um sistema de irrigação por pivô central, é utilizada a uniformidade de aplicação de água e eficiência na aplicação. Nascimento et al. (2017) alegam que os sistemas de irrigação devem apresentar altos valores de eficiência hídrica, energética e econômica que podem ser alcançados se o sistema de irrigação apresentar boa uniformidade de distribuição de água. Por outro lado, Cunha et al. (2013) afirmam que, por melhor que seja o dimensionamento de um sistema de irrigação, a distribuição da água aplicada, dificilmente, será plenamente uniforme; sendo assim, a determinação dessa variabilidade é fundamental na avaliação do desempenho da irrigação. Mendoza e Frizzone (2012) destacam que o desempenho da irrigação pode ser determinado, utilizando-se de um índice de uniformidade e dois índices de eficiência. O índice de uniformidade é usado, para medir a variabilidade espacial da lâmina de água aplicada, normalmente representada pelo coeficiente de uniformidade de Christiansen (CUC) (1942), e os dois índices de eficiência refletem o percentual da área adequadamente irrigada e a eficiência alcançada na aplicação da água (CUNHA et al., 2013; TOLEDO et al., 2017).

Um sistema de irrigação com uniformidade de Christiansen, equivalente a 80%, significa que, aproximadamente, 80% da área receberá uma lâmina superior ou igual à lâmina média aplicada (MENDOZA; FRIZZONE, 2012). Portanto a uniformidade é um parâmetro que afeta diretamente a lâmina bruta de irrigação. Sendo assim, quanto maior a uniformidade, menor será a lâmina necessária para se atingir a mesma produtividade (BORSSOI et al., 2012).

As literaturas apresentam outros coeficientes, além do CUC, sendo o coeficiente de uniformidade de distribuição (CUD) um dos mais utilizados. O coeficiente de uniformidade de distribuição (CUD) relaciona as menores lâminas aplicadas no quartil de área total (quartil que receberá menos água). Portanto um baixo valor de CUD indica que uma excessiva perda por percolação profunda ocorreria, se toda a área recebesse uma lâmina maior ou igual à real e necessária (TOLEDO et al., 2017).

De acordo com Cunha et al. (2009), esses indicadores de desempenho podem ser obtidos diretamente dos valores de lâmina de água, medidos pontualmente, ou por meio de modelos matemáticos.

Ao realizar avaliação no campo, a linha de coletores é disposta radialmente, ao longo do raio do pivô. Dependendo da finalidade da avaliação, bem como da disposição do equipamento na área, podem ser posicionadas uma, duas ou até quatro linhas de coletores. As normas ABNT. NBR 14244 (1998) e ASAE S436, (1992) indicam disposição de duas linhas de coletores (com 3º entre linha) e quatro linhas, perpendiculares, respectivamente. Porém, no campo, geralmente, faz-se avaliação com somente uma linha, procurando-se mais detectar problemas que ocorrem entre lances de emissores ou em áreas muito acidentadas. Diversos autores, como Ouazaa et al. (2015) e Mohamed et al. (2021) assinalam que, além de avaliação na direção do raio do pivô, as avaliações no sentido de movimentação do equipamento são importantes, uma vez que geralmente as torres dos pivôs não possuem movimento contínuo, fato que pode afetar a uniformidade de ao longo do seu percurso.

O coeficiente de uniformidade de Christiansen (1945) pode ser obtido pela Equação 10 (WILCOX; SWAILES, 1947). Já o coeficiente de uniformidade de distribuição (CRIDDLE et al., 1956) é representado pela Equação 11.

$$\mathrm{CUC} = 100\ .\left(\frac{\sum_{i=1}^{n}|X_i - \overline{X}|}{n\ .\overline{X}}\right) \tag{10}$$

$$\mathrm{CUD} = 100\ .\left(\frac{X_{25\%}}{\overline{X}}\right) \tag{11}$$

Em que:

X_i: lâmina coletada em cada coletor (mm);

$\overline{X}$: lâmina média coletada na área irrigada (mm);

n: número de lâminas observados; e

$X_{25\%}$: média das menores lâminas aplicadas em 25% da área irrigada (mm).

Mendoza e Frizzone (2012) asseveram que, no sistema de irrigação por pivô central, em razão do aumento da área, em função do distanciamento do centro pivô, cada coletor instalado representa área crescente. Sendo assim, há necessidade de se ponderar as lâminas coletadas, o que é feito multiplicando-se cada valor coletado pelo número correspondente do coletor. Portanto Heermann e Hein (1968) desenvolveram uma equação, para calcular a uniformidade da aplicação de pivô central (Equação 12), que resulta da modificação do coeficiente de uniformidade de Christiansen pela necessidade de se ponderar as lâminas coletadas. Já a menor uniformidade de distribuição (CUD) pode ser calculada usando a Equação 13.

$$\mathrm{CUC} = 100.\left[1 - \frac{\sum_{i=1}^{n} S_i.\left|L_i - \overline{L}_p\right|}{\sum_{i=1}^{n} L_i.S_i}\right] \tag{12}$$

$$\mathrm{CUD} = 100.\left(\frac{\sum_{i=1}^{j} L_i.S_i / \sum_{i=1}^{j} S_i}{\overline{L}_p}\right) \tag{13}$$

Em que:

n: número de coletores;

L_i: làmina de água coletada (mm);

S_i: distância do coletor ao ponto do pivô; e

$\overline{L}_p$: média ponderada da lâmina de água coletada, em uma área irrigada, que é calculada por meio da Equação 14.

$$\overline{L}_p = \frac{\sum_{i=1}^{n} L_i . S_i}{\sum_{i=1}^{n} S_i} \tag{14}$$

Valores elevados de coeficientes de uniformidade podem ser especialmente desejáveis, para fertirrigação e quimigação, visto que as aplicações de nutrientes ou compostos químicos não serão mais uniformes que a distribuição de água. De acordo com Bernardo et al. (2019); Borssoi et al. (2012); e Keller e Bliesner (1990) a classificação dos indicadores de desempenho do sistema de irrigação, segundo os valores de CUC e CUD, segue critérios e limites estabelecidos na Tabela 1.

Tabela 1 - Interpretação dos valores do coeficiente de uniformidade de Christiansen (CUC) e uniformidade de distribuição (CUD)

Classificação	CUC (%)	CUD (%)
Excelente	> 90	> 84
Bom	80 - 90	68 - 84
Razoável	70 - 80	52 - 68
Ruim	60 - 70	36 - 52
Inaceitável	< 60	< 36

Fonte: Adaptado de Bernardo et al. (2019); Borssoi et al. (2012); e Keller e Bliesner (1990).

3 CONSIDERAÇÕES GERAIS

O referencial teórico desta tese possibilitou entender que estudos semelhantes foram desenvolvidos, porém não chegaram a uma conclusão clara, no que concerne ao efeito de movimento das torres sobre a uniformidade de aplicação de água, principalmente pelo fato de a influência de variáveis climáticas e topográficas.

O estudo do efeito de movimento do pivô sobre suas características de aplicação de água foi subdividido em três etapas, que são: uma análise precisa do movimento discreto das torres; estudo do efeito dos ângulos de desalinhamento entre torres sobre a uniformidade de aplicação de água; e estudo da dependência entre a uniformidade de irrigação e a forma de amostragem das lâminas.

No que diz respeito à análise do movimento discreto das torres, acredita-se que o movimento descontínuo de torres pode gerar variação de velocidade média por parada da torres, afetando a distribuição de lâmina de água aplicada, no sentido de movimentação do equipamento, consequentemente, impede que o conjunto pivô central também seja utilizado para a aplicação defensivos, além de gerar distribuição desigual de fertilizantes na área, nos casos em que o pivô central é utilizado para fertirrigação.

Tem-se também que a amostragem radial, que geralmente é utilizada na avaliação de Pivôs Centrais, pode não detectar problemas de uniformidade de irrigação, causados pela parada das torres, e o efeito da deriva causada pelo vento, quando a sua direção não coincide com linha de disposição de coletores; sendo assim, uma alternativa simples, para que essas limitações sejam superadas, seria por meio de outras formas de amostragem de lâminas como a circular e em malha.

REFERÊNCIAS

AMERICAN SOCIETY OF AGRICULTURAL ENGINEERS – ASABE. ASAE S436.1: Test Procedure for Determining the Uniformity of Water Distribution of Center Pivot and Lateral Move Irrigation Machines Equipped with Spray or Sprinkler Nozzles. 1996. 8p.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS - ABNT. NBR 14244: Equipamentos de irrigação mecanizada – Pivô central e lateral móvel providos de emissores fixos ou rotativos – Determinação da uniformidade de distribuição de água. Rio de Janeiro, 1998. 11p

AGUIAR NETTO, A. DE O.; BASTOS, E. A. Princípios Agronômicos da Irrigação. 1 ed, Embrapa, 2013, 264 p.

BARBOSA, J. C., MALDONADO, J. R. W. (2010). AgroEstat: sistema para análises estatísticas de ensaios agronômicos. Versão 1.0. Jaboticabal: Departamento de Ciências Exatas.

BERNARDO, S.; MANTOVANI, E. C.; DA SILVA, D. D.; SOARES, A. A. **Manual de irrigação**, edição: 9ª. Editora: UFV, 1ª reimpressão. Viçosa, MG, 2019, 545p.

BERNUTH, R. D. von; GILLEY, J. R. Evaluation of center pivot application packages considering droplet induced infiltration reduction. **Transaction of the ASAE**, Saint Joseph, v. 28, n. 6, p. 1940-1946, 1985.

BORSSOI, A. L., VILAS BOAS, M. A., REISDÖRFER, M., HERNÁNDEZ, R. H., FOLLADOR, F. A. Water application uniformity and fertigation in a dripping irrigation set. **Engenharia Agrícola**, v. 32, n. 4, p. 718-726, 2012.

CHRISTIANSEN, J. E. 1942. Irrigation by sprinkling. California Agric. Exp. Station. Bulletin No. 570. Berkeley, Calif.: Univ. of Calif.:

CLARK, G. A.; SRINIVAS, K.; ROGERS, D. H.; STRATTON, R.; MARTIN, V. L. Measured andsimulated uniformity of low drift nozzle sprinklers. **Trans. ASAE**, v.46, n.2, p.321–330, 2003.

CORRÊA, M. F.; NAVROSKI, R.; SCHUCH, L. O. B.; VERNETTI JUNIOR, F. DE J.; DE ALMEIDA, T. L.; RODRIGUES, H. C. S.; NADAL, A. P.; GADOTTI, G. I. Efeito da irrigação por aspersão no rendimento e potencial fisiológico das sementes de soja. **Revista de Ciências Agroveterinárias**, v. 18, n. 4, p. 448 – 488, 2019.

CUNHA, F. N.; DE OLIVEIRA, R. C.; BASTOS, F. J. C.; TEODORO, J. P. R.; TEIXEIRA, M. B.; GOMES FILHO, R. R. Análise de coeficientes de uniformidade em pivôs centrais instalados na região sudoeste de goiás. **Revista Brasileira de Agricultura Irrigada** v.7, nº. 3, p. 181 - 190 , 2013.

CUNHA, F. F.; ALENCAR, C. A. B.; VICENTE, M. R.; BATISTA, R. O.; DE SOUZA, J. A. R. Comparação de equações para cálculo da uniformidade de aplicação de água para diferentes sistemas de irrigação. **Engenharia na agricultura**, v.17, n.5, 2009.

DEBOER, D. W.; MONNENS, M. J. Estimation of drop size and kinetic energy from a rotating *spray*-plate sprinkler. **Transactions of ASAE**, Saint Joseph, v. 44, n. 6, p.1571-1580, 2001.

DILLON, R. C.; HILER, E. A. J.; VITTEROE, G. Center-pivot sprinkler design based on intake characteristics. **Transactions of the ASAE**, Saint Joseph, v. 15, n. 5, p. 996-1001, 1972.

DUKES, M. D.; PERRY, C. Uniformity testing of a variablerate center pivot irrigation control systems. **Precision Agric**. v.7, n.3, p.205-218, 2006.

FRIZZONE, J. A.; REZENDE, R.; CAMARGO, A. P.; COLOMBO, A. **Irrigação por aspersão: sistema por pivô central**. 1 ed. Maringá, 2018. 355 p.

FREITAS, E. DE F. M.; DE FARIAS, H. F. L.; SILVA, S. M. DA C.; AVELINO NETO, S. Avaliação da velocidade de infiltração da água no solo e Uniformidade de distribuição da água de irrigação Por pivô central**. Revista Brasileira de Agricultura Irrigada** v.12, n.1, p. 2374 - 2384, 2018.

GILLEY, J. R. Suitability of reduced pressure center-pivot. **Journal of Irrigation and Drainage Engineering**, New York, v. 110, n. 1, p. 22-34, 1984.

HANSON, B. R.; WALLENDER, W. Bidirectional uniformity of water applied by continuous-move sprinkler machine. **Transaction of the ASAE**, v.29, n.4, p.1047-1053, July/Aug. 1986.

HEINEMANN, A. B.; FRIZZONE, J. A.; PINTO, J. M.; FEITOSA FILHO, J. C. Influência da altura do emissor na uniformidade de distribuição da água de um sistema pivô central. **Pesquisa Agropecuária Brasileira**, Brasília, v. 33, n.9, p. 1487-1491, 1998.

KINCAID, D. C. Application rates from center pivot irrigation with current sprinkler types. **Transaction of the ASAE**, Saint Joseph, v. 21, n. 4, p. 605-610, 2005.

KINCAID, D. C.; HEERMANN, D. F.; KRUSE, E. G. Application rates and runoff in center-pivot sprinkler irrigation under low-energy. **Transactions of the ASAE**, Saint Joseph, v. 12, n. 6, p. 790-794, 1969.

KISEKKA, I, T. OKER, G. NGUYEN, J. AGUILAR, D. ROGERS. Revisiting precision mobile drip irrigation under limited water. **Irrigation Science** (2020) 38: P.17-35.

LE GAT, Y.; MOLLE, B. Model of water application under pivot sprinkler I: theo-retical grounds. **J. Irrig. Drain. Eng**. v.126, n.6, p.343–347, 2000.

LOPES, J. D.; LIMA, F. Z.; OLIVEIRA, F. G. Irrigação por aspersão convencional. Viçosa, MG. 2017, cap. 6, p. 300-340.

MARTINS, R. A.; LARANJA, R. E. DE P.; FERREIRA, I. M.; DOS SANTOS, E. V. Evolução da prática de irrigação por pivô central no município de Morrinhos (GO) e a pressão sobre os recursos hídricos. **Ambiência Guarapuava**, v.12, n.3, p. 881 – 890, 2016.

MARTINS, J. D.; BOHRZ, I. S.; FREDRICH, M.; VERONEZ, R. P.; KUNZ, G. A. Levantamento da área irrigada por pivô central no estado do rio grande do sul. **Irriga, Botucatu**, v. 21, n. 2, p. 300-311, maio - junho, 2016.

MENDOZA, C. J. C.; FRIZZONE, J. A. Economia de energia em irrigação por pivô central em função da melhoria na uniformidade da distribuição de água. **Revista Brasileira de Agricultura Irrigada** v.6, nº. 3, p**.** 184 - 197, 2012.

