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Optimizing crop irrigation regimes considering groundwater level and mineralization in Turkmenistan

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Abstract. This study offers a comprehensive comparative analysis of surface methods, sprinkling, and drip irrigation techniques utilized in the cultivation of crops in Turkmenistan, taking into consideration the region's unique soil and climatic conditions. The primary objective is to assess the advantages and drawbacks of these irrigation methodologies in optimizing crop productivity. By conducting meticulous scientific data analysis, the research explores the performance of each technique in terms of water efficiency, crop yield, and environmental impact. Surface methods, although widely employed, demonstrate limitations in water conservation and susceptibility to weed proliferation. Conversely, sprinkling irrigation highlights effective water dispersion but raises concerns regarding heightened soil erosion. Drip irrigation surfaces as a promising solution due to its precise water application and minimal evaporation loss; however, factors such as technical intricacy and associated costs necessitate consideration. Drawing from the study's findings, it is advisable to selectively implement irrigation methods tailored to specific crop types and geographical regions within Turkmenistan. The adoption of suitable irrigation practices has the potential to significantly bolster agricultural output, while concurrently preserving water reservoirs and mitigating environmental repercussions. Consequently, these findings offer invaluable insights to farmers and researchers, facilitating the development of sustainable irrigation strategies customized to Turkmenistan's agricultural terrain. Ultimately, this research contributes to the advancement of agricultural practices by offering practical guidance for optimizing crop irrigation in Turkmenistan's unique agricultural ecosystem.

1. Introduction

The optimization of crop irrigation systems in arid regions, such as Turkmenistan, requires thorough consideration of groundwater levels and mineralization to ensure sustainable agricultural productivity [1]. To develop effective irrigation strategies adapted to challenging environments, it is imperative to have a comprehensive understanding of the intricate interplay between groundwater levels, soil moisture, and evaporation processes [2]. Such knowledge is essential for maximizing water use efficiency and promoting sustainable agricultural practices in these demanding environmental conditions [3].

Recent research has highlighted the significant impact of groundwater levels on moisture movement within the soil profile, focusing on the aeration zone in close proximity to the groundwater [4]. This emphasizes the need for a thorough

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exploration of the factors influencing moisture dynamics and their subsequent impact on crop productivity. Studies, such as those published by *Wang et al. (2023)* in the Journal of Hydrology, have underscored the critical role of groundwater depth in shaping soil moisture dynamics, emphasizing the need for customized irrigation methods that account for these complex relationships [5].

In addition to groundwater level, understanding the influence of mineralization on soil and groundwater is equally important. Investigations have revealed the varying proportions of soil and groundwater mineral uptake by cotton and alfalfa, contributing to the aquatic and mineral nutrition of plants [6]. These findings provide valuable insights into the physiological effects of mineralization on plant fertility, highlighting the intricate interplay between soil composition, groundwater properties, and plant growth. Notably, research by *Li et al. (2011)* in the Journal of Plant Physiology outlined the role of mineral nutrition in plant growth, emphasizing the need to consider mineralization in irrigation strategies [7].

Moreover, the quantitative assessment of the total moisture reserve in the upper meter layer of the soil during the growing season has revealed a direct correlation with the depth of the groundwater [8]. This correlation underscores the critical nature of groundwater depth as a determining factor in evaluating moisture availability for crops during the growing season. Research, such as that conducted by *Zhao et al. (2020)* in the Journal of Agricultural Water Management, has demonstrated the relationship between groundwater depth and soil moisture levels, providing essential insights into water availability for crops [9].

Furthermore, the accumulation of chloride ions in the soil during the growing season has been investigated, particularly in the context of groundwater mineralization. Studies have indicated that even with relatively low levels of mineralization (1-3 g/L), the accumulation of chloride ions can exceed 0.015% when the groundwater is at a depth of 1-1.5 meters. This emphasizes the necessity of considering the specific mineral content of groundwater concerning soil fertility and crop health [10]. The research conducted by *Zhang et al. (2018)*, published in the Journal of Soil and Water Conservation, highlighted the effects of chloride ion accumulation on soil health, advocating for tailored irrigation practices accounting for groundwater mineral content [11].

