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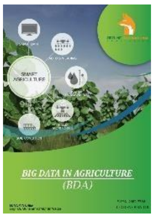

RESEARCH ARTICLE

SUSTAINABLE GROUNDWATER MANAGEMENT THROUGH GROUNDWATER IRRIGATION ADVISORY APPLICATION (GIAA)

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ABSTRACT

With the global population surpassing 7.9 billion, sustaining food production poses a formidable challenge, heavily reliant on groundwater for irrigation, particularly in regions with limited surface water. Concerns over groundwater sustainability are mounting as agricultural dependence grows, highlighting the need for robust management strategies to ensure long-term viability. The unchecked extraction of groundwater poses a threat to agricultural productivity, as excessive withdrawal leads to aquifer depletion and reduced water availability for irrigation. Numerous studies, including those conducted by organizations like the Food and Agriculture Organization (FAO) and the World Bank, underscore the detrimental effects of over-extraction on crop yields, food security, and agricultural expansion efforts. Furthermore, the depletion of groundwater exacerbates water scarcity, driving up food prices and jeopardizing dietary diversity and nutritional intake. Despite these challenges, groundwater remains indispensable for global food security, supporting approximately 60% of irrigated agriculture worldwide. In regions susceptible to climate variations and water scarcity, groundwater serves as a reliable irrigation source, enabling year-round crop cultivation and sustaining livelihoods. However, sustainable groundwater management is imperative to mitigate the risks of over-extraction, aquifer depletion, and environmental degradation. Pakistan exemplifies the intricate relationship between groundwater and agricultural sustainability. The nation's irrigation system heavily relies on diverse water resources, including the Indus River System and groundwater extracted through tube wells. While these resources bolster agricultural productivity and contribute significantly to the economy, challenges such as water scarcity and inefficient usage threaten their sustainability. Addressing these challenges requires a concerted effort to implement sustainable water management practices, enhance infrastructure, and mitigate the impacts of climate change. Amidst these challenges, the development of the Groundwater Irrigation Advisory Application (GIAA) emerges as a potential solution. By providing real-time groundwater monitoring, tailored irrigation schedules, and educational support, GIAA empowers farmers to make informed decisions regarding water usage, ultimately contributing to sustainable groundwater management and global food security. However, the successful implementation of GIAA necessitates collaboration among stakeholders, continuous updates, and a commitment to integrating new features and technological advancements. In this context, this paper explores the development, functionality, and potential impact of GIAA on sustainable groundwater management, agricultural productivity, and food security. Through a comprehensive analysis of its features, benefits, and limitations, this study aims to elucidate the role of GIAA in safeguarding groundwater resources and ensuring the resilience of agricultural systems in an era of increasing water scarcity and climate uncertainty.

KEYWORDS

Groundwater Irrigation Advisory, Water Scarcity, Sustainability, SDGs

1. INTRODUCTION

With the global population surpassing 7.9 billion people, sustaining food production to meet the needs of a growing populace presents a formidable challenge. Agriculture accounts for approximately 70% of freshwater withdrawals globally, with groundwater serving as a vital resource for irrigation, particularly in regions where surface water is limited. The reliance on groundwater for irrigation varies geographically, influenced by factors such as water availability, infrastructure, and economic conditions. In arid regions and areas lacking alternative water sources, farmers heavily depend on groundwater to sustain crop cultivation. Conversely, large-scale commercial agriculture often resorts to groundwater in regions with inadequate surface water supplies.

While groundwater irrigation significantly contributes to food production, concerns over its sustainability loom large. The unregulated extraction of groundwater poses a threat to agricultural productivity, as excessive withdrawal leads to aquifer depletion and reduced water availability for irrigation. Studies conducted by organizations like the Food and Agriculture Organization (FAO) and the World Bank underscore the detrimental effects of over-extraction on crop yields, food security, and agricultural expansion efforts. Furthermore, the depletion of groundwater resources exacerbates water scarcity, driving up food prices and jeopardizing dietary diversity and nutritional intake.