MOHAMED, A. Z.; PETERS, R. T.; SARWAR, A.; MOLAEI, B.; MCMORAN, D. Impact of the Intermittency Movement of Center Pivots on Irrigation Uniformity. **Water**, v.13, n.9, p.1167, 2021.

NASCIMENTO, V. F.; FEITOSA, E. DE O.; SOARES, J. I. Uniformidade de distribuição de um sistema de irrigação por aspersão via pivô central. **Revista de Agricultura Neotropical**, v. 4, n. 4, p. 65-69, 2017.

OKER, T. E., I. KISEKKA, A. Y. SHESHUKOV, J. AGUILAR, D. ROGERS. Evaluationof dynamic uniformity and application efficiency of mobile drip irrigation. Irrig Sci (2017) 35:483–500.

OUAZAA, S.; LATORRE, B.; BURGUETE, J.; SERRETA, A.; PLAYÁN, E.; SALVADOR, R.; PANIAGUA, P.; ZAPATA, N. Effect of the Start–stop Cycle of Center-pivot Towers on Irrigation Performance: Experiments and Simulations. **Agricultural Water Management,** v.147, p.163-174, 2015.

RIBEIRO, M. S. 2009. **Desenvolvimento de emissor tipo lepa de baixo impacto erosivo.** Tese (doutorado em Engenharia Agrícola), Universidade Federal de Lavras, 2009.

SAYYADI, H.; SADRADDINI, A. A.; FARSADI ZADEH, D.; MONTERO, J. Artificial neuralnetworks for simulating wind effects on sprinkler distribution patterns. **SPAN JAGRIC RES**, v.10, n.4, p.1143–1154, 2012.

SHAUGHNESSY, S. A. O; URREGO, Y. F.; EVETT, S. R.; COLAIZZI, P. D.; HOWELL, T. A. Assessing application uniformity of a variable rate irrigation system in a windy location. **American Society of Agricultural and Biological Engineers,** v.29, n.4, p.497-510, 2013.

SILVEIRA, J. M. C.; JÚNIOR, S. de L.; SAKAI, E.; MATSURA, E. E.; PIRES, R. C.de M.; ROCHA, A. M. Identificação de áreas irrigadas por pivô central na sub-bacia tambaú-verde utilizando imagens ccd/cbers. **Irriga**, Botucatu, v. 18, n. 4, p. 721-729, 2013.

SILVA, R. M.; COELHO, R. D.; FARIA, L. DO A.; MASCHIO, R. Coeficiente de descarga em emissores de pivô central. **Engenharia Agrícola**., v.35, n.3, p.419-429, 2015.

SMITH, R. J.; GILLIES, M. H.; NEWELL, G.; FOLEY, J. P. A decision support model for travelling gun irrigation machines. **Biosystems Engineering**, London, v. 100, n. 1, p. 126-136, 2008.

SOUZA, C. A.; AQUINO, B. G.; QUEIROZ, T. M. Expansão da agricultura irrigada por pivô central na região do Alto Teles Pires-MT utilizando sensoriamento remoto. **Revista**

GEAMA, Scientific Journal of Environmental Sciences and Biotechnology, v. 6, n. 2, p. 11-16, 2020.

TOLEDO, C. E.; ALBUQUERQUE, P, E. P.; SOUZA, C. M. P. Eficiência da aplicação da água por pivô central em diferentes regiões de minas gerais. **Irriga,** Botucatu, v. 22, n. 4, p. 821-831, outubro-dezembro, 2017.

YAN, H.; JIN, H.; QIAN, Y. Characterizing center pivot irrigation with fixed sprayplate sprinklers. **Sci. China Tech. Sci.** v.53, n.5, p.1398–1405, 2010.

VENTURA, K. M.; BISPO, R. DE C.; SANTOS, R. D. S.; SOUZA, M. H. C.; SÁNCHEZ-ROMÁN, R. M. Análise da uniformidade de aplicação em diferentes sistemas de cultivo com irrigação localizada. **Irriga**, v. 1, n. 1, p. 57-63, 2017.

VICENTE, M. R.; MANTOVANI, E. M.; FERNANDES, A. L. T.; DELAZARI, F. T.; FIGUEREDO, E. M. Efeito de diferentes lâminas de irrigação nas variáveis de desenvolvimento e produção do cafeeiro irrigado por pivô central. **Irriga,** Botucatu, v. 20, n. 3, p. 528-543, julho - setembro, 2015.

SEGUNDA PARTE

ARTIGO 1 – SAMPLING PATTERNS MAY INFLUENCE THE EVALUATION OF IRRIGATION UNIFORMITY OF CENTER PIVOT SYSTEMS

NORMAS DO PERIÓDICO WATER SUPPLY

(VERSÃO ACEITA E PUBLICADA)

Sampling patterns may influence the evaluation of irrigation uniformity of Center Pivot systems

Short title: Sampling patterns may influence evaluated irrigation uniformity

Fidel Luís Rodrigues Tambo*, Luiz Antonio Lima*, Michael Silveira Thebaldi*^ and Flávia Vilela Corrêa*

* Department of Water Resources, Universidade Federal Lavras, Campus Universitário, PO Box 3037, Lavras, Minas Gerais, BR. ZIP Code: 37.200-900

(E-mail*: fideltambo@gmail.com*; *lalima@ufla.br; michael.thebaldi@ufla.br; flavia-vilela-correa@hotmail.com)*

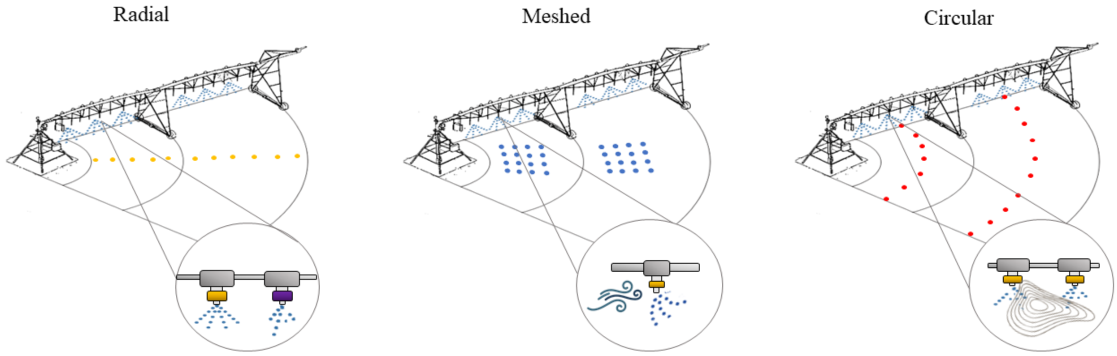
Abstract: The evaluation of irrigation uniformity can be affected by the sampling pattern in the field. Thus, this work aimed to compare the water application uniformities of a Center Pivot using three sampling patterns: along the equipment radius (radial), in the direction of movement of the pivot (circular) and in a two-dimensional way (meshed). For this, samplers were positioned under the spans of a Center Pivot system, being evaluated the effects of the sampling pattern and of the span, in a 3 x 3 statistical factorial design, with 3 replications. The results showed that circular and meshed arrangements were statistically equal and had higher values of Christiansen's and Distribution Uniformity Coefficients. The mesh type arrangement represented a more uniform distribution profile of irrigation depths on the surface. For areas of flat or slightly undulating topography and when using pressure regulating valves for the emitters, sampling in a radial pattern is sufficient, but for terrains with irregular topography or when pressure head variations along the lateral line are important for the operation of the emitters, the combination of the radial and circular pattern is interesting. The meshed sampling detects the stoppage effect of the towers and drift, however, in a reduced area.

Keywords: Christiansen Uniformity Coefficient, Distribution Uniformity Coefficient, performance of irrigation systems, water application spatial variability.

Highlights:
1 - Irrigation uniformity for Center Pivot systems is affected by factors such as stoppage time, relief, and emitter distribution along the lateral line
2 - Sampling in meshed pattern detects the stoppage effect of the towers and drift
3 - Sampling in radial pattern detects uniformity problems caused by emitters and nozzles
4 - Sampling in circular pattern detects uniformity problems due to irregular topography

Graphical Abstract

Collector patterns recommendation to test the uniformity of water application in a Center Pivot system



Introduction

The water application uniformity is one of the main technical variables to evaluate an irrigation system because it is by this that irrigation management, water and energy saving can be improved, in addition to guaranteeing production (Al-Gaadi *et al.* 2019; Mohamed *et al.* 2021). Dwomoh *et al.* (2013) and Zhang *et al.* (2013), cite that an irrigation system that operates under optimal conditions must apply water to the soil uniformly, to satisfactorily achieve the water needs for crops and their development, which is dependent on the uniformity of water applied to the surface and soil moisture in its subsurface.

Al-Gaadi *et al.* (2019) and Mohamed *et al.* (2021), point out that the analysis of uniformity coefficients is essential to evaluate the performance of any irrigation system, in addition, Lecina *et al.* (2016) and Darko *et al.* (2017), present that the economic benefits of irrigation increase due to the increase in water distribution uniformity.

However, there are several factors that affect irrigation uniformity, and, in the case of Center Pivot systems, there are some related to the equipment (sprinkler type and model, operating pressure, spacing, travel speed, lateral line alignment, and emitter height); climate-related factors (evaporation, air temperature, relative humidity, and wind drift); and factors related to the relief conformation of the irrigated area (Ortiz *et al.* 2010; Rajan *et al.* 2015; Li *et al.* 2016). With all these variables on which the uniformity of irrigation systems depends, it is inferred that there is a spatial dependence of the collected water depths, that would lead to a possible link between the sample pattern on the observed uniformity.

The water application uniformity of a Center Pivot is measured by collectors that are positioned radially, from the center to the edge of the equipment (ASAE 2020; ABNT 1998). Additionally, Shaughnessy *et al.* (2013) and Ouazaa *et al.* (2015) state that the uniformity in the direction that the Center Pivot moves is not much explored and can be questioned. For example: when a tower has its movement interrupted, its emitters continue to apply water in the same place and, if the water contains a chemical product, such as fertilizers, the plants of this area will receive a greater amount of it, since the dosage is proportional to the applied water. Thus, this fact can affect the development uniformity of the irrigated crop.

Consequently, some manufacturers offer systems equipped with solenoid valves, that open only if the tower is in motion, a technique that has not been effective due to the rapid wear of the valves and is its high cost (Mostacero *et al*. 2012). Mohamed *et al.* (2021) mention that several models are developed to assess the impact of mobile tower misalignment on irrigation uniformity. There are also Center Pivots activated by pumping hydraulic oil or variable-frequency drivers. All these solutions are adopted so that the movement of the towers is continuous and so, the head on the lateral line to be most uniform, to be possible to obtain a good irrigation uniformity (Ouazaa *et al.* 2015). However, the poor quality of electricity in rural areas does not allow the proper functioning of these equipments. It is important to emphasize that all these attempts would not exist if the discrete movement of the towers against the general movement was a negligible phenomenon in terms of system performance.

Therefore, it is proposed, with the present article, to study the dependence of the sampling method of the applied water depth over the observed uniformity of a Center Pivot system, when evaluating its effect on the Christiansen (CUC) and Distribution Uniformity Coefficient (DUC).

Methods

The tests were carried out on a Tifton 85 grass and hay producing farm, located in Bom Despacho city, state of Minas Gerais, Brazil, at geographic coordinates 19º36' 23.88" S; 45º16' 14.98" W and 631.5 m altitude, on a flat terrain topography.

The evaluated Center Pivot equipment irrigates an area of 10.95 ha and had three mobile towers plus an overhang with no end gun. Its technical characteristics are revolution time with the percent timer set to 100% of 7.10 hours, 185.7 m of lateral line length (57.1 m in the first span, 51.4 m in the second span, 51.1 m in the third span, and 25.4 m of overhang), which leads to 1007.19 m of useful perimeter. The average design water depth is 3.59 mm for a flow of 86.58 $m^3.h^{-1}$.

Two types of sprinklers (Superspray and I-Wobler) were installed in spans 1 and 2, alternating along each span. The span 3 and the overhang had only "I-Wobler" type sprinklers. All emitters were connected to a pressure regulating valve with an operating pressure of 10 mca. The combinations of emitters and nozzles used in each span of the evaluated system are listed in Table 1.

Table 1 - Emitters and nozzles used in each span of the evaluated Center Pivot irrigation system.

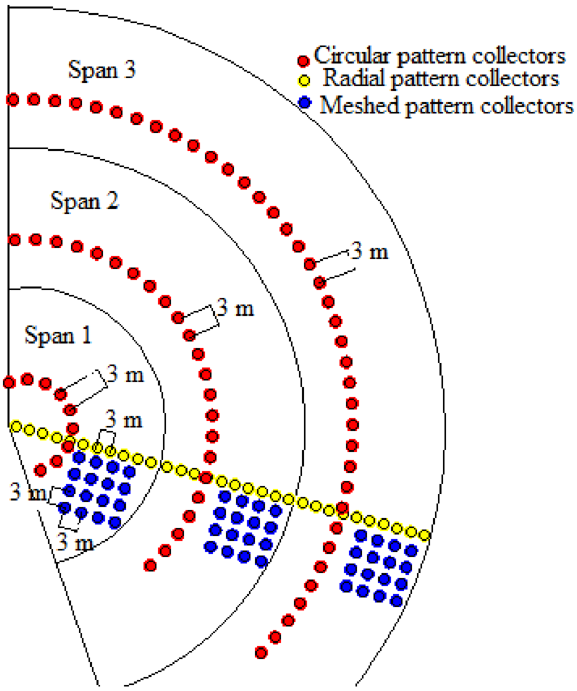
Span 1		Span 2		Span 3		Overhang	
Emitter	Nozzle	Emitter	Nozzle	Emitter	Nozzle	Emitter	Nozzle
Superspray	7.0	I-Wobler	14.0	I-Wobler	17.5	I-Wobler	17.5
I-Wobler	9.0	Super spray	9.0	I-Wobler	14.0	I-Wobler	18.0
Superspray	4.5	I-Wobler	14.5	I-Wobler	14.5		
Super spray	5.0	I-Wobler	15.0	I-Wobler	15.0		
I-Wobler	7.5	Super spray	10.0	I-Wobler	15.0		
Super spray	6.0	I-Wobler	15.5	I-Wobler	15.5		
I-Wobler	8.5	I-Wobler	16.5	I-Wobler	16.0		
I-Wobler	10.0	Super spray	10.5	I-Wobler	16.5		
Super spray	6.5	I-Wobler	17.0	I-Wobler	16.5		
I-Wobler	11.0	I-Wobler	17.5	I-Wobler	17.0		
I-Wobler	12.0	Super spray	11.5				
Super spray	8.0	I-Wobler	18.0				
I-Wobler	13.0	I-Wobler	18.5				
I-Wobler	13.5	I-Wobler	19.0				
Super spray	8.5	Super spray	12.0				
Super spray	9.0	I-Wobler	19.5				
		Super spray	12.5				

Data collection was performed with the equipment operating with the percent time set at 66%. The collectors used had a diameter of 0.08 m and so, an area greater than 50 cm^2, as recommended by ASABE (ASAE 2020), and were placed on fixed rods attached to the ground, keeping them at an elevation of 0.3 m in relation to the surface (ASAE 2020; ABNT 1998).