The precise calculation of irrigation rates for agricultural crops has been a significant area of research, emphasizing the need for accurate and efficient water management practices tailored to the unique environmental conditions of Turkmenistan. These studies serve as fundamental building blocks for developing optimal irrigation strategies that can maximize water use efficiency while ensuring sustainable growth of agricultural crops in arid regions. Notably, the work of *Fernández-Cirelli et al (2009)*, in the Chilean Journal of Agricultural Research provided insights into the development of efficient irrigation strategies in arid environments, laying the groundwork for improved water management practices [12].

The complexities and critical interdependencies highlighted by these research findings underline the clear and pressing need for comprehensive investigation into the techniques for optimizing crop irrigation regimes while considering groundwater levels and mineralization in Turkmenistan. Addressing these challenges will enable the development of strategic approaches that safeguard agricultural productivity while promoting sustainable water resource management in arid environments. Through a multidisciplinary approach that integrates hydrology, soil science, and agronomy, this research aims to provide a comprehensive understanding of the intricate relationships between groundwater, soil moisture, and crop productivity.

2. Materials and Methods

In order to comprehensively investigate the optimization of crop irrigation regimes with due consideration to groundwater levels and mineralization in Turkmenistan, this research employed a physically based modeling approach that integrates principles from hydrology, soil science, and agronomy. The study utilized a homogeneous soil model incorporating a specified groundwater level and a root-habitable soil layer to facilitate the analysis of soil moisture dynamics and their interrelationship with groundwater characteristics.

Lysimetric data, obtained from controlled experimental setups designed to measure water movement through soil columns [13], played a pivotal role in elucidating the correlation between groundwater depth and the total moisture reserve in the upper meter of the soil throughout the growing season. The integration of this data with relevant literature sources contributed to the computation of the available moisture reserve, thereby offering valuable insights into the water availability for agricultural crops in response to varying groundwater levels.

The calculation of irrigation rates for a diverse range of agricultural crops harnessed a formulation proposed by A.N. Kostikov, incorporating factors such as total evaporation and capillary recharge of groundwater during the growing season. By factoring in these parameters, the study aimed to establish precise irrigation rates tailored to the specific characteristics of the study region, thereby optimizing water use efficiency and enhancing crop yield potential.

Furthermore, the study placed emphasis on determining the optimal pre-irrigation moisture content of unsalted soil within the root-habitable soil layer during the critical fruit formation period. This assessment sought to establish irrigation norms and the depth of moisture required for different plant species, thereby considering the influence of groundwater mineralization on soil and plant health.

The physical model and data-driven approach adopted in this study serve as fundamental tools in elucidating the complex interdependencies between groundwater dynamics, soil moisture, and agricultural productivity. Through the integration of empirical data and established theoretical frameworks, the study aimed to contribute to the development of tailored irrigation strategies specifically adapted to the arid environment of Turkmenistan.

Expanding on the information provided, it is crucial to highlight the significance of considering the specific soil characteristics and crop water requirements in Turkmenistan. The country's arid climate and diverse agricultural practices necessitate a nuanced approach to irrigation management [14]. Additionally, incorporating advanced techniques such as remote sensing and geographic information systems (GIS) for spatial analysis of groundwater levels and soil moisture content can provide a more comprehensive understanding of the factors influencing crop irrigation regimes in Turkmenistan's unique agricultural landscape.

Furthermore, the study incorporated the use of advanced modeling techniques, such as numerical simulations and computational fluid dynamics, to explore the intricate dynamics of water movement within the soil profile concerning varying groundwater levels. This approach allowed for a robust analysis of the impact of groundwater depth on soil moisture and its implications for crop irrigation in Turkmenistan. Moreover, considering the evolving climate patterns and potential shifts in groundwater availability, the study also examined the adaptability of the proposed irrigation strategies to future scenarios, emphasizing the need for sustainable and flexible water management practices in agriculture.

In conclusion, this study aims to contribute to the advancement of sustainable agricultural practices in arid regions, particularly in Turkmenistan, by providing in-depth insights into the optimization of crop irrigation regimes considering groundwater levels and mineralization. By leveraging a multidisciplinary approach, including advanced modeling techniques and empirical data, the research seeks to furnish practical and tailored irrigation strategies that can enhance water use efficiency and promote agricultural sustainability in the region.