Despite these challenges, groundwater remains indispensable for global food security, supporting approximately 60% of irrigated agriculture worldwide. In regions susceptible to climate variations and water scarcity, groundwater serves as a reliable irrigation source, enabling year-round

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crop cultivation and sustaining livelihoods. However, sustainable groundwater management is imperative to mitigate the risks of over-extraction, aquifer depletion, and environmental degradation.

Pakistan exemplifies the intricate relationship between groundwater and agricultural sustainability. The nation's irrigation system heavily relies on diverse water resources, including the Indus River System and groundwater extracted through tube wells. While these resources bolster agricultural productivity and contribute significantly to the economy, challenges such as water scarcity and inefficient usage threaten their sustainability. Addressing these challenges requires a concerted effort to implement sustainable water management practices, enhance infrastructure, and mitigate the impacts of climate change.

The unrestricted extraction of groundwater poses significant risks to both water resources and ecosystems, including aquifer depletion, land subsidence, and saltwater intrusion. Sustainable groundwater management practices, such as monitoring extraction rates, promoting water conservation, and regulating well drilling activities, are essential to preserve groundwater resources for future generations.

Amidst these challenges, the development of the Groundwater Irrigation Advisory Application (GIAA) emerges as a potential solution. By providing real-time groundwater monitoring, tailored irrigation schedules, and educational support, GIAA empowers farmers to make informed decisions regarding water usage, ultimately contributing to sustainable groundwater management and global food security. However, the successful implementation of GIAA necessitates collaboration among stakeholders, continuous updates, and a commitment to integrating new features and technological advancements.

In this context, this paper explores the development, functionality, and potential impact of GIAA on sustainable groundwater management, agricultural productivity, and food security. Through a comprehensive analysis of its features, benefits, and limitations, this study aims to elucidate the role of GIAA in safeguarding groundwater resources and ensuring the resilience of agricultural systems in an era of increasing water scarcity and climate uncertainty.

2. BACKGROUND AND CONTEXT

Water scarcity has emerged as a pressing issue globally, driven by factors such as population growth, climate change, and unsustainable water management practices. Pakistan, in particular, faces significant challenges regarding water availability and management, with groundwater resources being particularly vulnerable. The country's per capita water availability is alarmingly low, projected to decrease further in the coming years. This scarcity is exacerbated by unauthorized water consumption and the adverse impacts of climate change.

In response to these challenges, there is a growing recognition of the need for effective strategies to conserve and manage groundwater resources sustainably. Groundwater serves as a crucial source of water for various sectors, including agriculture, industry, and domestic use. However, overexploitation and pollution threaten the availability and quality of groundwater, necessitating urgent action to ensure its sustainable management and preservation.

Developing innovative solutions to address groundwater scarcity and promote sustainable water management practices is imperative. An irrigation advisory application represents one such solution, offering farmers and water managers precise and timely information on groundwater availability, usage patterns, and efficient irrigation practices. By empowering users to make informed decisions, the application can help prevent over-pumping, depletion of groundwater reserves, and negative environmental impacts.

The need for a comprehensive irrigation advisory application is underscored by the importance of groundwater in sustaining agriculture, livelihoods, and ecosystems. Sustainable groundwater management is critical for maintaining agricultural productivity, economic viability, and environmental integrity. By promoting responsible irrigation practices and providing policymakers with valuable insights into groundwater use patterns, the application can contribute to more effective water management policies and regulations.

Against this backdrop, this working paper aims to explore the development and implementation of a Groundwater Irrigation Advisory Application (GIAA) in the context of Pakistan's water scarcity challenges. By examining the need, significance, and potential benefits of such an application, this paper seeks to provide insights into its role in promoting sustainable groundwater management practices and enhancing agricultural resilience in the face of water scarcity and climate uncertainty. Through a thorough analysis of scientific data, modeling techniques, and predictive analytics, the paper aims to offer evidence-based recommendations for optimizing irrigation scheduling, improving crop yields, and reducing water-related costs. Ultimately, the goal is to facilitate informed decision-making and contribute to the conservation and sustainable use of groundwater resources in Pakistan and beyond.