To determine the application uniformity of sampling in the radial direction, a line of collectors was positioned in the direction of the radius of the Center Pivot, i.e., following the lateral line, with a spacing of 3 m between collectors, with 20 collectors being used in each span, corresponding to a total of 60 collectors for all three spans (ASAE 2020; ABNT 1998).

Sixteen collectors were used in each span for the meshed pattern sampling, that is, square meshes of 4 x 4 collectors, spaced at 3 m, totaling 48 collectors considering the three spans. For the sampling in the circular pattern, 10 collectors were positioned in the first span, 21 in the second span and, 36 in the third span, arranged in an arch in the direction of the pivot movement, spaced 3 m apart, resulting in a total of 67 collectors. The arrangement scheme of collectors, for each sample pattern, is represented in Figure 1.

Figure 1 – Arrangement scheme of collectors in field, to test the uniformity of water application in a Center Pivot system, considering samples in radial, circular and meshed pattern.



The center of the equipment and all collectors were georeferenced using a GPS signal receiver equipment, geodesic type, Spectra Precision ProMark 220 (GNSS L1,L2 GLONASS), so that it was possible to measure the location of each collector in the field using the UTM coordinate system, to obtain the surfaces profiles of the water depths over the irrigated area, by span, in the three evaluated sampling patterns.

During the tests, the irrigation system traveled an arc of 120º for a period of 2 hours and 30 minutes. This process occurred simultaneously with the collection of meteorological data, which were recorded at 5-minute intervals, by an automatic meteorological station positioned infield, but in an area adjacent to the irrigated one. Wind speed ($m.s^{-1}$), wind direction, relative humidity (%), solar radiation, and air temperature (ºC) were recorded. The wind speed and direction varied during the tests, being they recorded at two-meter altitude, from the ground level. The average values of the climatic variables observed during the tests are presented in Table 2.

Table 2 - Average values of the climatic variables observed during the first, second and third tests.

Essay	Wind velocity ($m.s^{-1}$)		Air humidity (%)		Temperature (°C)		Solar radiation ($W.m^{-2}$)	
	Mean	σ	Mean	σ	Mean	σ	Mean	σ
1	5.30	±2.13	56.81	±2.21	29.26	±1.01	865.22	±68.79
2	3.26	±2.30	52.41	±6.22	30.50	±1.36	920.41	±304.93
2	4.80	±1.70	49.41	±6.55	31.70	±2.07	1033.10	±0.47

Note: σ – standard deviation.

The volume of water collected was measured using a graduated cylinder. The calculation of the water depths corresponding to each volume collected was made using Equation 1.

$$L = \frac{1000 \cdot V_c}{A} \tag{1}$$

where L is the collected irrigation water depth (mm), V_c is the collected water volume (L) and A is the Collector cross-sectional area (m^2).

Thus, the Christiansen Uniformity Coefficient (CUC) adapted for the evaluation of Center Pivot systems was calculated (Equation 2, Heermann & Hein 1968).

$$CUC = 100 \cdot \left[1 - \frac{\sum_{i=1}^{n} S_i \cdot \left|L_i - \bar{L}_p\right|}{\sum_{i=1}^{n} L_i \cdot S_i}\right] \tag{2}$$

where n is the number of collectors, L_i is the water depth in collector *i* (mm), S_i is the distance from collector to the system center (m) and $\bar{L}_p$ is the weighted average of water depths collected in the managed area, which is calculated by Equation 3.

$$\bar{L}_p = \frac{\sum_{i=1}^{n} L_i . S_i}{\sum_{i=1}^{n} S_i} \tag{3}$$

The DUC was calculated using Equation 4, also adapted for the evaluation of Center Pivot systems (Heermann & Hein 1968).

$$\mathrm{DUC} = 100 \cdot \left(\frac{\sum_{\mathrm{i}=1}^{\mathrm{j}} \mathrm{L_i} \cdot \mathrm{S_i} / \sum_{\mathrm{i}=1}^{\mathrm{j}} \mathrm{S_i}}{\bar{\mathrm{L}}_\mathrm{p}}\right) \tag{4}$$

In this equation, the numerator represents the mean applied volume of the smallest quarter of samples (*j*) in the span. As shown, the calculation of this uniformity coefficient reflects the weighted area represented by each collector. The interpretation of the evaluated coefficients was performed using the limits presented in Table 3.

Table 3 - Christiansen (CUC) and Distribution Uniformity Coefficient (DUC) values ratings.

Rating	CUC (%)	DUC (%)
Excellent	> 90	> 84
Good	80 - 90	68 - 84
Fair	70 - 80	52 - 68
Bad	60 - 70	36 - 52
Unacceptable	< 60	< 36

Source: Adapted from Bernardo *et al.* (2019); Borssoi *et al.* (2012); and Keller & Bliesner (1990).

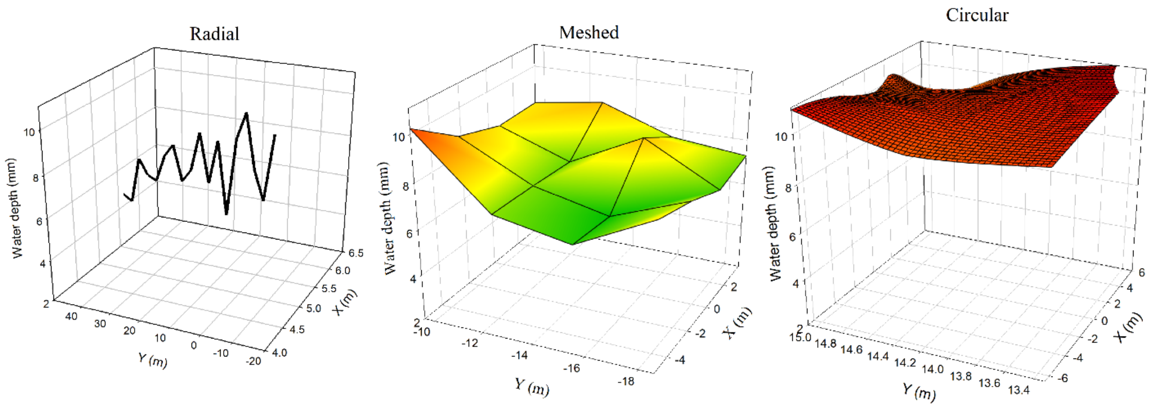
To evaluate the results, a Completely Randomized Design (CRD) was adopted, in a 3 x 3 factorial scheme. The treatments were defined as the sampling pattern (three levels: radial, circular and, meshed); and sampling positions (three levels: span 1, span 2 and, span 3), with three repetitions.

The Analysis of Variance (ANOVA) was performed using the F test, at 5% statistical probability. When significant differences were verified, the Scott-Knott mean test was used, also at 5% probability. All the statistical analysis were made with the AGROESTAT software (Barbosa & Maldonado 2010).

Results and Discussion

Figure 2 shows the distribution profiles of irrigation water depths on the surface for the three collectors arranging patterns, under Span 1.

Figure 2 – Irrigation water depths distribution profiles under Span 1 for radial, meshed, and circular layouts.

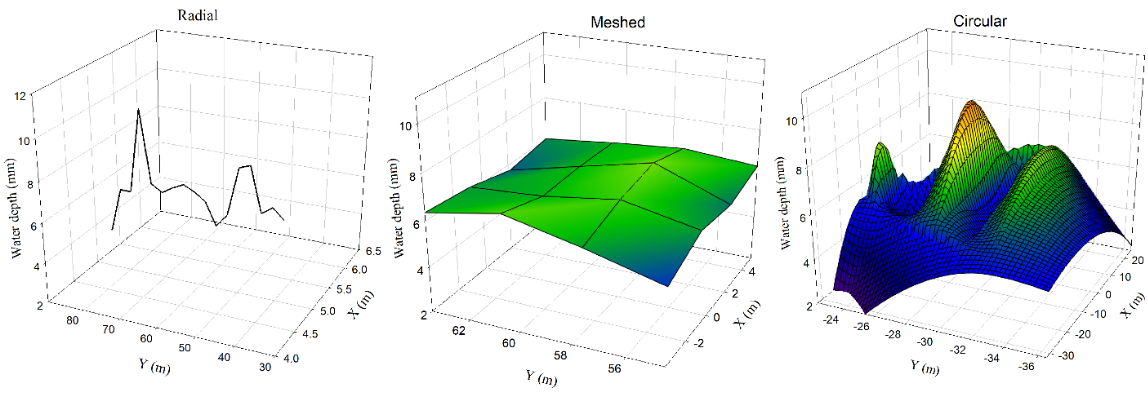


There is a difference between the distribution profiles of water depths along the surface. The collectors arranged in the radial pattern showed the greatest water depths variation, while the ones arranged in the circular shape showed the smallest. One factor that influenced the variation of the water depths, mainly for the radial pattern, was the use of two sprinkler models arranged alternately along the span. This fact occurs because, in the radial profile, the collectors are positioned parallel to the lateral line of the Center Pivot, and they sample a very small region in the perpendicular direction to the movement, being these more sensitive to the effect of the flow variation of the sprinklers along the lateral representing a smaller sample surface, being, therefore, a practically unidirectional sampling; while in the circular profile the collectors are positioned perpendicular to the lateral line, so they sample a very small region between the position of the nozzles, on the direction of the Center Pivot radius, which makes them less sensitive to this variation. For meshed profile, the collectors are also parallel to the lateral line, however, the perpendicular sampling is greater, which also makes them less sensitive. Studies carried out by Rajan *et al.* (2015) and Li *et al.* (2016) with collectors in the radial arrangement, also observed that the use of different sprinklers along the lateral line of the pivot interfered in the irrigation water depth distribution.

The effect of towers movement is also a factor that cannot be neglected because, when they are in motion, the collectors in the circular and meshed patterns receive water applied by the emitters for a longer period, while for the collectors in the radial pattern the sprinklers pass over them for a short period.

The climatic variables observed during the essays (Table 2) also affected the distribution of water depths for all arrangement patterns of collectors. Wind speed, relative air humidity and temperature had mean values considered high according to Bishaw *et al.* (2016) and Molle *et al*. (2011), which causes water losses by drift and evaporation. The water depths distribution profiles for collectors positioned under Span 2 are shown in Figure 3.

Figure 3 – Irrigation water depths distribution profiles under Span 2, for collectors arranged in radial, meshed and circular patterns.

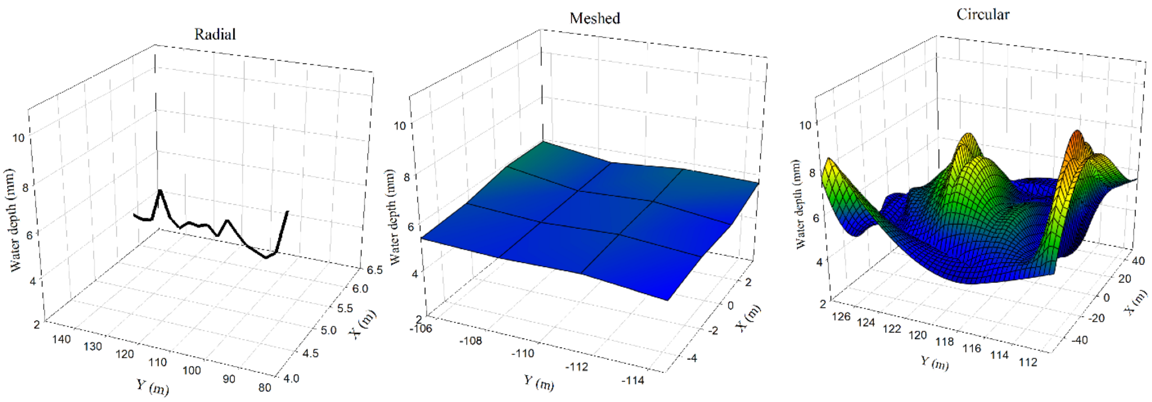


With the analysis of Figure 3, it was also possible to notice a difference between the distribution profiles of water depths for the three arrangements of collectors in Span 2, this one being more accentuated in relation to what was observed for the first span. It was observed that the meshed type showed less variation of water depths on the surface. The higher variations were verified for the radial and circular patterns. As for Span 1, the arrangement of nozzle diameters in this span (Table 1) was not increasing: each larger diameter “Super Spray” nozzle was followed by a smaller diameter “I-Wobler” nozzle, which resulted in flow variation and applied water depths. The variation caused by this installation feature was detected by sampling irrigation water depths at radial patterns.

The wind effect also affected, mainly, the values of water depths obtained for the meshed arrangement of the collectors, regardless of their direction, precisely because in this pattern the collectors are arranged two-dimensionally. In the circular and radial profiles, the collectors are arranged in a unidirectional way and, according to several authors, such as Ortiz *et al*. (2010) and Shaughnessy *et al.* (2013), the influence of the wind can be detected only when its direction coincides with the arrangement direction of collectors, therefore, as the wind direction was not measured at the exact moment that the lateral line passed over the collectors, it cannot be asserted with certainty its effect on the uniformity calculated for the radial and circular patterns.

The stoppage effect of the mobile towers affected the irrigation water depths distribution since it was possible to observe during the essays, in places where the towers have their movement interrupted, higher collected water depths. This effect was easy to observe at the circular profile as it has a single line of collectors perpendicular to the lateral line, that is, there is certain parallelism to the direction of the equipment's movement. For the meshed profile, the towers stoppage does not have a great effect, as the collectors are positioned bidirectionally. In the radial profile, the collectors are arranged in the direction of the system radius, that is, perpendicular to the lateral line movement direction so, the towers stoppage also does not significantly influence water depths sampling. The irrigation water depths distribution profiles for the three evaluated patterns of collectors, under Span 3, are shown in Figure 4.

Figure 4 – Irrigation water depths distribution profiles under Span 3, for collectors arranged in radial, meshed and circular patterns.



When observing Figure 4, it is noted that this span has the worst irrigation water distribution profile for the collectors in the circular pattern but, for the meshed pattern, the best sampling uniformity was obtained. There was also an improvement on the sampling profile for the radial pattern in relation to Spans 1 and 2, as only a single sprinkler model was installed in this area, in addition to an increasing arrangement of nozzle models, except for the first one (Table 1). Additionally, the area relief favored this result, by not presenting great variations, being considered flat.

In addition to the stoppage effect, the velocity of towers also affected, mainly, the circular profile, since the farther away from the equipment center, the linear displacement speed of the mobile towers tends to be higher, which means that tower 3 moves faster. According to several authors such as Rajan *et al.* (2015), Ouazaa *et al.* (2015) and Mohamed *et al.* (2021), the higher the equipment displacement velocity, the lower the uniformity, and this fact had more impact on the circular pattern because they were parallel to the movement direction of towers. Furthermore, Al-Gaadi *et al.* (2019), studying the uniformity within 8 spans of a Center Pivot system, observed a decreasing trend in spans farther away from the center.

Considering the results obtained by Shaughnessy *et al.* (2013) for 5 $m.s^{-1}$ wind velocity, the effect of wind direction and speed cannot be disregarded on irrigation water depth variation, especially for the meshed profile, since the observed wind speed by the aforementioned authors was between 3.26 and 5.30 $m.s^{-1}$, similar to the average observed in the present study. Furthermore, Bernardo *et al*. (2019) present a classification for wind velocity in irrigated areas, with speeds above 3.89 $m.s^{-1}$ considered "high". Furthermore, Bishaw *et al.* (2016) also observed that both wind intensity and direction, change the fate of water droplets, drifting them out of the disposition area of collectors.