3. Results and Discussion

The upward movement of moisture from the groundwater level to evaporation and soil moisture in the aeration zone, particularly in the vicinity of the groundwater (up to 3-3.5 meters), is intricately linked to the depth of the groundwater [15]. This phenomenon reflects the complex interplay between groundwater levels and soil moisture dynamics, indicating the need for a comprehensive understanding of these relationships.

From a physical modeling perspective, a homogeneous soil with a groundwater level (H) and a calculated root-habitable soil layer (h) can serve as a framework for understanding the regulation of humidity in the aeration zone. This model provides valuable insights into the mechanisms governing moisture movement within the soil profile, as depicted in Figure 1.

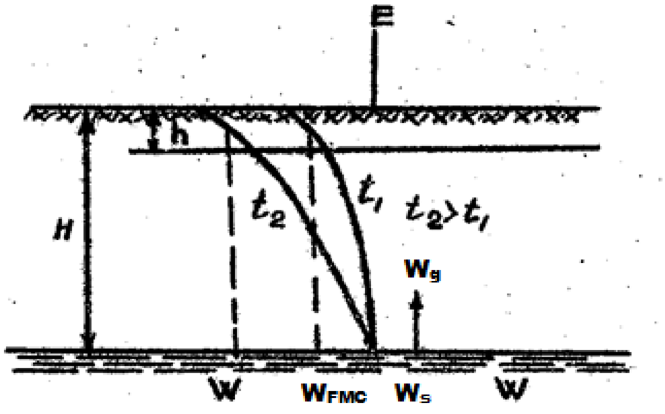

Fig. 1. Moisture Exchange Model of the Aeration Zone in Soils with Groundwater: Schematic Representation

The distribution of moisture within the soil following irrigation is a critical element in understanding the dynamics of water movement and utilization in agricultural settings [16]. When irrigation is applied at a specific rate, the soil's moisture distribution aligns with a predictable pattern where the moisture reserve in the root layer attains a predetermined value (WFMC – maximum field moisture capacity). Beneath this layer, soil moisture gradually increases in a distinct pattern until it reaches full saturation (Ws) at the groundwater level [17]. After watering, the gravitational component of downward flow is at its maximum, while the capillary component of upward flow is minimal. Throughout the irrigation duration, moisture is utilized for evaporation from the soil surface and transpiration by crops (total evaporation), denoted as E, utilizing moisture from the upper soil layers [18]. As a result, significant moisture gradients develop in the upper layers of the soil, leading to an increased intake of moisture from the lower layers and groundwater into the upper ones. In areas where the groundwater is in close proximity to the surface, subirrigation is frequently utilized to hydrate the root zone of the soil by capillary action [19]. This process involves the artificial elevation and sustained maintenance of the necessary groundwater level. Multiple techniques are employed to achieve this, such as the controlled release of water, the manipulation of drainage and irrigation systems, the use of finely filtered water channels for irrigation, and the deployment of tubular humidifiers at specific depths. Additionally, the management of natural groundwater discharge and the exploitation of artesian aquifers by puncturing impermeable layers are integral components of the strategies aimed at elevating the groundwater level artificially [20]. These methods collectively constitute a vital aspect of water management in regions where the proximity of groundwater influences agricultural practices and soil moisture levels.

The utilization of underground irrigation (subirrigation) is widespread due to the close proximity of groundwater. This method involves moistening the root layer of the soil through capillary feeding, achieved by elevating and maintaining the necessary groundwater level. There are various techniques for artificially elevating the groundwater level, including flushing discharge, drainage and irrigation channels, utilizing highly filtering channels for supplying irrigation water, and employing tubular humidifiers positioned at a depth of 0.5-0.6 m. Additionally, regulating the natural outflow of groundwater and introducing artesian waters by breaching a waterproof layer are also employed to control the groundwater level.

Subsurface irrigation, often employed for moisture-loving plants with deep root systems, requires homogeneous unsalted soils with good capillary properties and shallow fresh groundwater [21]. Fresh and slightly mineralized groundwater, located at depths of 1-2 meters, is generally well suited for plant growth. Studies have shown that an increase in the groundwater level in close proximity to the soil surface is associated with increased yields of cotton and alfalfa, accompanied by reduced irrigation water costs. It is noteworthy that the use of groundwater for cotton cultivation at various depths yields varying water consumption patterns, with usage increasing as the depth of groundwater decreases. This trend is similarly observed in alfalfa cultivation, where groundwater at shallow depths results in significantly higher water usage compared to cultivation in cotton fields.