3. LITERATURE REVIEW

The Indus Basin Irrigation System stands as a monumental feat of engineering, spanning Pakistan's agricultural landscape and significantly shaping its agricultural sector. With its intricate network of canals, barrages, and tubewells, the system plays a pivotal role in sustaining agriculture across vast swathes of arable land. By harnessing the waters of the mighty Indus River and its tributaries, this irrigation system facilitates the cultivation of crops ranging from wheat and rice to cotton and sugarcane, thereby serving as the lifeblood of Pakistan's agrarian economy. Its potential is vast, offering increased agricultural productivity, enhanced food security, and improved livelihoods for millions of rural inhabitants.

However, the system also faces challenges, including water scarcity, inefficient water management practices, and infrastructure constraints (Anwar et al., 2016; Hussain et al., 2011; Irfan et al., 2019; Liaqat et al., 2015; Ullah et al., 2001; Usman et al., 2015). Addressing these challenges requires concerted efforts to modernize infrastructure, improve water governance, and promote sustainable agricultural practices. Nonetheless, the Indus Basin Irrigation System remains a cornerstone of Pakistan's agricultural sector, driving economic growth, supporting rural livelihoods, and ensuring food security for millions. Furthermore, the system's reliance on groundwater, which contributes approximately 50% of Pakistan's agricultural water needs, underscores the critical importance of sustainable groundwater management in maintaining the resilience of the agricultural sector.

The groundwater management in Pakistan highlights the evolution of irrigation practices and the dominant role of groundwater in agricultural productivity. Historically, gravity-fed surface irrigation prevailed, but by the early 1990s, groundwater irrigation had surpassed surface irrigation in popularity, with over 50% of irrigated lands relying on groundwater wells. This shift reflects significant investment in private tubewells, reaching approximately US$400 million, and substantial annual benefits in agricultural production, totaling around US$2.3 billion. However, over 80% of groundwater exploitation occurs without regulation, posing sustainability challenges.

Studies emphasize the importance of balancing surface and groundwater resources for optimal farm performance. Access to both sources lead to five times higher farm incomes compared to relying solely on surface water. Moreover, over-pumping of groundwater poses a direct threat to the country's growing population, highlighting the urgent need for sustainable management practices. Research demonstrates the potential of technologies in identifying groundwater potential zones, groundwater extraction and groundwater contribution in agriculture. By integrating various data sources, these technologies enable the mapping of suitable areas for groundwater extraction, contributing to sustainable water management and development planning.

The well-established methodologies on the groundwater potential zone mapping, groundwater contribution is presented by the (Awan et al., 2016a, 2016b; Liaqat et al., 2016; Waqas et al., 2019, 2021). The issues, challenges along with the potential and prospects of water management on groundwater sustainability is well described by the (Ahmad, 2002; Awan and Ismaeel, 2014a, 2014b; Cheema et al., 2014; Giordano, 2009; Gleeson et al., 2016; Konikow and Kendy, 2005; Latif and Ahmad, 2009; Margat and Van der Gun, 2013; Mehmood et al., 2020; Qureshi et al., 2003; Qureshi, Gill, et al., 2010; Qureshi, McCornick, et al., 2010; Shah, 2000; Shah et al., 2000; Siebert et al., 2010; Smith et al., 2016; Wada et al., 2010; Werner et al., 2013). The IoT application in the agriculture can be studied in the (Shahab et al., 2024).

Groundwater management faces numerous challenges worldwide, including over-extraction, saltwater intrusion, quality degradation, lack of data, legal and institutional issues, and climate change impacts. These challenges underscore the need for comprehensive strategies that integrate surface and groundwater management, engage local communities, address policy gaps, utilize advanced technologies, and enhance capacity building.