Differences between water application profiles were also found in a study developed by Jardim *et al.* (2018), who evaluated the uniformity of water distribution under different collector arrangements. These authors concluded that for different forms of arrangement, the water depth applied by a sprinkler behaves in different ways, mainly due to the difference in overlap zones. The results regarding the ANOVA for the collectors pattern, span, and their interaction, are shown in Table 4.

Table 4 - ANOVA for collectors pattern, span, and their interaction over measured values of CUC and DUC.

Sources of variation	DF	F	
		CUC	DUC
Collectors Pattern (CP)	2	13.21**	13.21**
Span (S)	2	10.26**	10.26**
CP x S	4	3.65*	3.65*
Error	18		
Total	26		
General Mean		88.81%	82.22%
Coefficient of variation		3.71	6.38

**statistically significant at 1% probability; *statistically significant at 5% probability; DF: degrees of freedom.

The ANOVA showed that there is a significant difference due to the effect of collectors patterns, both for CUC and DUC values. The span effect also showed a significant difference at 1% probability. The interaction between factors also showed a significant difference, but at 5% probability. The means comparison between the radial, circular and meshed patterns can be seen in Table 5.

Table 5 – Means comparison test of the values of CUC and DUC, for different collectors patterns in field.

CP	CUC (%)	DUC (%)
Radial	84,20b	74,88b
Circular	90,99a	85,67a
Meshed	91,24a	86,10a

Values followed by the same lowercase letter do not differ significantly by the Scott–Knott test at 5% probability

Analyzing Table 5 could be noted that the radial type of arrangement is statistically different of other patterns. It was obtained with the meshed and circular dispositions higher values of CUC and DUC, being these rated as “Excellent” (Table 3). The radial pattern had lower means, with 84.20% CUC and 74.88% DUC, being them rated “good”.

Although the circular and meshed patterns have uniformities rated as excellent, this rating may not be extrapolated to the overall performance of the system. For the meshed, two-dimensional arrangement, the collectors are more concentrated, close together and covering a small area, relative to the total area, and the equipment movement, thus, it cannot accurately detect problems that occur between nozzles and on the Center Pivot movement direction. The circular pattern, on the other hand, does not detect problems located between spans but detects possible flowrate variations due to the area relief on the Center Pivot movement direction, thus, having the evaluated equipment pressure regulating valves installed for each emitter and the area being flat, a high uniformity value was expected.

The results obtained for the radial pattern are similar to those found by Bishaw *et al.* (2016) who had a CUC of 79% and a DUC of 70% in wind conditions of 2.5 m.s^{-1} which, according to these authors, was the main factor that affected the uniformity.

Li *et al.* (2016), when studying the effect of nozzle arrangement on the uniformity of a Center Pivot with radially arranged collectors, obtained an increase of 8.9% for CUC and 25.67% for DUC, along the spans when the nozzle arrangement was increasing. The same authors obtained a decrease of 21.81% for CUC and 43.71% for DUC when their disposition did not follow the ascending order. Al-Gaadi *et al*. (2019) obtained a variation in CUC from 76.83% to 93.45% over 8 pivot spans where, in addition to the wind, the difference in nozzles installed on the lateral line was also cited as the main factor affecting uniformity.

Based on what is observed in Table 5 and on the results and conclusions of the aforementioned authors, it is evident that the radial arrangement is an interesting sampling method to detect uniformity problems that occur between sets of nozzles. In the Center Pivot evaluated in this study, neither the pressure variation nor the relief affected, in a relevant way, the uniformity, being, mainly, the uniformity affected by the installation of nozzles that varied along the lateral line incorrectly, which led to a lower uniformity for radial sampling.

Rodrigues *et al.* (2019) studying the water application uniformity of a solid set sprinkler system for different collector patterns, obtained better coefficients for meshed arrangement, with a CUC of 92.85% and DUC of 86.98%. These authors cite that this was due to the better spatial sampling of this arrangement in relation to the overlapping irrigation water depths applied by the sprinklers. These results are similar to those presented in Table 5, in which it can also be seen that the arrangement of the collectors associated with the greater overlap had an influence on the uniformity sampled for the meshed arrangement.

The results referring to the mean comparison test between Spans 1, 2, and 3 can be seen in Table 6.

Table 6 - Means comparison test between Spans 1, 2 and 3, for the values of CUC and DUC.

Span	CUC (%)	DUC (%)
1	92,86a	88,65a
2	87,12b	79,52b
3	86,46b	78,47b

Values followed by the same lowercase letter do not differ significantly by the Scott–Knott test at 5% probability

There is a significant difference between Span 1 in relation to Spans 2 and 3 for both CUC and DUC. On Span 1, higher means were observed with a CUC of 91.80% and DUC of 88.65%, which are rated as “Excellent”. In Span 2, there was a CUC of 87.12% and a DUC of 79.52%, classified as “Good”; for Span 3, the CUC was 86.46% and the DUC 78.48%, also rated as “Good”.

Analyzing these results, it is noted that the further away from the center of the equipment, the values of CUC and DUC, for each span, have decreased. This is due to the towers period of movement because the closer to the center of the system, the towers tend to be less time in movement and more time stopped, in addition, the velocity of the towers closer to the center of the pivot is lower, what increases the uniformity of water application mainly in the direction of lateral line movement. During the tests it was observed that the period in which the mobile towers 1, 2, and 3 were functioning was 16; 27; and 46 s respectively, which shows that the first tower moves less time. Moreover, the effect of the wind cannot be neglected, as already explained. Several authors such as Ouazaa *et al.* (2015) and Mohamed *et al.* (2021) also observed that the effect operating cycles, as well as variations in the speed of the towers, affect the uniformity of irrigation on the travel direction.

Another fact to note is that the radial arrangement is always parallel to the meshed in the direction of the Center Pivot radius. As for the circular pattern, as it moves away from the center, it tends to be parallel to the meshed on the equipment direction of movement. This happens due to the increase in the diameter of the circles of each span in the direction of the radius, therefore, to some extent this influenced the fact that Spans 2 and 3 are statistically equal in terms of uniformity.

The comparison of the uniformity coefficients means for each of the patterns along the evaluated spans are presented in Table 7.

Table 7 – CUC and DUC mean values comparison for the interaction effect of the patterns of collectors and spans.

CP	CUC (%)			DUC (%)		
	Span			Span		
	1	2	3	1	2	3
Radial	78.99bB	82.00bB	91.62aA	66.60bB	71.37bB	86.68aA
Circular	93.45aA	87;23aA	92.30aA	89.60aA	79,70aA	87.75aA
Meshed	88.92aA	90.15aA	94.67aA	82.38aA	84.34aA	91.52aA

Values followed by the same lowercase letter on columns and uppercase on lines, do not differ significantly by the Scott–Knott test at 5% probability

Observing the results within each span, it is noted that in Spans 1 and 2, the uniformity values for the radial pattern were statistically different from the circular and meshed. On Span 3, all sampling patterns are statistically equal and are rated as “Excellent”. With this result, it is evident that for terrains with flat topography, constant pressure on the nozzles, and adequate sequencing of the nozzles along the lateral line, any sample pattern can be adopted to evaluate the uniformity performance of a Center Pivot.

Note that the radial pattern showed a higher CUC, of 91.62%, and DUC of 86.96%, in relation to the first two spans. For the third span, the water depths uniformity sampled on radial pattern could be classified as “Excellent”, while the rating for the first ones was considered as “Good”.

The circular pattern generated statistically equal uniformities along the spans, with CUC and DUC values rated as “Excellent”, except in Span 2, where CUC was 87.23% and DUC 79.70%, rated as “Good”. The meshed pattern was also statistically equal for all spans, with CUC and DUC rated as “Excellent” mostly, but not in Span 1 where CUC and DUC were “Good”.

Shaughnessy *et al.* (2013) studying CUC and DUC in a 6-span Center Pivot system observed variations along the spans in the order of 3% for circular and meshed layout, 9% for radial, where the wind was pointed out as the main factor affecting uniformity. Ortiz *et al.* (2010), studying the application uniformity of a Center Pivot for different application rates with collectors arranged in two radial lines, obtained a variation of CUC around 73.80% to 81.00% along the spans, where the wind was also cited as the factor that influenced most the results. The results of the aforementioned authors show how sensitive the radial type of arrangement is.

In general, radial sampling characterizes the longitudinal profile and better represents the influence of emitters on the behavior of the applied irrigation water depths. In this way, with few collectors, it is possible to observe the water depth behavior along with the irrigation lateral, which makes possible to make an inference about the need for changes in the system regarding the emitters. However, the fact that the sample width is smaller is a limitation, so it does not accurately express the behavior of the water depths along the entire irrigated circle, on the system movement direction.

The circular-type sampling pattern characterizes the behavior of the irrigation depths over the movement direction of the Center Pivot, along the circle irrigated by the equipment. Its limitation is that it does not cover all emitters installed along the lateral line, presenting only the behavior of the water depths applied by the emitters close to the line of collectors.

The meshed pattern sampling characterizes the irrigation depths applied both in the radial and on the movement direction of the Center Pivot. It provides coverage of a two-dimensional area in each span; however, its limitation is linked to the sample range, narrow in both directions, that is, it does not allow observing the behavior of the water depths in the entire irrigated circle. Thus, to have a larger area of coverage with this sample pattern, a high number of collectors is necessary.

Conclusions

In practical terms, it was possible to evaluate that, for areas with flat or slightly undulating topography and when using pressure regulating valves for the emitters, sampling in a radial pattern is sufficient, as causes of reduction in water uniformity application due to installed emitters and nozzles will be detected.

The combined use of the radial and circular sampling pattern is interesting for the evaluation of the uniformity of Center Pivots on situations of terrain with irregular topography and when there are sensitive variations in the dynamic operation pressure of the emitters.

Meshed-type sampling detects the effect of wind in any direction, as well as tower stoppage during the system operation. The radical and circular sampling patterns are only effective for detecting wind drift of sprayed drops when the wind direction coincides with the collector arrangement direction.

Finally, based on the results obtained in this article, it is recommended to investigate the spatial and temporal dependence between the applied water depth and the movement of Center pivot irrigation towers, in future works.

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Data availability statement

All the relevant data are included in the paper or its Supplementary Information.

Conflicts of interest

The authors have no conflict of interest to declare.

REFERENCES

ABNT. 1998. *NBR 14244: Equipamentos de irrigação mecanizada – Pivô Center e lateral móvel providos de emissores fixos ou rotativos – Determinação da uniformidade de distribuição de água*. ABNT, Rio de Janeiro, Brazil.

Al-Gaadi, K. A., Hassaballa, A. A., Tola, E., Kayad, A. G., Madugundu, R., Assiri, F., Edrris, M., Alameen, A., Edrees, H. 2019. Impacts of center pivot irrigation system uniformity on growth of potato crop and residual soil nitrogen. *International Journal of Agricultural and Biological Engineering*, **12** (1), 126-131. https://doi.org/10.25165/j.ijabe.20191201.3684

ASAE Standards. 2020. *ASAE S436.2: Test procedure for determining the uniformity of water distribution of center pivot and lateral move irrigation machines equipped with spray or sprinkler nozzles*. ASAE: St. Joseph, MI, USA. Volume ANSI/ASAE S436.2.

Barbosa, J. C. & Maldonado J. W. 2010. *AgroEstat: sistema para análises estatísticas de ensaios agronômicos*. Versão 1.0. Jaboticabal, FCAV/UNESP.

Bernardo, S., Mantovani, E. C., Silva, D. D., Soares, A. A. 2019. *Manual de irrigação*. 9th edn, UFV, Viçosa-MG, Brazil.

Bishaw D. & Olumama, M. 2016. Evaluating the effect of operating pressure and riser height on irrigation water application under different wind conditions in Ethiopia. *Asia Pacific Journal of Energy and Environment,* **3** (1), 41-48. https://doi.org/10.18034/apjee.v3i1.230

Borssoi, A. L., Vilas Boas, M. A., Reisdörfer, M., Hernández, R. H., Follador, F. A. 2012. Water application uniformity and fertigation in a dripping irrigation set. *Engenharia Agrícola*, **32** (4), 718-726. https://doi.org/10.1590/S0100-69162012000400011

Darko, R. O., Yuan, S. Q., Liu, J. P., Yan, H. F., Zhu, X. Y. 2017. Overview of advances in improving uniformity and water use efficiency of sprinkler irrigation. *International Journal of Agricultural and Biological Engineering,* **10** (2). https://doi.org/10.3965/j.ijabe.20171002.1817

Dwomoh, F. A., Yuan, S., Hong, L. 2013. Field performance characteristics of fluidic sprinkler. *Applied Engineering in Agriculture,* **29** (4), 529–536. http://dx.doi.org/10.13031/aea.29.10070

Heermann, D. F. & Hein, P. R. 1968. Performance caracteristics of self propeled center pivot sprinkler irrigation system. *Transaction of the ASAE, Saint Joseph*, **11** (1) 11-15. https://doi.org/10.13031/2013.39320

Jardim, C. C. S., Motomiya, A. V. A., Armando, E. J., Santos, R. O., Oliveira, R. A. 2018. Distribuição da lâmina de água em aspersão em diferentes arranjos de sobreposição. Convibra. https://convibra.org/congresso/res/uploads/pdf/2018_146_14989.pdf

Keller, J. & Bliesner, R. D. 1990. *Sprinkler and Trickle Irrigation*. Van Nostrand Reinhold, New York.