Underground irrigation is particularly suited for moisture-dependent plants with deep root systems, situated on flat topography, uniform unsalted soils with favorable capillary properties, and shallow presence of fresh groundwater. According to academician V.A. Kovda, the utilization of soil and groundwater by cotton and alfalfa for water and mineral nutrition commences with a mineralization level of approximately 10-12 g/l or lower. Groundwater featuring a mineralization of 5-6 g/l is physiologically accessible to plants, but using it for irrigation can lead to seasonal soil salinization and reduced fertility.

Groundwater with a mineralization level of 2-3 g/l or lower is physiologically beneficial for plants. A rise in the level of freshwater close to the earth's surface enhances the yield of cotton and alfalfa, while reducing the cost of irrigation water. For cotton, groundwater at depths of 1m, 2m, and 3m is utilized in the ranges of 330-1000 mm, 160-444 mm, and 50-200 mm, respectively, from April to October. The use of alfalfa groundwater at depths of 1-3 m is twice as much as in a cotton field [22].

Lysimetric data has been utilized to conduct an extensive assessment of the complete moisture reserve within the top meter layer of the soil throughout the growth period, under the influence of groundwater. This investigation has unveiled a noticeable correlation, shedding light on the interplay between groundwater and soil moisture. The identified dependence yields important knowledge for enhancing irrigation methodologies amidst diverse groundwater levels and mineralization, underscoring the intricacy of irrigation management in regions with varied groundwater conditions. These insights stress the necessity of customized approaches to guarantee effective water utilization and enduring crop productivity.

$$W = \frac{350}{\mathrm{H}^{\frac{2}{3}}} \qquad (1)$$

The equation is expressed as follows: W represents the overall moisture reserve within the 0-100 cm layer, measured in millimeters, whereas H symbolizes the depth of the groundwater, with measurements ranging from 1 to 3 meters. In calculating the available moisture reserve (W_{AMR}) originating from groundwater, the following correlation is presented:

$$W_{AMR} = \frac{\mathrm{B}}{\mathrm{H}^{n}},\ \mathrm{m}^3/\mathrm{ha} \qquad (2)$$

Here, B and n represent coefficients that rely on the mechanical composition, pre-irrigation moisture, and the computed soil layer. Estimated values of B and n for computed soil layers spanning 0-60, 0-80, and 0-100 cm, as per H. A. Amanov, are detailed in Table 1. These B and n values are suggested for optimal conditions of agricultural technology for crops cultivated on unsalted heavy soils.

Table 1. Coefficients *B* and *n* for Different Soil Layers

Pre-irrigation Soil Moisture, %	Depth of Calculated Soil Layers, cm	B	n
65	0-60	40	2,10
	0-80	70	1,50
	0-100	110	1,50
75	0-60	35	2,77
	0-80	65	1,83
	0-100	90	1,73

Special sluice devices are employed in drainage systems for underground irrigation, allowing for the flexible regulation of desalinated groundwater depth to ensure adequate water supply to plant root systems. Drainage systems are required to bi-directionally regulate the water-salt composition of irrigated soils following soil salinization and groundwater desalination. This irrigation method has been long practiced in Central Asia. In the groundwater-wedging zone of the Fergana Valley, plots measuring 1-1.5 hectares are enclosed with channels up to 1 meter deep, where water is introduced to elevate the groundwater level. At the Pakhta-Aral state farm in the Golodnaya Steppe (Kazakhstan), substantial washing irrigation over mineralized groundwater led to the creation and maintenance of a layer of fresh groundwater close to the earth's surface (1.2-2.5 meters). Utilizing 3-5 rounds of sprinkler watering and small water volume of 400-500 m^3 / ha, a yield of 30 kg/ha of raw cotton is achieved.