Existing groundwater advisory systems, such as the USGS National Water Information System and India's Central Ground Water Board, play crucial roles in providing data, information, and decision support tools. However, gaps persist in data availability, integration, climate change adaptation, community engagement, policy enforcement, and funding, necessitating concerted efforts to ensure sustainable groundwater management.

4. METHODOLOGY

4.1 Features and Functionality of GIAA

4.1.1 Development of GIAA

The methodology for the development of the application encompasses three major components: Flow Measurement, Irrigation Water Demand, and Time of Operation. Flow measurement is crucial for accurately assessing the amount of water available for irrigation. The application employs various methods for flow measurement, including the Trajectory Method, which accounts for the trajectory of water flow within the tubewell pipe. Additionally, the Full Pipe Flow method is utilized when the tubewell pipe is flowing at full capacity, while the Partial Pipe Flow method is employed when the pipe is only partially full. The Velocity Area Method is also utilized, which involves measuring flow in an open channel based on the cross-sectional area and velocity of the water. Velocity measurement is facilitated through the Floating Body method, where velocity (V) is calculated as the distance traveled by a floating object divided by the time taken. Moreover, the application includes methods for accurately measuring the cross-sectional area of the channel, considering various channel geometries such as Rectangular, Triangular, Trapezoidal, and Irregular Channels.

Determining the irrigation water demand is essential for efficient water management. The application incorporates both direct and indirect methods for estimating water demand. The Direct Method relies on soil moisture conditions, providing insights into the immediate water requirements of the soil. In contrast, the Indirect Method utilizes meteorological information to gauge water demand based on environmental factors. Furthermore, the application considers the water demand specific to major crops, aligning with the irrigation practices commonly observed in the Indus basin irrigation system. Additionally, irrigation methods employed by farmers play a significant role in determining water demand, with the application incorporating efficiency factors based on different irrigation techniques.

The time of operation for tubewells is crucial for optimizing irrigation schedules and resource allocation. The application calculates the operation time required for a tubewell to irrigate a specified area of land in acres. This calculation considers both the irrigation water demand, calculated in inches, and the discharge rate from the irrigation water source (tubewell). By accurately estimating the time required for irrigation operations, farmers can effectively manage water resources and maximize agricultural productivity while minimizing resource wastage.

The Application is divided into three major parts as shown in figure 1 and each is described below in details:

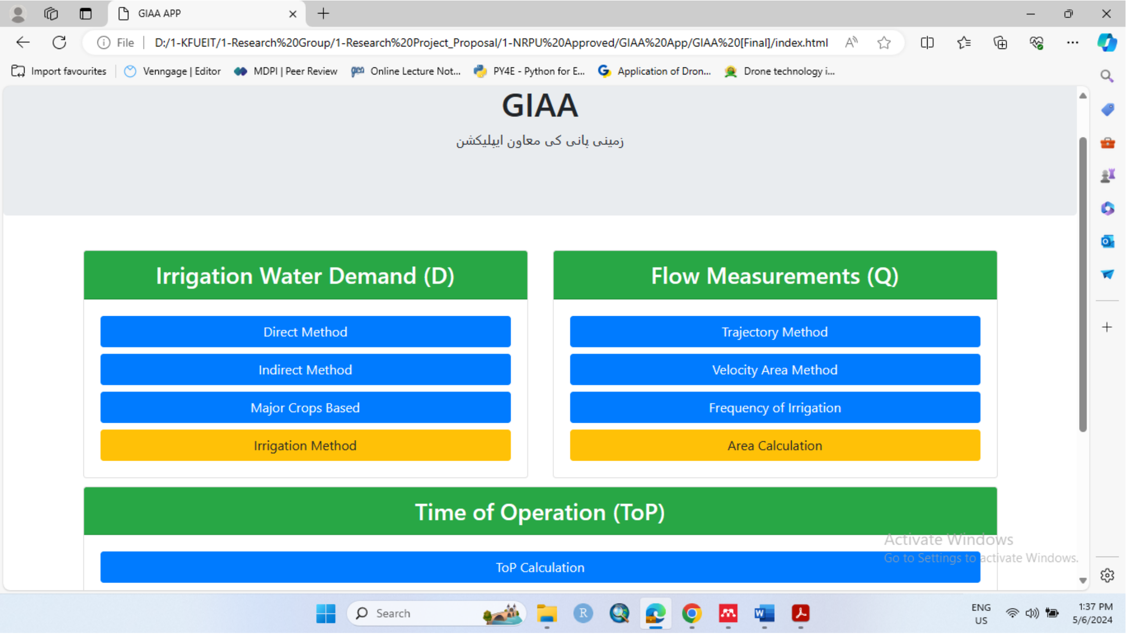

Figure 1: GIAA Main Tab

4.2 Flow Measurement

Flow measurement, particularly in the context of tubewells, holds paramount importance in agricultural water management. Accurate measurement of water flow enables farmers to efficiently utilize water resources by ensuring precise irrigation scheduling tailored to crop needs, thus preventing both over-irrigation and under-irrigation. This optimization of water usage not only conserves valuable resources but also minimizes operational costs associated with pumping and water application. Additionally, flow measurement facilitates the identification and mitigation of inefficiencies within tubewell irrigation systems, such as leaks and improper sizing, leading to improved system performance and reduced environmental impact. Furthermore, compliance with regulatory frameworks governing water allocation and reporting is facilitated through transparent and verifiable flow data. Trajectory method is a well-established method for the discharge measurement from the tubewell for both full pipe flow and partial pipe flow conditions.

4.2.1 Trajectory Method

4.2.1.1 Full Pipe Flow

Flow measurement, particularly in tube wells or pipe sections, is commonly facilitated through a straightforward method requiring three essential parameters for discharge determination:

- The inside diameter of the pipe (D)
- The x-coordinate of flow (X)
- The y-coordinate of flow (Y)

The internal diameter of the pipe is crucial for discharge calculation, while the horizontal distance from the pipe's end to the flow observation point aids in determining the flow's position. Additionally, the vertical distance from the horizontal reference point to the water jet's top enables the determination of flow elevation. In cases of full-flowing pipes, where water completely fills the pipe, these parameters are essential for accurately calculating discharge.

By integrating the pipe's diameter, horizontal and vertical distances, discharge can be determined using:

$$Q = \frac{0.0174 \times D^2 \times X}{Y^{\frac{1}{2}}} \tag{1}$$

Where, Q is discharge (lps)

D is the inside diameter of the pipe (cm)

X is the horizontal water flow coordinate (cm)

Y is the vertical water flow coordinate (cm)

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In this Application the conversion unit was also introduced to calculate the discharge in Cusecs.

4.2.1.2 Partial Pipe Flow

Flow measurement, especially in tube wells or pipe sections, often relies on a simple method that involves three key parameters for determining discharge:

$$Q = \left(\frac{0.0174 \times D^2 \times}{Y^{\frac{1}{2}}}\right) \times \left(\frac{a}{A}\right) \qquad (2)$$

The inside diameter of the pipe (D)

The z-coordinate depth of pipe flowing empty (Z)

The horizontal flow of water x-coordinate (X)

The vertical distance from water to X y-coordinate of flow (Y)

a/A is the ratio of the area that can be found from the Z values

The internal diameter of the pipe is critical for calculating discharge, while the horizontal distance from the pipe's end to the flow observation point helps pinpoint the flow's position. Moreover, the vertical distance from the horizontal reference point to the water jet's apex allows for the determination of flow elevation. In cases where pipes are fully filled with water, these parameters are crucial for accurately calculating discharge. By considering the pipe's diameter, along with the horizontal and vertical distances, discharge can be calculated effectively.