Lecina, S., Hill, R. W., Barker, J. B. 2016. Irrigation Uniformity under Different Socio-economic Conditions: Evaluation of Centre Pivots in Aragon (Spain) and Utah (USA). *Irrigation and Drainage*, **65** (4), 549-558. https://doi.org/10.1002/ird.2031

Li, L. H., Zhang, X. Y., Qiao X. D., Liu, G. M. 2016. Analysis of the decrease of center pivot sprinkling system uniformity and its impact on maize yield. *International Journal of Agricultural and Biological Engineering*, **9** (4), 108-119. https://doi.org/10.3965/j.ijabe.20160904.1129

Molle, B., Tomas, S., Hendawi, M., Granier, J. 2011. Evaporation and wind drift losses during sprinkler irrigation influenced by droplet size distribution. *Irrigation and Drainage*, **61** (2), 240–250. https://doi.org/10.1002/ird.648

Mohamed, A. Z., Peters, R. T., Sarwar, A., Molaei, B., Mcmoran, D. 2021. Impact of the Intermittency Movement of Center Pivots on Irrigation Uniformity. *Water*, **13** (9), 1167. https://doi.org/10.3390/w13091167

Mostacero, J. A. L., Magdaleno, H. F., Hernández, R. A. 2012. Implementación de riego a precisión en un sistema de pivote Center**.** *Revista Mexicana de Ciencias Agrícolas,* **3** (4), 705-718. http://www.scielo.org.mx/pdf/remexca/v3nspe4/v3nspe4a13.pdf

Ortiz, J. N., De Juan, J. A., Tarjuelo, J. M. 2010. Analysis of water application uniformity form a centre pivot irrigator and its effect on sugar beet (Beta vulgaris L.) yield. *Biosys Engr.*, **105** (3), 367-379. https://doi.org/10.1016/j.biosystemseng.2009.12.007

Ouazaa, S., Latorre, B., Burguete, J., Serreta, A., Playán, E., Salvador, R., Paniagua, P., Zapata, N. 2015. Effect of the Start–stop Cycle of Center-pivot Towers on Irrigation Performance: Experiments and Simulations. *Agricultural Water Management***, 147,** 163-174. https://doi.org/10.1016/j.agwat.2014.05.013

Rajan, N., Stephan, M., Rick, K., Monty, D., Song, C., Sumit, S., Ahmed, A. 2015. Emitter Uniformity and Application Efficiency for Centre-Pivot Irrigation Systems. *Irrigation and Drainage*, **64**, 353-361. https://doi.org/10.1002/ird.1878

Rodrigues, L. R., Nery, A. R., Sousa, F. R. R., Rodrigues, L. N. 2019. Uniformity coefficients in low-flow sprayers with different arrangements and height. *Green Journal of Agroecology and Sustainable Development*, **14** (2), 170-180. https://doi.org/10.18378/rvads.v14i2.6016

Shaughnessy, S. A. O., Urrego, Y. F., Evett, S. R., Colaizzi, P. D., Howell, T. A. 2013. Assessing application uniformity of a variable rate irrigation system in a windy location. *American Society of Agricultural and Biological Engineers,* **29** (4), 497-510. http://dx.doi.org/10.13031/aea.29.9931

Zhang, L., Merkley, G. P., Pinthong, K. 2013. Assessing whole-field sprinkler irrigation application uniformity. *Irrigation Science,* **31**, 87–105. https://doi.org/10.1007/s00271-011-0294-0

ARTIGO 2 – SPATIAL AND TEMPORAL VARIABILITY OF A CENTER PIVOT WATER APPLICATION

NORMAS DO PERIÓDICO *IRRIGATION SCIENCE*

(VERSÃO PRELIMINAR)

Spatial and temporal variability of a Center Pivot water application

Fidel Luís Rodrigues Tambo[1], Luiz Antonio Lima[1], Michael Silveira Thebaldi[1,2] and Flávia Vilela Corrêa[1]

[1]Department of Water Resources, Universidade Federal Lavras, Campus Universitário, PO Box 3037, ZIP Code: 37.200-900, Lavras, Minas Gerais, Brazil.

(E-mail*: fideltambo@gmail.com*; *lalima@ufla.br; michael.thebaldi@ufla.br; flavia-vilela-correa@hotmail.com)*

^[2] Corresponding author. E-mail address: *michael.thebaldi@ufla.br.*

Abstract

The effect of discrete movement of Center Pivot towers on water distribution uniformity is a phenomenon difficult to demonstrate at field; thus, in this paper, dependence of uniformity of water application on movement of towers was investigated. For this, GNSS receivers were installed on 3 Center Pivot's towers to track their location during system operation. The data obtained were modeled by a computer program developed in Visual Basic for Applications, in an Excel® software spreadsheet. Analysis of the temporal behavior of water depths due to the movement of each tower was described by Fourier series. The results showed that towers closer to the center of irrigated circle presented longer stopping times, short movement times and lower displacement speeds, which resulted in greater variability in applied water depth. Irrigation uniformity was also affected by misalignment angle between the Center Pivot spans, being the uniformity greater the smaller the misalignment angles is. Misalignment angles below 2° are not recommended as they result in very short cycle times (time in motion) which can cause the alignment sensors of the towers closer to the center not to detect it and, therefore, keeping tower stopped. Finally, it was noticed that the amplitude of water depths as function of the tower movement increased when maximum misalignment angle increases.

Introduction

The Center Pivot is an irrigation equipment with circular motion that applies water by sprinkling. It is formed by a movable lateral line supported by towers that move on wheels. In this way, they irrigate a circular area by rotating the lateral line around a fixed point (Graf et al. 2020). The low maintenance and labor costs, high degree of flexibility in relation to the variation of the irrigation depth by sector and by culture, made this system attractive in several countries, mainly in the current context of water resources management and environmental concern (from Albuquerque et al. 2020; Graf et al. 2020). For example, in Brazil, by the year 2020, the irrigated area by Center Pivot systems reached 1.6 million hectares, which corresponds to about 20% of the total irrigated area (EMBRAPA 2020); in the USA, by 2021, it reached 7.9 million hectares, which corresponds to about 60% of the total sprinklers irrigated area (Agricultural Systems Research Unit 2021).

There are Center Pivots that move by hydraulic oil pumping, being these capable of keeping the towers in continuous movement, which guarantees a perfect alignment of the lateral line. However, these systems are rare, especially in Brazil and even in USA. Therefore, it is more common to use Center Pivots powered by electric motors, because of their simplicity and low operating cost. In these systems, each tower is equipped with an independent electric motor, whose activation occurs discontinuously. The last tower is the one that guides the movement of the equipment and triggers the movement of the other towers in response to the misalignment of the span closer to it (Ouazaa et al. 2015).

However, this type of movement generates a problem regarding the maximum uniformity that can be achieved during water application by this type of system: as the system's mobile towers move at constant speed and they run on different perimeter lengths, the alignment is done by mechanical sensors; when there is a deflection, usually 5º between a span and the adjacent one, its movement is automatically activated or deactivated, so that the misalignment is corrected (Rajan et al. 2015; Li et al. 2016; Mohamed et al. 2021).

Ouazaa et al. (2015) mention that the performance of a Center Pivot Pivot starts to be compromised when the misalignment angle between towers is greater than 5º, since above this value the towers remain at rest for a long time, which makes that sprinklers closer to a stopped tower to apply water for a long time in the same place, which affects, therefore, the irrigation uniformity of the equipment. Thus, Mohamed et al. (2021) states that, in part, the uniformity of water application can be achieved by aligning the Center Pivot towers, mostly along the direction of movement of the equipment. The same authors also state that as the Center Pivot towers move discontinuously, in movement cycles that occur at time intervals with different durations, the applied water depth varies with the application time on an area affecting, thus, water uniformity.

Hanson and Wallender (1986) evaluated the effect of successive activations and interruptions of the movement of a Center Pivot with ten towers, on its irrigation uniformity; and they observed that the low uniformity in the direction of movement of the equipment is partly related to this effect, but they were not able to precisely define its level of importance, since when performing field tests, several environmental factors act simultaneously on the system (wind velocity and water drift, for example), and also the movement of the towers (position versus time) as well as the fact that in a subsequent irrigation towers rarely stop at same position as at previous irrigation.

In this way, the use of computer simulations can be a viable alternative to accurately evaluate the effect of discrete movement of towers on system performance, without the intervention of other variables that affect the field performance. It is expected that the fitting of time series that relate applied water depths as a function of tower movement time can explain the variations that occur due to the stoppage time and the towers movement cycles.

Therefore, it is proposed at this research to study the dependence between uniformity of water application and the movement of the towers of a Center Pivot, by the observation of the mechanical movement of the mobile towers using GNSS receptors, and its modeling and simulation; to estimate Christiansen's uniformity coefficient due to the variation of the misalignment angle between its mobile towers; and to analyze the temporal behavior of the distribution of water depths applied according to the movement of the towers, using Fourier series, what is an innovative approach to this problem.

Material and methods

The study was carried out on a Tifton 85 grass field for hay production in a farm, located in Bom Despacho city, state of Minas Gerais, Brazil, at geographic coordinates 19º36'23.88" S; 45º16’14.98” W and 631.5 m of altitude.

The evaluated Center Pivot system irrigates an area of 10.95 ha and has three mobile towers plus an overhang with no end gun. Its technical characteristics are revolution time with the percent timer set to 100% (complete revolution in 7.10 hours), 185.7 m length of lateral line (57.1 m in the first span, 51.4 m in the second span, 51.1 m in the third span and 25.4 m of overhang). At its maximum speed (100%), the expected average irrigation depth is 3.59 mm for an 86 m^3h^{-1} flow.

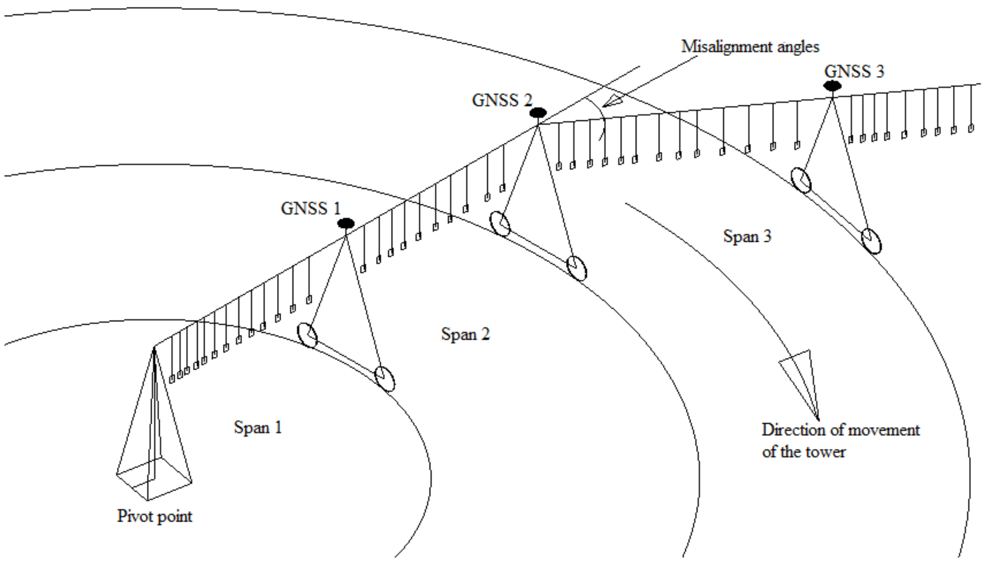
At first and second spans two types of sprinklers (Superspray and I-Wobler) alternate along each span. At third span and at overhang, only I-Wobler type sprinklers were installed. Each sprinkler was connected to a pressure regulating valve with a working pressure head of 10 psi. The combinations of emitters and nozzles used in each span of the evaluated system are listed in Table 1.

Table 1 Emitters and nozzles used in each span of the evaluated Center Pivot irrigation system

Span 1		Span 2		Span 3		Overhang	
Emitter	Nozzle	Emitter	Nozzle	Emitter	Nozzle	Emitter	Nozzle
Superspray	7	I-Wobler	14	I-Wobler	17.5	I-Wobler	17.5
I-Wobler	9	Super spray	9	I-Wobler	14	I-Wobler	18
Superspray	4.5	I-Wobler	14.5	I-Wobler	14.5		
Super spray	5	I-Wobler	15	I-Wobler	15		
I-Wobler	7.5	Super spray	10	I-Wobler	15		
Super spray	6	I-Wobler	15.5	I-Wobler	15.5		
I-Wobler	8.5	I-Wobler	16.5	I-Wobler	16		
I-Wobler	10	Super spray	10.5	I-Wobler	16.5		
Super spray	6.5	I-Wobler	17	I-Wobler	16.5		
I-Wobler	11	I-Wobler	17.5	I-Wobler	17		
I-Wobler	12	Super spray	11.5				
Super spray	8	I-Wobler	18				
I-Wobler	13	I-Wobler	18.5				
I-Wobler	13.5	I-Wobler	19				
Super spray	8.5	Super spray	12				
Super spray	9	I-Wobler	19.5				
		Super spray	12.5				

To study the movement of towers, three high precision differential GNSS receivers (Spetral Precision GNSS L1, L2, GLONASS PROMARK220) were installed on top of the mobile towers, to determine their location along its perimeter, during irrigation time. The GNSS receivers were programmed to georeference the position of towers in UTM coordinates every 3 seconds, along the half-irrigated circle, that is, 180º. The arrangement of GNSS signal receivers in field, for tracking the positions of the towers and misalignment between spans, is presented in Fig. 1.

Fig. 1 Arrangement scheme of GNSS receivers in field for tracking the positions of the towers and misalignment between spans, due to the system's movement.



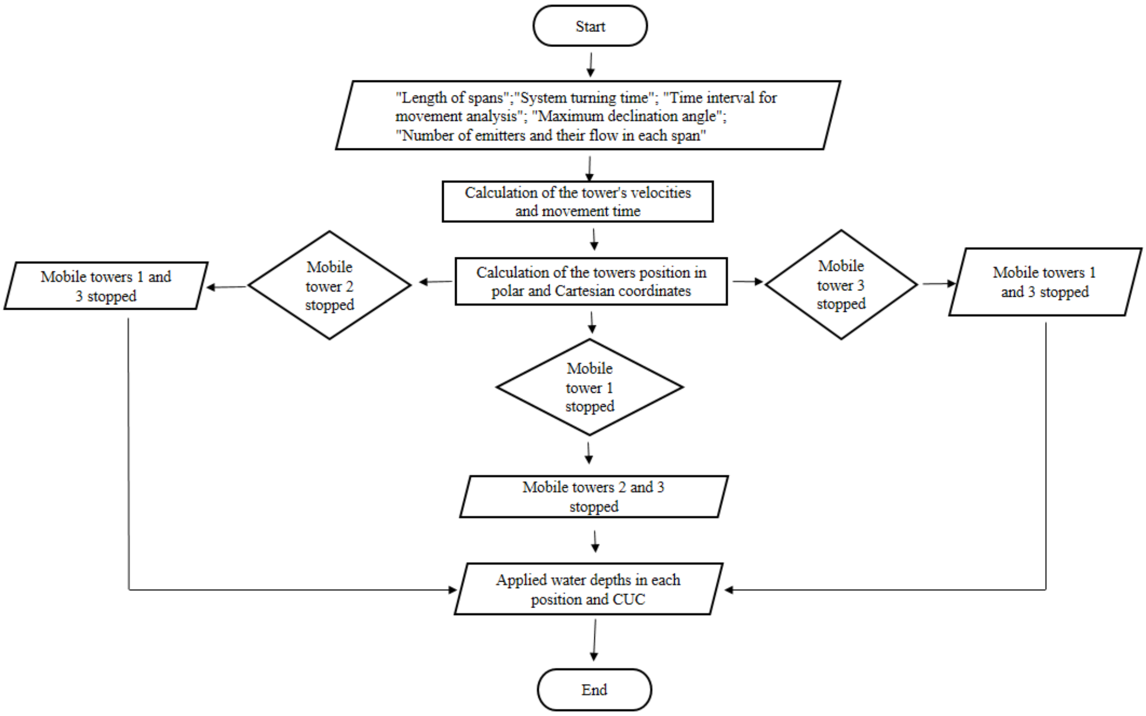
During the study, the Center Pivot was set up to operate at 66% velocity, and the GNSS receivers were adjusted to have a horizontal accuracy of 5mm + 1ppm and a vertical accuracy of 10mm + 1ppm, sufficient to characterize the movement of towers. With the data collected in the field by the GNSS receivers, linear models were fitted to describe the movement of each tower as a function of time, in addition to allow the observation how long each tower would be in motion or stopped. The time that the tower remained stopped was determined by observing the intervals in which the GNSS receivers did not register a variation of the coordinates along the total path traveled by the tower. These data also made possible to calculate the misalignment angle between towers, which was determined for each tower movement cycle using the coordinates of neighboring towers.