According to the reclamation cadastre, distinct groundwater depth categories are delineated as follows: less than 1 meter, covering an area of 48.7 thousand hectares; 1-1.5 meters, spanning 127.1 thousand hectares; and 1.5-2 meters, encompassing 444 thousand hectares. The cumulative area with a groundwater depth of up to 2 meters accounts for 615.9 thousand hectares, equivalent to 46% of the total irrigated land. Furthermore, the land extent characterized by groundwater mineralization up to 1 gram per liter covers 146.4 thousand hectares, constituting 11% of the total area, while those with mineralization levels of 1 to 3 grams per liter span 665.8 thousand hectares, encompassing 50% of the area. These details are explicitly outlined in Table 2.

Table 2. Distribution of Irrigated Lands by Groundwater Depth and Mineralization Level in Turkmenistan (Thousand Hectares)

Province	Groundwater depth, m			Mineralization of groundwater, g/L	
	< 1,0	1-1,5	1,5-2,0	<1	1-3
Areas of state subordination	2,5	11,6	54,3	34,4	103,4
Mary	36,4	32,1	83,6	32,4	137,7
Lebap	3,4	43,0	126,8	41,1	181,1
Dashoguz	6,4	40,4	175,4	38,5	243,6
Total	48,7	127,1	440,1	146,4	665,8

The implementation of bilateral regulation of the water system within the nation will enable the comprehensive utilization of both groundwater and irrigation water for agricultural irrigation purposes [25]. The proposed approach involves the regulation of the water system in the unsaturated zone through capillary replenishment from groundwater, while maintaining it at an optimal depth, as well as the regulation of the soil's thermal system and the microclimate of the surface air layer through minimal irrigation norms. When operating dual-regulation systems, capillary groundwater recharge ensures that the moisture in the unsaturated zone remains within the range of 75-80% of the plant-available water, thereby ensuring continuous moisture supply to crops. The water demand of plants is met with 65% from capillary groundwater feeding and 35% from irrigation.

A study by F.M. Rahimbayev in the Khorezm oasis (Turkmenistan, Uzbekistan) examining the buildup of chloride ions in the unsaturated zone and the uppermost soil layer at groundwater depths of 1-3 meters, featuring mineralization levels between 1-10 g/L, demonstrated that the accumulation of chloride ions over a single growing season may surpass 0.015%. This phenomenon occurs even with groundwater mineralization levels of 1-3 g/L, particularly when the groundwater depth ranges from 1-1.5 meters. Furthermore, in cases where the groundwater mineralization level is at 10 g/L, the quantity of chloride ions reaches the same level at a depth of 2.8 meters. As per F.M. Rakhimbaev's findings, the critical depth of saline groundwater (Hcd) for the conditions of Southern Khorezm varies between 1.0-2.8 meters from the earth's surface, depending on the chloride ion content in the 0-100 cm layer and the groundwater mineralization (refer to Table 3).

The adoption of the bilateral regulation of water resources within the country offers a comprehensive strategy for optimizing the utilization of groundwater and irrigation water for agricultural needs. The proposed approach involves regulating the water regime of the unsaturated zone through capillary replenishment from groundwater, maintaining it at an optimal depth, and regulating the thermal regime of the soil and the microclimate of the surface air layer through minimal irrigation norms. When operating with a dual-regulation system, capillary groundwater replenishment ensures that the moisture in the unsaturated zone remains within the range of 75-80% of the plant-available water, ensuring a consistent supply of moisture to crops. Plants' water demand is met by 65% through capillary groundwater feeding and 35% through irrigation.

Table 3. Critical Depth of Groundwater Occurrence Analysis

Groundwater mineralization, g/L		**The average critical depth of groundwater for vegetation (m) given an initial soil layer chlorine content (%) within the range of 0-100 cm**		
total	**Cl^-**	**0,005**	**0,01**	**0,015**
1-3	0,16-0,49	1,0	1,0-1,1	1,0-1,5
3-5	0,49-0,82	1,0-1,2	1,1-1,8	1,9-2,5
5-8	0,82-1,31	1,2-1,8	1,8-2,2	2,5-2,7
8-10	1,31-1,64	1,8-2,0	2,2-2,5	2,7-2,9

The optimal depth of groundwater, denoted by h_d, is a critical factor determined by its depth and mineralization. Based on these considerations, it is recommended to adopt a value of hd within the range of 1.0 to 1.5 times the natural capacity for retention (H_{cd}) (h_d=(1,0 - 1,5) H_{cd}) [26]. This recommendation accounts for the specific soil conditions and is essential for the efficient management of groundwater resources in agricultural practices.