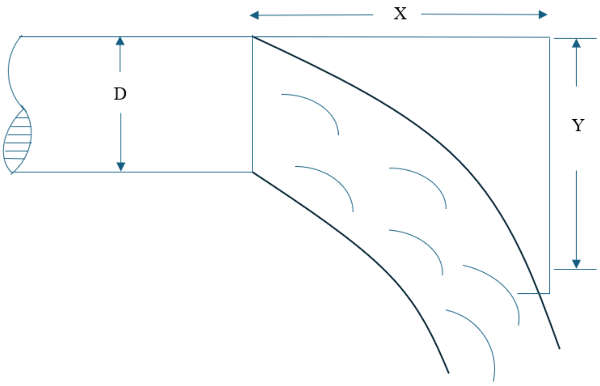

Figure 2 (a): Full Pipe Flow Parameter Calculation

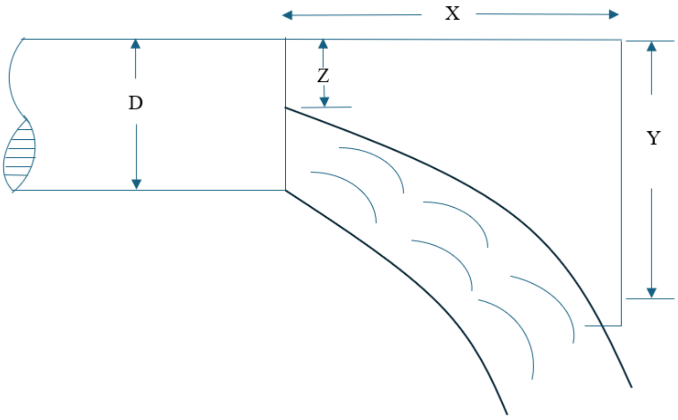

Figure 2 (b): Partial Pipe Flow Parameter Calculation

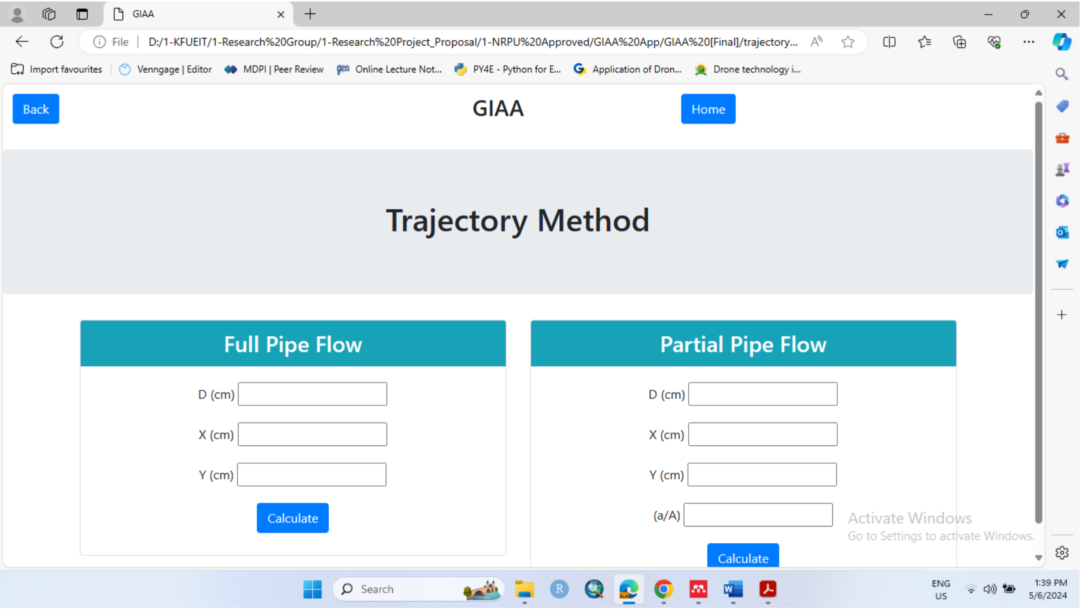

Figure 2 (c): Full Pipe Flow Application Tab and Partial Pipe Flow Application Tab

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Figure 3: Field visits to calculate the discharge of the tubewells

4.2.2 Velocity Area Method

Measurement of flow in an open channel based on the cross-sectional area of the channel and velocity of the water in the channel.