The linear models that describe the movement of each Center Pivot tower as a function of time were inserted, as programming codes, in a computer program developed in Visual Basic for Applications programming language, in an Excel® software spreadsheet.

The program was designed to simulate the movement of the irrigation system, determining the geometric position of each tower in relation to the adjacent one, both in polar and rectangular coordinates; it also calculates the water depth applied in each geometric position along the path covered by the mobile towers; the movement and stoppage times of each tower, as well as their travel velocities; and water application uniformity coefficients.

The computer simulations aim to study the irrigation system by controlling several factors that act in field interfering on results, such as: possibility of establishing the absence of wind and desired working pressure, defining a time interval for water depth applied by the emitters and to vary the maximum declination angle between spans. A flowchart that presents the operating steps of the developed program to simulate the movement of a Center Pivot, can be seen in Fig. 2.

Fig. 2 Flowchart of the operating steps of the software developed to simulate the movement of a Center Pivot irrigation system



The developed program is available for free on the website of the Department of Water Resources of the Universidade Federal de Lavras. To develop the program, text boxes were initially generated to allow the entry of technical data of the studied Center Pivot, in addition to the time interval to be considered for towers movement; command buttons were also inserted to make possible to perform the calculations by a single mouse click, and the data output is shown as an Excel® spreadsheet.

Eq. 1 was inserted to calculate the speed of each tower in relation to the pivot point.

$$V_{rs} = \frac{2\pi \, . \, R_s}{Tg} \tag{1}$$

Where:

Tg: Revolution time (s);

V_{rs}: displacement velocity of the tower (m s^{-1}); and

2π . R_s: perimeter travelled by the mobile towers of R_s radius in relation to the pivot point (m).

The positions of towers, in radians, at each time interval until completing the Center Pivot revolution time were determined by the mathematical models fitted with the positions collected with GNSS receivers. A text box was fixed for the entry of the maximum misalignment angle value between towers. With this value, the code calculates the cycle time or the time that each tower remains on movement before activating the adjacent tower, using Eq. 2.

$$t = \frac{\theta_{max}}{\omega} \tag{2}$$

Where:

t: Tower movement time (s);

θ_{max}: Misalignment between towers (rad); and

ω: Tower angular velocity (rad.s^{-1}).

Additionally, the polar coordinates of towers were converted into Cartesian coordinates by Eqs. 3 and 4.

$$X = R_s . \sin\theta \tag{3}$$

$$Y = R_s . \cos\theta \tag{4}$$

Where:

X e Y: Tower positions in Cartesian coordinates (m); and

θ: Tower position in polar coordinates (rad).

Comparison of the movement of the Center Pivot’s towers evaluated in field with the movement of the towers simulated by the computer program was carried out by calculating the mean absolute error (MAE – Eq. 5), mean bias error (MBE – Eq. 6) and root mean square error (RMSE – Eq. 7) (Willmott and Matsuura 2005). The MAE was calculated to compare how close the values of tower positions obtained with the spreadsheet are to those measured with GNSS; the MBE was calculated to determine the bias of the values calculated by the electronic spreadsheet; and RMSE was calculated to provide an indication of accuracy between observed field and simulated positions.

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|\widehat{p_i} - O_i| \tag{5}$$

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(\widehat{p_i} - O_i) \tag{6}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - \widehat{p_i})^2} \tag{7}$$

Where:

$\widehat{p_i}$: observed value, by the GNSS receiver, at position i;

O_i : value calculated by the spreadsheet at position i; and

n: number of observations.

When verifying the accuracy of the simulated positions in relation to those observed, the program was used to simulate the movement of the Center Pivot with different misalignment angles to make a correlation between angles and irrigation uniformity, in the direction of equipment movement. Therefore, Eq. 8 was implemented into the programming code, to simulate water depths applied by the spans at each position during the mobile towers travelling course, considering a time interval of 3 s, which was the same interval adopted for the collection of observed data.

$$D_a = \frac{N_e . q_b . t}{\theta . (R_s - R_{s-1})^2} \quad (8)$$

Where:

D_a: Applied gross water depth (mm);

q_b: Average emitter flow ($L.h^{-1}$);

N_e: Number of emitters on each span;

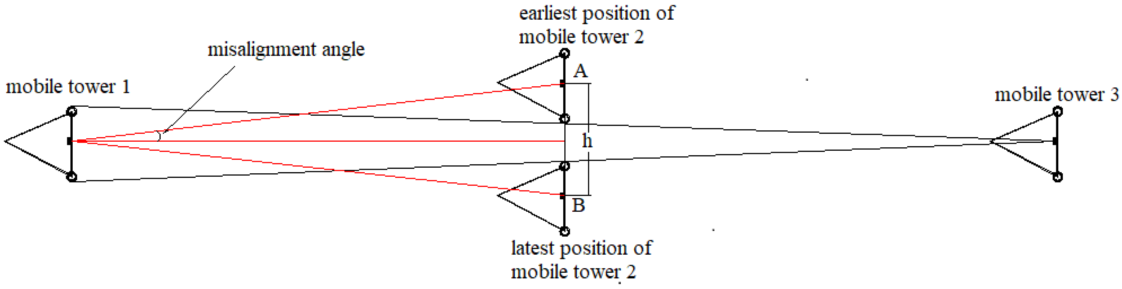
Rs: Tower travelling radius (m); and

R_{s-1}: Previous tower travelling radius (m).

To obtain the emitters flow, all sprinkler models and their respective installed nozzles were verified in each span and, through the manufacturer's catalog, the flow for the regulated working pressure was determined.

The three-tower method, proposed by several manufacturers, mentions that the pivot alignment procedure begins at the last tower, where from this, an imaginary line is drawn from the edge of the gearmotor of mobile tower 1 to the center of the gearmotor of mobile tower 3, as illustrated in Fig. 3. With the imaginary lines drawn, the central tower (mobile tower 2) must be positioned in such a way that its gearmotor stops its movement in position “A” and starts in position “B”. Alignment is considered correct when the gearmotor of tower 2 starts and stops its movement at equal distances from gearmotor 3, and the first mobile tower (located near the pivot point) can be aligned by making to coincide an imagine line between its gearmotor and the vertical riser pipeline.

Fig. 3 Sketch of the three-tower method for aligning the lateral line of a Center Pivot



Considering the three-tower method, the maximum misalignment angle can be calculated from Eq. 9.

$$\theta_{max} = \tan^{-1}\left(\frac{h}{2.\ L}\right) \quad (9)$$

Where:

θ_{max}: maximum misalignment angle (degrees);

L: span length (m); and

h: width measured from the center of the gearmotor of the middle tower, when it is positioned at point “A”, to the center of the gearmotor when it is positioned at point “B” (m).

Depending on the length of the spans generally used by Center Pivot systems manufacturers and for a 4 m long width (distance from one wheel to the other one at same tower) como Valley Irrigation; ZIMMATIC BY LINDSAY, the maximum misalignment angle obtained by the three-point method may vary as shown in Table 2.

Table 2 Maximum misalignment angles allowed depending on the span lengths adopted by different Center Pivot manufacturers

L (m)	θ_{max}
34.3	6.12º
34.6	6.07º
41.1	5.12º
41.5	5.07º
47.8	4.40º
48.16	4.37º
48.8	4.31º
51.8	4.06º
54.6	3.86º
54.86	3.84º
56.92	3.70º
61.3	3.44º

To determine the effect of misalignment angle on uniformity, simulations of movement of the Center Pivot were performed for different adopted misalignment angles (0.45º; 1.20º; 2.23º; 3.45º; 4.02º and 5.23º) without exceeding the largest angle shown in Table 2, keeping the analysis time interval of 3s. With this, different movement times and applied water depths could be evaluated. With the obtained water depths, the Christiansen Uniformity Coefficient (CUC) modified by Heermann and Hein (1968) were calculated in each span, in the direction of movement of the irrigation system, for all misalignment angles adopted in the simulation, using Eq. 10. Subsequently, the CUC values were related to maximum misalignment angles adopted, to observe their effect on irrigation uniformity.

$$\mathrm{CUC} = 100.\left[1 - \frac{\sum_{i=1}^{n} S_i . \left|D_i - \overline{D}_p\right|}{\sum_{i=1}^{n} D_i . S_i}\right] \tag{10}$$

Where:

n: number of simulated water depths;

D_i: simulated water depth at point i (mm);

S_i: distance from a water depth application point to the pivot point; and

$\overline{D}_p$: weighted average water depth applied in an irrigated area, which is calculated by Eq. 11.

$$\overline{D}_p = \frac{\sum_{i=1}^{n} D_i . S_i}{\sum_{i=1}^{n} S_i} \tag{11}$$

The classification of calculated CUC was made using the limits presented in Table 3.

Table 3 Classification of the Christiansen Uniformity Coefficient (CUC).

Rating	CUC (%)
Excellent	> 90
Good	80 - 90
Fair	70 - 80
Bad	60 - 70
Unacceptable	< 60

Source: Adapted from Bernardo *et al.* (2019); Borssoi *et al.* (2012); and Keller & Bliesner (1990).

Finally, in order to evaluate how stopping and moving times of each tower can affect the applied water depths, the depths in each geometric position were analyzed, as a function of time, continuously, during towers travelling course, in time intervals of 3 s. The analysis of the water depths applied by the Center Pivot, per unit of time, was performed using a Fourier series, by fitting a periodic equation of the water depths with Eq. 12.

$$f(t) = \frac{A_o}{2} + \sum_{n=1}^{\infty}\left[A_n \cos\frac{n\pi t}{Z} + B_n \sin\frac{n\pi t}{Z}\right] \tag{12}$$

Where: A_o, A_n e B_n are the Fourier coefficients related to the periodic properties of the function f(t), as mentioned by Humes et al. (1984), obtained by Eqs. 13, 15 and 15.

$$A_0 = \frac{1}{2Z}\sum_{j=1}^{2L} D_j \tag{13}$$

$$A_n = \frac{1}{Z}\sum_{j=1}^{2L}\left(D_j \cos\frac{n\pi t_j}{Z}\right) \tag{14}$$

$$B_n = \frac{1}{Z}\sum_{j=1}^{2L}\left(D_j \operatorname{sen}\frac{n\pi t_j}{Z}\right) \tag{15}$$

Where:

D_j: corresponds to the values of the water depth (mm) applied in time t_j. In this case, it is the value of the water depth obtained by simulation every 3 s, during the towers movement;

t: time (s);

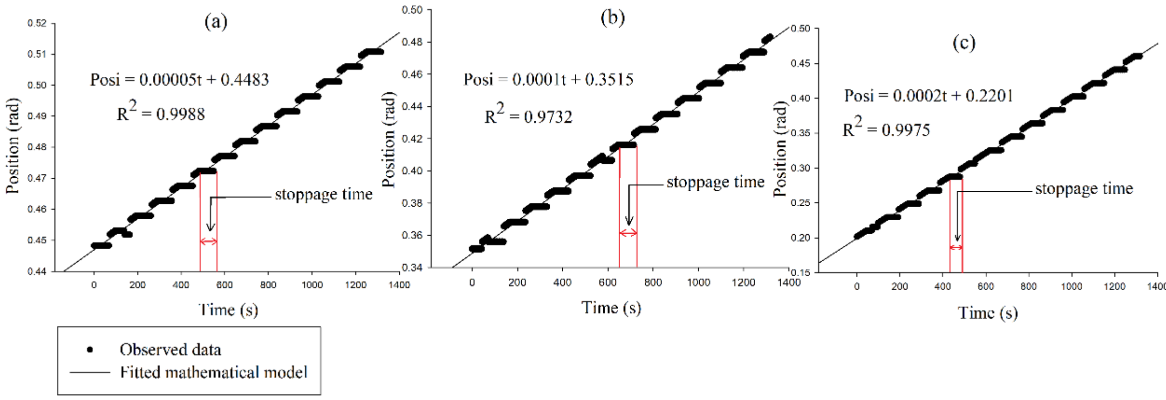
n: sequence number; and

Z half the width of the observed data range.

Results and discussion

The graphs with the movement of the Center Pivot towers, as well as the fittings of the models that describe the movement of each tower, obtained by the coordinates recorded with the GNSS receivers, are shown in Fig. 4.

Fig. 4 Graphs and models that describe the movement of mobile towers 1 (a), 2 (b) and 3(c) of the evaluated Center Pivot system



The fitted mathematical models that describe the movement of towers showed very strong fitting coefficients, with R^2 equal to 0.99; 0.97 and 0.99 for mobile towers 1 (Fig. 4a); 2 (Fig. 4b) and 3 (Fig. 4c), respectively. This means that these models accurately determine the positions of the mobile towers, as a function of time, during irrigation.

When observing Fig. 4, it is noted that mobile tower 3 (Fig. 4c) moved faster than towers 1 (Fig. 4a) and 2 (Fig. 4b) with an average linear velocity of 0.040 $m.s^{-1}$, higher 0.014 and 0.027 $m.s^{-1}$, for towers 2 and 3, respectively. This fact occurs because mobile tower 3 is farther from the center of the equipment and, therefore, must travel around a a larger perimeter and complete the turn in a time interval similar to towers 1 and 2. Since the features of the towers' motors were the same, this difference in velocities was due to different stoppage times, since the determined velocity was the average, considering the movement and stopping processes.

Regarding the stoppage times, they are represented by the time intervals in which the observed data is invariant. The mobile tower 1 (Fig. 4a) has a longer stoppage time of 70 s, thus, the movement cycles of this tower, between activations and interruption, occur less frequently, causing its movement to be slower. For mobile tower 3 (Fig. 4c), the stopping time is shorter, with 42 s of duration, motive why this tower's movement cycles are more frequent, making its movement faster.

The declination angle between mobile towers 1 and 2 was 3.5º; and between towers 2 and 3 was 4.9º. Note that the declination angles between towers were different, reason why there is a difference in the stopping times. In addition, the fact that the angle between towers 2 and 3 is greater, leads to a greater stoppage time for tower 1, as it remains at rest longer, until tower 3 travels the 4.9º path and the tower 2 corrects this misalignment.

Ouazaa et al. (2015) and Mohamed et al. (2021) mention that the stoppage time is what leads the emitter to apply more water in the same place during a certain time interval, which affects the equipment performance. Therefore, it can be said that the emitters installed in mobile tower 1 can affect more the uniformity in the direction of central pivot movement, and that the effect of the towers' stopping time on the water application uniformity increases as it approaches of the system's center (Tambo et al. 2022). Another fact to note is that a long stoppage time is not recommended in soils with surface sealing problems, because the impact of irrigation water droplets in the same region for a long period can disaggregate the soil close to the surface, leading to the formation of a fine particulate that can generate sealing, reduce infiltration and generate surface runoff (Rodrigues et al. 2001; King and Bjorneberg 2011; Al-Baaj and Lewis 2019; Mohamed et al. 2021).

When analyzing data referring to velocity of towers of central pivot irrigation systems, Rajan et al. (2015) and Al-Gaadi et al. (2019) cite that a higher tower velocity is also one of the factors that affects center pivot irrigation uniformity. Therefore, it can be said that the emitters installed at third span can affect the overall performance of the equipment, due to its displacement velocity. After the computational simulation of the operational conditions of the evaluated center pivot, the simulation errors are shown in Table 4.