Subsurface irrigation represents a highly efficient water-saving method, particularly suitable for soil-reclamation conditions, requiring a comprehensive analysis of groundwater regimes and mineralization. This necessitates an in-depth examination of the water-salt balance within the aeration zone, along with the development of strategies to optimize it. Additionally, the effectiveness of proposed measures aimed at enhancing crop yields must be thoroughly assessed. Furthermore, it is crucial to investigate the impact of bilateral regulation of soil water regimes on the intricate interplay of plant life factors and crop yields. The operational mode of drainage plays a pivotal role in the development of technology for regulating groundwater levels to maintain specified depths. In this context, it is vital to determine the optimal design parameters of double-acting dehumidification and humidification systems, as well as to identify suitable areas for their application in irrigation practices. These initiatives necessitate the preparation of feasibility studies for the recommended measures, ensuring their practical and economic viability.

The permissible values of groundwater and surface water mineralization are inherently linked to soil water permeability, drainage characteristics, and the salt tolerance levels of cultivated crops [27]. It is imperative to consider these parameters to determine the acceptable mineralization levels for effective irrigation practices. Specifically, drained loamy ferrous compositions allow for mineralizations of up to 3 g/L, while light loamy and sandy soils facilitate mineralization levels ranging from 3 to 4 g/L. It is essential to tailor water drainage rates based on regional considerations; for example, Lebap province requires a drainage rate of 40-50%, exceeding the norm, while Dashoguz province necessitates a rate of 20-25%, falling below the norm. Inadequate rates are observed in Mary province (15-20%) and areas under state subordination (10-13%), highlighting the substantial variations in regional water drainage requirements.

The mineralization levels of groundwater and surface waters are crucial determinants in influencing secondary salinization during irrigation processes. Groundwater containing less than 3-2 g/L of easily soluble sulfate-chloride salts and exhibiting an outflow of 15% of the intake has been shown to minimally induce secondary salinization during irrigation. Furthermore, the desalination of groundwater, coupled with effective outflow, facilitates the formation of fertile cultivated meadow hydromorphic soils in irrigated fields.

Notably, when the mineralization of groundwater exceeds 4 g/L and surface water reaches 2-3 g/L, the utilization of groundwater with two-way regulation is unadvised. The phytotoxicity of salts on plants is closely linked to their developmental phase, with cotton being particularly sensitive to salinity before the flowering phase, causing delays in growth only under weak salinization conditions.

An essential aspect of irrigation management is the determination of the irrigation rate (M) for agricultural crops, calculated according to the formula devised by A.N. Kostikov. This calculation is a fundamental component of planning and implementing effective irrigation practices to optimize crop yield and water utilization.

$$M = E - 10mP\,(W_{st} - W_e) - W_g \tag{3}$$

E represents the total evaporation measured in m^3/ha, while P signifies the precipitation received during the growing season, expressed in mm. The precipitation utilization factor is denoted by m, with recommended values ranging from 0.1 to 0.2. Additionally, W_{st} and W_e correspond to the soil moisture reserves at the start and end of the growing season, respectively, whereas W_g specifies the capillary supply of the soil's root layer from neighboring groundwater sources. The specific formulas for calculating E and W_g can be found in Table 4. The information pertaining to the overall evaporation and capillary replenishment of groundwater during the vegetation period in the Kopetdag subzone of Turkmenistan has been analyzed using the equations established by H.A. Amanov and is documented in Table 5. It is imperative to employ a leaching irrigation method in all regions susceptible to salinization, necessitating an average elevation of 15-25% in irrigation standards compared to non-saline soils. The net irrigation rate, encompassing the leaching strategy, is expressed as $Mf = M + \Delta M$; where the quantity of extra water (ΔM) essential to maintain the leaching regimen is ascertained according to the hydrological characteristics of the soils, the levels of mineralization in both groundwater and irrigation water, the depth of the groundwater, permissible salt content within the root layer, and other relevant variables. An initial approximation of the correlation $\Delta M = (0.15\text{-}0.25)\,M$ can be applied for preliminary calculations.