4.2.2.1 Velocity Measurement

I. Select an appropriate channel section with minimal turbulence, ideally at least three channel widths long.

II. Mark the starting and ending points for the distance your floating object will traverse. We suggest a minimum of 20 feet, but aim for a travel time of approximately 20 seconds for optimal accuracy. Shorter distances can make timing challenging, particularly with higher velocities.

III. Release your floating object into the stream upstream of the starting marker.

IV. Begin timing as the object passes the starting marker and stop the timer when it crosses the ending marker downstream.

V. Repeat the measurement at least three times and calculate the average speed by adding the three measurements and dividing by 3.

VI. Measure the width and depth of the stream at the downstream marker section. Ensure safety before entering the channel. Utilize a yardstick or staff gauge to measure depth at regular intervals across the channel. Taking ten depth measurements is the minimum recommendation, but more are advantageous, especially in larger channels (approximately every foot across). The formula for velocity (V) calculation is, Distance Traveled / Time to travel (feet traveled divided by seconds).

$$V = \frac{d}{t} \tag{3}$$

Where, V is the velocity in ft/sec , d is the distance of the water channel, t is the time traveled by the float to cover the distance d

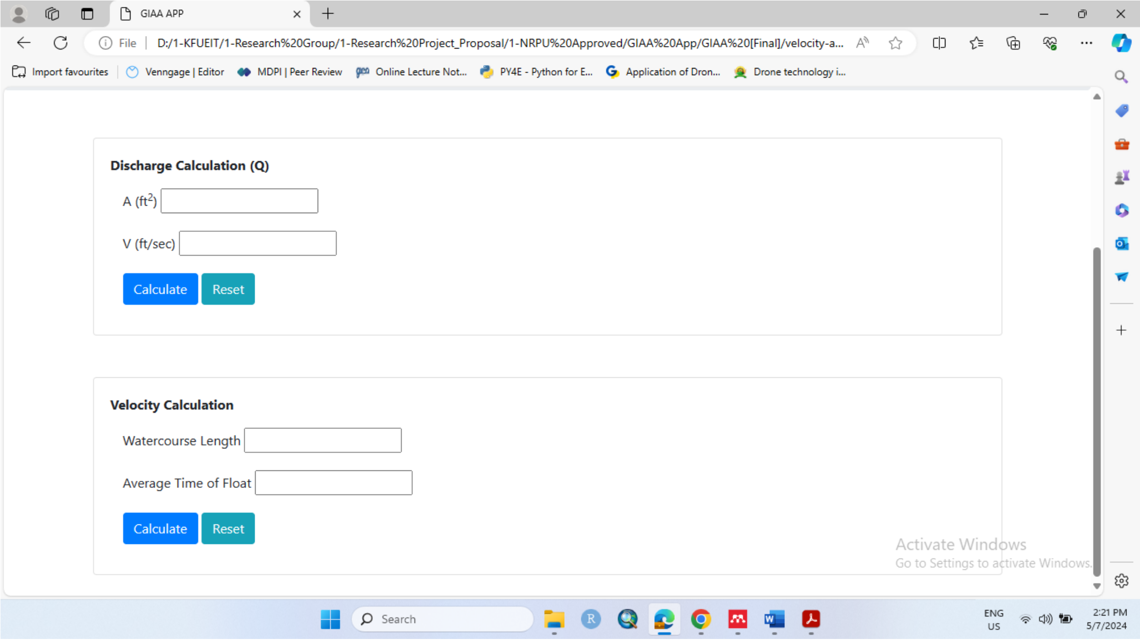


Figure 4: Velocity Calculation Tab

4.2.2.2 Area Measurement

Cross Sectional Area of the Channel will be measured through:

4.2.2.2.1 Rectangular Channel

The cross-sectional area of an open channel of rectangular type can be determined by following these steps:

I. Choose a section of the channel where the water depth and width are relatively uniform. This section should ideally be straight and free from obstructions or irregularities.