Table 4 Movement simulation error (MAE, MBE and RMSE) of the evaluated center pivot irrigation system

Mobile tower	MAE (rad.)	MBE (rad.)	RMSE (rad.)
1	0.013	-0.013	0.00025
2	0.018	-0.015	0.00055
3	0.042	-0.039	0.003

It was observed, for all mobile towers, small values of RMSE and MAE, which determines that the program developed to simulate the movement of the center pivot towers presents results that are close to the values observed in the field. It is observed that there is a tendency for the RMSE value to increase from the mobile tower 1 to the towers further away from the center of the irrigation system; greater or lesser errors in the movement simulation, by the first order models, are related to the stoppage time, that is, the more stopped the tower is, the greater the error. Although low errors were observed, negative MBE values lead to the verification of an underestimation of the position of the towers. Table 5 presents the results of irrigation uniformity coefficients obtained by simulation, due to different misalignment angles between towers.

Table 5 Simulation of the uniformity coefficient of water application by center pivot system, from the different misalignment angles simulation

Maximum misalignment angle	Cycles movement duration (s)	Stoppage time (s)	Average CUC (%)
0.45º	32	40	99.03
1.20º	50	63	98.33
2.32º	76	95	97.91
3.45º	99	124	96.48
4.02º	120	150	95.59
5.23º	150	188	92.50

Different maximum misalignment angles adopted in the simulation generated different duration periods of tower stoppage and movement cycles, as can be seen in Table 4. It can be pointed that for all misalignment angles the CUC values could be classified as excellent, according to Bernardo et al. (2019); Borssoi et al. (2012) and Keller and Bliesner (1990) reminding that the simulation was performed only as effect of misalignment angles between spans, establishing conditions of null wind speed and constant pressure head of 10 psi. It is possible to conclude that the smaller the declination angle between spans, the greater the irrigation uniformity. On the other hand, the maximum deviation of 5 to 6 degrees existing in center pivots seems to be, according to table 4, defined to guarantee a uniformity value (CUC) greater than 90%.

For the smallest adopted maximum misalignment angle, 0.45º, the duration time of the movement and stoppage cycles of the tower were 32 s and 40 s respectively, which resulted in the highest value of CUC, 99.03%. For the highest adopted maximum misalignment angle of 5.23º, the duration time of the movement and stoppage cycle of the tower were 150 s and 188 s respectively, the highest observed. As result, the lowest CUC value of 92.50% was obtained. With these results, it can be seen that the more aligned the lateral line during equipment operation, the higher the irrigation uniformity.

In a study developed by Mohamed et al. (2021), from the simulations of a high-velocity center pivot operation, at different time intervals and for a final tower displacement velocity of 0.025 $m.s^{-1}$, for a movement cycle of 60 s, a CUC value of 95 % was obtained; and for a movement time of 30 s the CUC was 98%, while for 120 s the CUC was 80%.

Ouazaa et al. (2015), when studying the effect of tower stoppage time on a 4 mobile towers center pivot performance, found that the variability in uniformity increased with increasing misalignment, and concluded that a misalignment above 5º, has a negative impact on the irrigation uniformity in the direction of equipment's movement, in an evaluation that considered the wind action. It was observed that misalignment above this angle in the present study also led to a lower CUC, but this continued to be classified as excellent level.

Omary and Sumner (2001) evaluated the performance of a center pivot irrigation system by computer simulations, changing the cycle time of the towers and movement time percentages. They observed that the water distribution uniformity was 98.4%. According to these authors, the uniformity coefficient of water application was improved by 14.2% due to the decrease in cycle time, as result of a maximum declination angle between towers reduction.

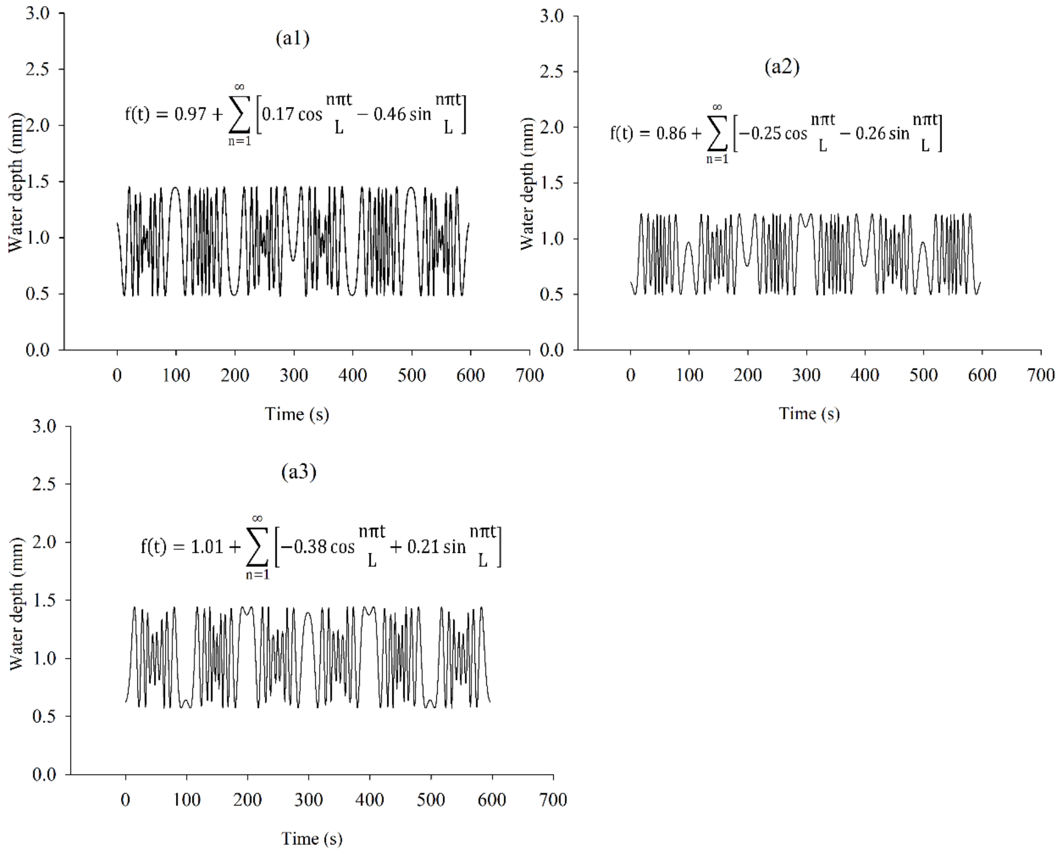
Despite the smaller misalignment angles present high CUC, what leads to water savings, Mohamed et al. (2021) cite that the most common cycle time of the final tower (considering different center pivot manufacturers) is 60 s. Therefore, observing Table 4, it is noted that when the angles are reduced below 2º, the uniformity variation is not significant and the movement occurs more frequently due to the reduction of cycle times, becoming less than 60 s. With this, it can be said that very small misalignment angles require very precise tower drive mechanisms, which are difficult to find in the field; thus, possible failures can occur, regarding mostly alignment sensors, to detect such small angles at the risk of towers remain stopped.

In this sense, a study developed by Ouazaa et al. (2015) with a center pivot with 4 mobile towers, shows that it was only possible to verify uniformity variability for misalignment between spans above 2º. Thus, the angles of 0.45º and 1.20º used in the present study for water application evaluation can be discarded.

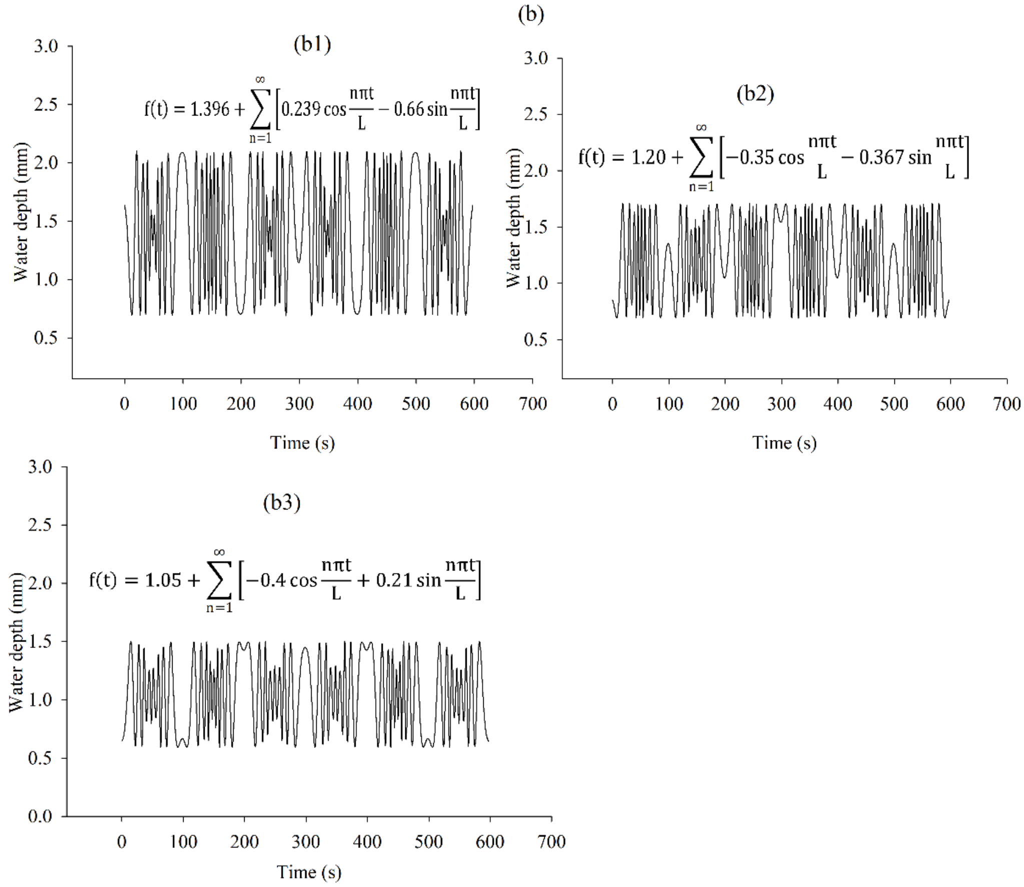
Fig. 5 shows the Fourier time series referring to the water depths applied due to the simulated movement time, for time intervals of 3 s and misalignment angles equivalent to 2.32º; 3.45º; 4.02º; and 5.23º along the course covered by each mobile tower.

Fig. 5 Water depths applied during the movement of mobile towers 1, 2 and 3, for misalignment angles of 2.32º (a); 3.45º (b); 4.02 (c); and 5.23º (d), fitted to Fourier time series.

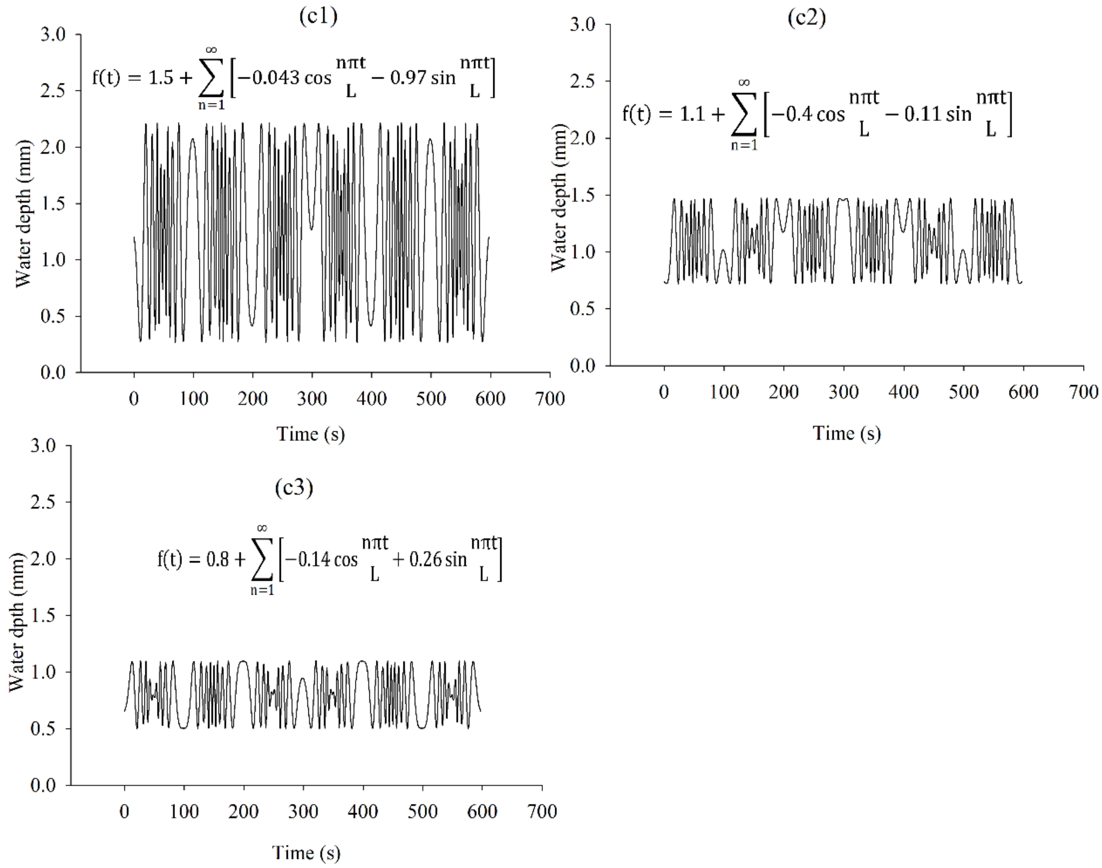
(a)



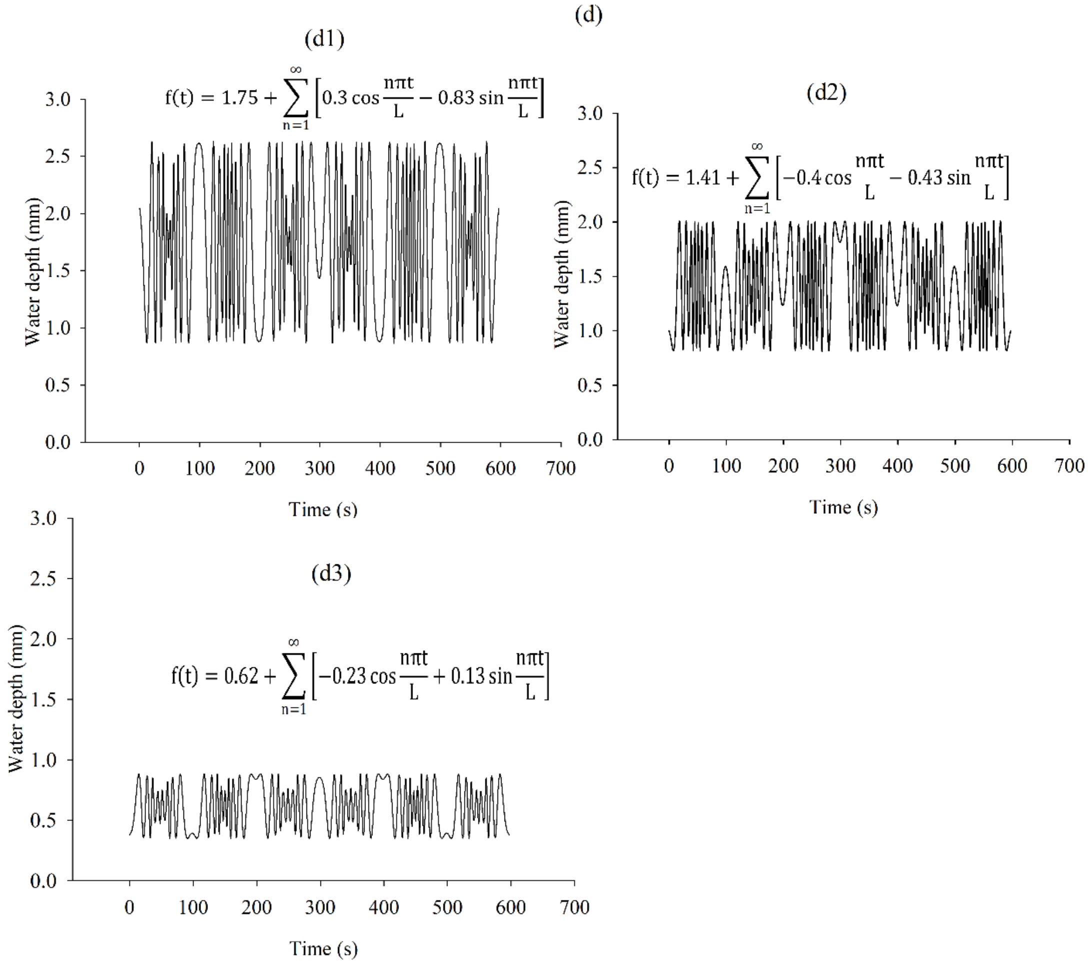
(b)