In instances where there is a shallow presence of fresh groundwater, the formula for determining the irrigation rate (m^3/ha) for agricultural crops is as follows:

$$m = 100\alpha h\,(\beta_{FMC} - \beta_{min})\,K_r \tag{4}$$

Here, α represents the soil's volume mass measured in g/cm^3, while h denotes the depth of soil moisture in meters. Additionally, β_{FMC} and β_{min} refer to the maximum field moisture capacity and permissible pre-irrigation soil moisture, both represented in percentages. The coefficient of soil recharge by groundwater, denoted as K_r and based on H.A. Amanov's research, is detailed in Table 6. The prescribed initial soil moisture level for non-saline soil is 70% of the maximum field moisture capacity (FMC) for cotton before reaching maturity, while during maturity; it is suggested to be within the range of 60-65%. As for alfalfa, maize, and vegetable crops, the pre-irrigation moisture level should ideally be maintained at 70-75%. In saline soils, the initial soil moisture content rises, reaching 75% for cotton and corn, and 75-80% for alfalfa and vegetable crops.

Table 4. Calculation Formulas for *E* and W_g According to H.A. Amanov

Field	For the overall evaporation (E)	For the replenishment of groundwater
Cotton	$E_c = 523\sqrt[4]{\frac{\Sigma t \cdot y_c}{H}}$	$W_g^c = \frac{\Sigma t \cdot y_c}{50\sqrt{H^3}}$
Alfalfa	$E_a = 200\sqrt[3]{\frac{\Sigma t \cdot y_a}{H}}$	$W_g^a = \frac{\Sigma t \cdot y_a}{90\sqrt{H^3}}$
Maize	$E_m = 410\sqrt[4]{\frac{\Sigma t \cdot y_m}{H}}$	$W_g^m = \frac{\Sigma t \cdot y_m}{80\ H^2}$
Long-term vegetable	$E_v = 340\sqrt[4]{\frac{\Sigma t \cdot y_v}{H}}$	$W_g^v = \frac{\Sigma t \cdot y_v}{735\sqrt{H^3}}$

A study by F.M. Rakhimbaev in the Khorezm oasis (Turkmenistan, Uzbekistan) examining the buildup of chloride ions in the unsaturated zone and the uppermost soil layer at groundwater depths of 1-3 meters, featuring mineralization levels between 1-10 g/L, demonstrated that the accumulation of chloride ions over a single growing season may surpass 0.015%. This phenomenon occurs even with groundwater mineralization levels of 1-3 g/L, particularly when the groundwater depth ranges from 1-1.5 meters. In contrast, saline soils require higher pre-irrigation moisture levels, reaching 75% for cotton and maize, and 75-80% for alfalfa and vegetable crops. The calculated soil depth averages 0.7 meters before flowering and increases to 1.0 meter during the period of cotton fruit formation. These measurements also apply to maize. Irrigation standards for alfalfa should be calculated based on the moisture deficit within the 1-meter soil layer, while for vegetable crops, a moisture depth of 0.7-0.8 meters may be utilized for optimal plant growth. It is essential to closely monitor these moisture levels to ensure efficient water management and to support the healthy growth of the crops, particularly in regions susceptible to salinization. Understanding and adhering to these guidelines will contribute to the successful cultivation of these crops and help mitigate the challenges posed by varying soil conditions. E_c, E_a, E_m, E_v, W_g^c, W_g^a, W_g^m, W_g^m are parameters that denote both the total evaporation and recharge of groundwater from cotton, alfalfa, maize, and vegetable fields during the respective growing seasons, and these measurements are expressed in cubic meters per hectare (m^3/ha). The symbol Σt represents the cumulative sum of the average daily air temperatures during the growing season. Specifically, for cotton, alfalfa, and long-term vegetable crops, this is calculated for the period extending from April to October, whereas for maize, it pertains to the period from April to September. The variable H represents the depth of the groundwater, which typically ranges from 1 to 3 meters, and is measured in meters.