(c)


(c1)
f(t) = 1.5 + ∑_{n=1}^{∞} [−0.043 cos nπt/L − 0.97 sin nπt/L]
(c2)
f(t) = 1.1 + ∑_{n=1}^{∞} [−0.4 cos nπt/L − 0.11 sin nπt/L]
(c3)
f(t) = 0.8 + ∑_{n=1}^{∞} [−0.14 cos nπt/L + 0.26 sin nπt/L]
Water depth (mm)
Water dpth (mm)
Time (s)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0
100
200
300
400
500
600
700

(d)


(d1)
f(t) = 1.75 + ∑_{n=1}^{∞} [0.3 cos nπt/L − 0.83 sin nπt/L]
(d2)
f(t) = 1.41 + ∑_{n=1}^{∞} [−0.4 cos nπt/L − 0.43 sin nπt/L]
(d3)
f(t) = 0.62 + ∑_{n=1}^{∞} [−0.23 cos nπt/L + 0.13 sin nπt/L]
Water depth (mm)
Time (s)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0
100
200
300
400
500
600
700

It is noted that in almost all misalignment angles, the A0 coefficient was lower in mobile tower 3 and higher in mobile tower 1, since this coefficient represents the applied water depth, at the moment of Center Pivot activation and the beginning of the towers movement. Thus, as the mobile tower 3 is the first to have the movement started after pressurizing the lateral line, the water depth applied as a function of its movement tends to be smaller at the beginning; mobile tower 1, on the other hand, takes longer to move, after pressurizing the lateral line, so there is a greater application of water at the beginning of the system's operation, which increases the A0 coefficient of it.

The coefficients An and Bn define the water depths amplitudes that can reach during the towers movement, which is why it is noted that the mathematical models generated for the mobile tower 3 presented lower values of these, mostly due to the shorter stoppage time, which means that an adjustment of the percent timer to higher velocity can significantly affect the coefficients Ao, An and Bn of the Fourier model. The results of the water depths applied by the emitters due to towers movement time, for different maximum misalignment angles, obtained by the Fourier series fitting, are presented in Table 6.

Table 6 Water depths applied by emitters due to towers movement time, for different maximum misalignment angles.

Misalignment angle	Repouso			Movimento		
	Mobile tower 1	Mobile tower 2	Mobile tower 3	Mobile tower 1	Mobile tower 2	Mobile tower 3
	Applied water depth (mm)					
2.32º	1.10	0.97	1.20	1.46	1.23	1.45
3.45º	1.50	1.36	1.36	2.10	1.70	1.70
4.02º	1.75	1.20	0.80	2.23	1.47	1.10
5.23º	1.85	1.60	0.75	2.64	2.00	1.15

Note that there is a decrease tendency of the water depths applied by the emitters, both in motion and at rest, for misalignment angles of 4.02º and 5.23º, as it moves away from the center of the Center Pivot. In addition, there is also an increase in the water depths due to the movement of mobile towers 1 and 2, as the maximum misalignment angle increases. Both the reduction and the increase of the applied water are related to the stoppage time of the towers because, according to Hanson and Wallender (1986) and Mohamed et al. (2018), the longer the mobile tower remains at stopped in the same region, obviously the greater the water applied at that point, which can negatively impact the system performance.

For all adopted angles, the series of generated water depths due to the movement time of the mobile tower 1, presented the highest applied water depth amplitudes because it must remain stopped for a longer time, in relation to the others, until the adjacent towers complete their movement cycle. Also, this tower movement cycle is completed in a short interval, with lower average velocity. Mobile tower 3 presented the lowest amplitudes because it remains stationary for less time, takes longer to complete the movement cycle, and has a higher average velocity.

Studies developed by Heermann and Stahl (1986) and Kincaid (1996) found that the cycles of movement, as well as the difference between the velocity of adjacent towers affected the uniform application of water depths in the displacement direction of a center pivot. Mohamed et al. (2021), while studying the movement of a center pivot irrigation system, which had towers with different movement cycle times, noticed that the water application was greater for cycles of 30 s and 60 s and that smaller water depths were obtained 120 s. The authors concluded that this is due to longer stoppage times for 30 and 60 s cycles, equivalent to 180 and 150 s respectively; while for the mobile tower with a cycle time of 120 s, the stoppage time were 90 s, shorter when compared to the others. In short, the smaller the cycle time, the longer the stopping time and, in turn, the greater the amplitude of the water depths.

In the evaluated center pivot it was also observed that the arrangement of the nozzle diameters along the lateral line did not follow an ascending order, as recommended (Campêlo et al. 2014; Rajan et al., 2015; Li et al., 2016; Nascimento et al., 2017). Thus, to some extent this is also a factor that contributed to the difference between amplitudes observed in the generated time series, in different towers, for the same misalignment angle. For the same misalignment angle, the difference between amplitudes observed in the time intervals when the towers are in motion is smaller, when compared to the difference between the amplitudes when the towers are stopped: usually in the nozzle's diameter combination process for the lateral line the displacement velocity of the equipment is considered, disregarding the stoppage time. Regarding the occurrence intervals of dominant peaks, for the time series generated by the movement of the Center Pivot towers, the results are presented in Table 7.

Table 7 Periods between dominant peaks of the water depths time series, as a function of the movement of the Center Pivot towers.

Misalignment angle	Mobile tower 1	Mobile tower 2	Mobile tower 3
	Time (s)		
2.32	12	11.2	12
3.45	12.4	11.2	13.1
4.02	12.4	12	13.5
5.23	12.3	13.2	14.2

Thus, it could be noticed that, for mobile towers 2 and 3, there is a tendency to increase the periods of occurrence between dominant peaks, as the misalignment angle increases. This is due to the angle increase that causes the towers to travel increasingly larger semicircles before stopping their movement, that is, the movement cycles of these towers become bigger, because they are farther from the center.

For mobile tower 1, the angle increase had no effect on the variation of the intervals between dominant peaks, since there was not a sufficient increase in the movement cycles, to have a significant change. Omary and Sumner (2001) developed a model to calculate the applied water as a function of the movement of the towers of a central pivot system and, in this work, the authors also found that for mobile towers closer to the center of the equipment there was no significant effect on the variation of applied water in a short movement cycle. In addition, the differences between intervals of occurrence of the maximum domain peaks observed in the present study reinforce the citation that the differences between cycles of movement of the center pivot towers affect the distribution of applied water depths in the displacement direction (Heermann and Stahl 1986); Ouazaa et al. 2015).

Conclusions

The misalignment angle between spans affects irrigation uniformity. This is reduced as such angle increases, being significantly greater when adopting an angle of 0.45º and smaller for an angle of 5.23º. However, maximum misalignment angles below 2º generate shorter cycle times, which can make the alignment sensors of the towers closer to the center to miss sensitivity to detect it, however, it is for these angles that the uniformity is invariable.

The applied water depths as function of tower movement time vary slightly with the change of misalignment angles between towers, being observed that the variability is greater as the angles increase. For misalignment angles of 3.45º; 4.02º and 5.23º, the applied water depths due to the movement time of the towers closer to the center of the system, showed the highest amplitudes, as they remain at rest for a longer time, until the adjacent towers complete their cycle.

To ensure CUC values greater than 90%, it is recommended to set the misalignment angle to values smaller than 5º. The movement tracking of Center Pivot by GNSS receivers, its modeling and simulation, and the Fourier series fittings, allowed a detailed understanding regarding the effect of discrete movement of the central pivot towers on its water application uniformity.

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Statements and Declarations

Conflict of interest: The authors declare no conflicts of interest.

References

Agricultural Systems Research UNIT, Northern plains agricultural research laboratory, (2021) Center pivot irrigation - USDA ARS. IOP Publishing PhysicsWeb. https://www.ars.usda.gov. Accessed May 06, 2022.

Al-Baaj AAA, Lewis A (2019) Variable Pulsed Irrigation Algorithm (VPIA) to Reduce Runoff Losses Under a Low-Pressure Lateral Move Irrigation Machine. *Horticulturae 5:10.* https://doi.org/10.3390/horticulturae5010010

Al-gaadi KA, Hassaballa AA, Tola E, Kayad AG, Madugundu R, Assiri F,Edrris M, Alameen A, Edrees H (2019) Impacts of Center Pivot Irrigation System Uniformity on Growth of Potato Crop and Residual Soil Nitrogen. International Journal of Agricultural and Biological Engineering 12:126-131. https://doi.org/10.25165/j.ijabe.20191201.3684

Bernardo S, Mantovani EC, Da Silva DD, Soares AA (2019) Manual de irrigação, 9rd edn. UFV, Viçosa-MG.

Borssoi AL, Vilas Boas MA, Reisdörfer M, Hernández RH, Follador FA (2012) Water application uniformity and fertigation in a dripping irrigation set. Engenharia Agrícola 32:718-726. https://doi.org/10.1590/S0100-69162012000400011

Empresa Brasileira de Pesquisa Agropecuária - EMBRAPA (2020) Georreferenciamento dos pivôs centrais de irrigação no Brasil: ano base 2020. IOP Publishing PhysicsWeb. https://www.embrapa.br/busca-de-publicacoes/-/publicacao/1128368. Accessed May 06, 2022

Hanson BR, Wallender WW (1986) Bidirectional uniformity of water applied bycontinuous-move sprinkler machines. Transactions of the ASAE 29:1047-1053. https://doi: 10.13031/2013.30268

Graf L, Bach H, Tiede D (2020) Semantic Segmentation of Sentinel-2 Imagery for Mapping Irrigation Center Pivots. Remote Sensing (Basel, Switzerland) 12:3937. https://doi.org/10.3390/rs12233937

Heermann DF, Hein PR (1968) Performance caracteristics of self propeled center pivot sprinkler irrigation system. Transaction of the ASAE, Saint Joseph 11: 0011-0015. https://doi.org/10.13031/2013.39320

Heermann DF, Stahl KM (1986) Center Pivot Uniformity for Chemigation. American Society of Agricultural Engineers, Microfiche Collect. (USA).

Humes AFPC, Melo ISH, Yoshida LK, MartinsWT (1984) Noções de cálculo numérico. São Paulo, McGraw-Hill.

Keller J, Bliesner RD., (1990) Sprinkler and Trickle Irrigation. Van Nostrand Reinhold, New York.

Kincaid DC (1996) Sprinkler Pattern Analysis for Center Pivot Irrigation. Irrigation Business and Technology 4:14–15.

King BA, Bjorneberg DL (2001) Evaluation of Potential Runoff and Erosion of Four Center Pivot Irrigation Sprinklers. Applied Engineering in Agriculture 27: 75-85. https://doi.org/10.13031/2013.36226

Li LH, Zhang XY, Qiao XD, Liu GM (2016) Analysis of the decrease of center pivot sprinkling system uniformity and its impact on maize yield. International Journal of Agricultural and Biological Engineering 9:108-119. https://doi.org/10.3965/j.ijabe.20160904.1129

Mohamed AZ, Peters TR, Sarwar A, Mcmoran D (2018) The Accuracy of Distribution Uniformity Test under Different Moving Irrigation Systems. In: Proceedings of the 2018 ASABE Annual International Meeting, Detroit, MI, USA. https://elibrary.asabe.org/abstract.asp?aid=49360. Accessed May 06, 2022

Mohamed AZ, Peters RT, Sarwar A, Molaei B, Mcmoran D (2021) Impact of the Intermittency Movement of Center Pivots on Irrigation Uniformity. Water 13:1167. https://doi.org/10.3390/w13091167

Nascimento VF, Feitosa EO, Soares JI (2017) Uniformity of distribution of the central pivot aspire irrigation system. Revista de Agricultura Neotropical 4:65-69. https://doi.org/10.32404/rean.v4i4.1643

Omary M, Sumner H (2001) Modeling water distribution for irrigation machinewith small spray nozzles. J. Irrig. Drain. Eng. ASCE 127:156–160.

Ouazaa S, Latorre B, Burguete J, Serreta A, Playán E, Salvador R, Paniagua P, Zapata N (2015) Effect of the Start–stop Cycle of Center-pivot Towers on Irrigation Performance: Experiments and Simulations. Agricultural Water Management 147:163-174. https://doi.org/10.1016/j.agwat.2014.05.013

Rajan N, Stephan M, Rick K, Monty D, Song C, Sumit S, Ahmed A (2015) Emitter Uniformity and Application Efficiency for Centre- Pivot Irrigation Systems. Irrigation and Drainage 64:353-36. https://doi.org/10.1002/ird.1878

Rodrigues LN, Pruski FF, da Silva DD, Martinez, MA (2001) GEOPIVO: Simulation model for evaluating center pivot irrigation system performance Revista Brasileira de Engenharia Agrícola e Ambiental 5:397-402. https://doi.org/10.1590/S1415-43662001000300006

Tambo FLR, Lima LA, Thebaldi MS, Corrêa FV (2022) Sampling patterns may influence the evaluation of irrigation uniformity of Center Pivot systems. Water Supply, 22: 6532. https://doi.org/10.2166/ws.2022.286

Willmott CJ, Matsuura K (2005) Advantages of the mean absolute error (MAE) over the root mean square error (RMSE) in assessing average model performance. Climate Research, Oldendorff 30:79-82. https://doi.org/10.3354/cr030079

Willmott CJ, Matsuura K (2005) Advantages of the mean absolute error (MAE) over the root mean square error (RMSE) in assessing average model performance. Climate Research, Oldendorff 30:79-82. https://doi.org/10.3354/cr030079

Valley Irrigation, Catalog de products Valley Pivot Central Model 8000. IOP Publishing PhysicsWeb: https://www.valleyirrigation.com.br/8000 . Accessed November 16, 2022.