Table 5. Total Evaporation and Groundwater Recharge during the Growing Season (m^3/ha)

Depth of groundwater , m	Cotton (U_c=30 c/ha)	Alfalfa (U_a=150 c/ha)	Maize (U_m=75 c/ha)	Long-term vegetables (U_v= 1000 c/ha)
Total evaporation (E)				
1,0	10395	18338	9955	16189
1,5	9398	16000	8995	14625
2,0	8715	14558	8372	13605
2,5	8237	13509	7913	12871
3,0	7875	12719	7564	12297
Groundwater recharge (W_g)				
1,0	3084	8572	4346	7000
1,5	1680	4671	1938	3813
2,0	1090	3040	1086	2481
2,5	787	2187	695	1785
3,0	594	1650	483	1347

Table 6. Coefficient of Groundwater Recharge for Groundwater Level of 1-3 m (Kr)

Soil layer	Cotton			Alfalfa			Maize and vegetable crops		
	1 m	**2 m**	**3 m**	**1 m**	**2 m**	**3 m**	**1 m**	**2 m**	**3 m**
0-50	0,84	0,96	1,0	0,70	0,80	0,90	0,75	0,96	1,0
0-70	0,60	0,82	0,92	0,50	0,70	0,85	0,55	0,87	1,0
0-100	0,30	0,55	0,86	0,30	0,58	0,75	0,40	0,78	1,0

4. Conclusions

Based on the extensive research conducted on optimizing crop irrigation regimes in Turkmenistan, several significant findings have come to light, providing valuable insights into the intricate relationship between groundwater levels, soil moisture dynamics, and their profound impact on enhancing agricultural practices. The comprehensive analysis of the data and discussion has laid the foundation for critical considerations and innovative strategies aimed at ensuring efficient water use and sustainable crop productivity in diverse and challenging agricultural environments.

The upward movement of moisture from the groundwater level to evaporation and soil moisture in the aeration zone, particularly in close proximity to the groundwater, has been identified as a pivotal factor in understanding the complex interplay between groundwater levels and soil moisture dynamics [27]. The distribution of moisture within the soil following irrigation has demonstrated predictable patterns, emphasizing the necessity of tailoring irrigation practices to varying groundwater levels and mineralization to optimize crop productivity.

In addition, the utilization of lysimetric data has shed light on the crucial interaction between groundwater and soil moisture, providing vital information for formulating irrigation strategies conducive to the specific conditions of diverse groundwater levels and mineralization. This underscores the complexity of managing irrigation in regions with varying groundwater conditions and highlights the need for tailored approaches to ensure successful water use and sustainable crop development.

Moreover, the research has exemplified the significant role of subsurface irrigation as an efficient water-saving method, particularly suited for soil-reclamation conditions. It has emphasized the paramount importance of comprehensive analysis of groundwater regimes and water-salt balance within the aeration zone, guiding the development of innovative strategies to enhance crop yields and mitigate the challenges posed by varying soil conditions. This highlights the need for thorough assessments of proposed measures and the critical impact of bilateral regulation of soil water regimes on the interplay of plant life factors and crop yields.

The comprehensive examination of the mineralization levels of groundwater and surface waters has underscored their crucial influence on secondary salinization during irrigation processes. Furthermore, the study has illuminated the need for careful consideration of permissible mineralization levels in relation to soil characteristics and regional water drainage requirements to ensure effective irrigation practices. These findings offer valuable guidance for implementing efficient drainage rates tailored to specific regional considerations, ensuring optimal irrigation practices aligned with varying soil permeability and cultivated crop salt tolerance levels.

The insights obtained from the study also stressed the critical nature of determining the irrigation rate for agricultural crops, a fundamental aspect in planning and implementing effective irrigation practices to optimize crop yield and water utilization. It has emphasized the necessity to employ a leaching irrigation method in regions susceptible to salinization, underscoring the importance of meticulous monitoring of moisture levels to support the healthy growth of crops, particularly in challenging agricultural environments.

In conclusion, the findings and discussions presented in this study offer a comprehensive understanding of the complex dynamics of groundwater levels, soil moisture distribution, and their profound implications for optimizing crop irrigation regimes in Turkmenistan. These insights provide a solid foundation for the development of tailored and innovative strategies aimed at efficient water use and sustainable crop productivity in diverse agricultural landscapes. This research lays the groundwork for further exploration and practical implementation of optimized irrigation practices in challenging agricultural environments, ensuring the continued advancement of sustainable and efficient agricultural practices in Turkmenistan.

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