II. Measure the width of the channel perpendicular to the direction of flow. This is typically done using a measuring tape or a ruler.

III. Measure the depth of the water at various points across the width of the channel. For rectangular channels, this depth is measured from the water surface to the channel bottom.

IV. Once you have obtained measurements of the width and depth, you can calculate the cross-sectional area of the channel using the formula:

$$A = b \times d \tag{4}$$

Where, A is the cross-sectional area (ft^2)

b is the width of the channel (ft)

d is the depth of the water (ft)

4.2.2.2.2 Triangular Channel

I. Choose a section of the channel where the water depth and width are relatively uniform. Ensure that the channel has a triangular cross-section, with sloping sides.

II. Measure the depth of the water at various points across the width of the channel. This depth (d) is measured from the water surface to the channel bottom.

III. Determine the side slope of the channel, which is the ratio of the horizontal distance to the vertical distance. This can be calculated by measuring the horizontal distance (H) along the slope and the vertical distance (V) from the top of the slope to the bottom. Then, calculate

$$Z = \frac{H}{V} \tag{5}$$

IV. Once you have obtained measurements of the depth (d) and side slope (Z), you can calculate the cross-sectional area of the channel using the formula:

$$A = Zd^2 \tag{6}$$

Where:

A is the cross-sectional area (ft^2)

d is the depth of the water (ft)

z is the side slope ratio

4.2.2.2.3 Trapezoidal Channel

I. Choose a section of the channel where the water depth and width are relatively uniform. Ensure that the channel has a trapezoidal cross-section, with sloping sides and a flat bottom.

II. Measure the width of the channel at the bottom, which represents the distance between the two banks at the channel bed. This is typically done using a measuring tape or a ruler.

III. Measure the depth of the water perpendicular to the bottom width at various points across the width of the channel. For trapezoidal channels, this depth is measured from the water surface to the channel bottom.

IV. Measure the slopes of the channel sides. These slopes are typically represented by the ratio of the horizontal distance to the vertical distance. Measure the horizontal distance (H) along the slope and the vertical distance (V) from the top of the slope to the bottom. Then, calculate

$$Z = \frac{H}{V} \tag{7}$$

V. Once you have obtained measurements of the bottom width (B), water depth (D), and side slopes (Z), you can calculate the cross-sectional area of the channel using the formula:

$$A = b \times d + Zd^2 \tag{8}$$

Where, A is the cross-sectional area (ft^2)

b is the bottom width of the channel (ft)

d is the depth of the water (ft)

Z is side slope ratio

4.2.2.2.4 Irregular Chennel

First, measure the depth of the channel using an extended meter rod or tape at marked points of sections b_1, b_2, b_3, and b_4, denoting the depths as d_1, d_2, d_3, and d_4, respectively, with the initial depth (d_0) and last depth (d_4) as zero. Calculate the average depth for each section (1, 2, 3, and 4) as D1, D2, D3, and D4. Record the data and proceed to estimate the cross-sectional area (A1, A2, A3 and A4) for each subsection (1, 2, 3, 4) according to the established procedure. Finally, calculate the total cross-sectional area of the channel by summation, as shown in Table 1.

Table 1: Estimation of Cross-Sectional Area of Irregular Channel

Subsection	Top Width	Average Depth	Area of Subsections
1	b_1	$D_1 = (d+d_1)/2$	$A_1 = b_1 \times (d+d_1)/2$
2	b_2	$D_2 = (d_1+d_2)/2$	$A_2 = b_2 \times (d_1+d_2)/2$
3	b_3	$D_3 = (d_2+d_3)/2$	$A_3 = b_3 \times (d_2+d_3)/2$
4	b_4	$D_4 = (d_3+d_4)/2$	$A_4 = b_4 \times (d_3+d_4)/2$
Cross Sectional Area of Channel $A = A_1 + A_2 + A_3 + A_4$			

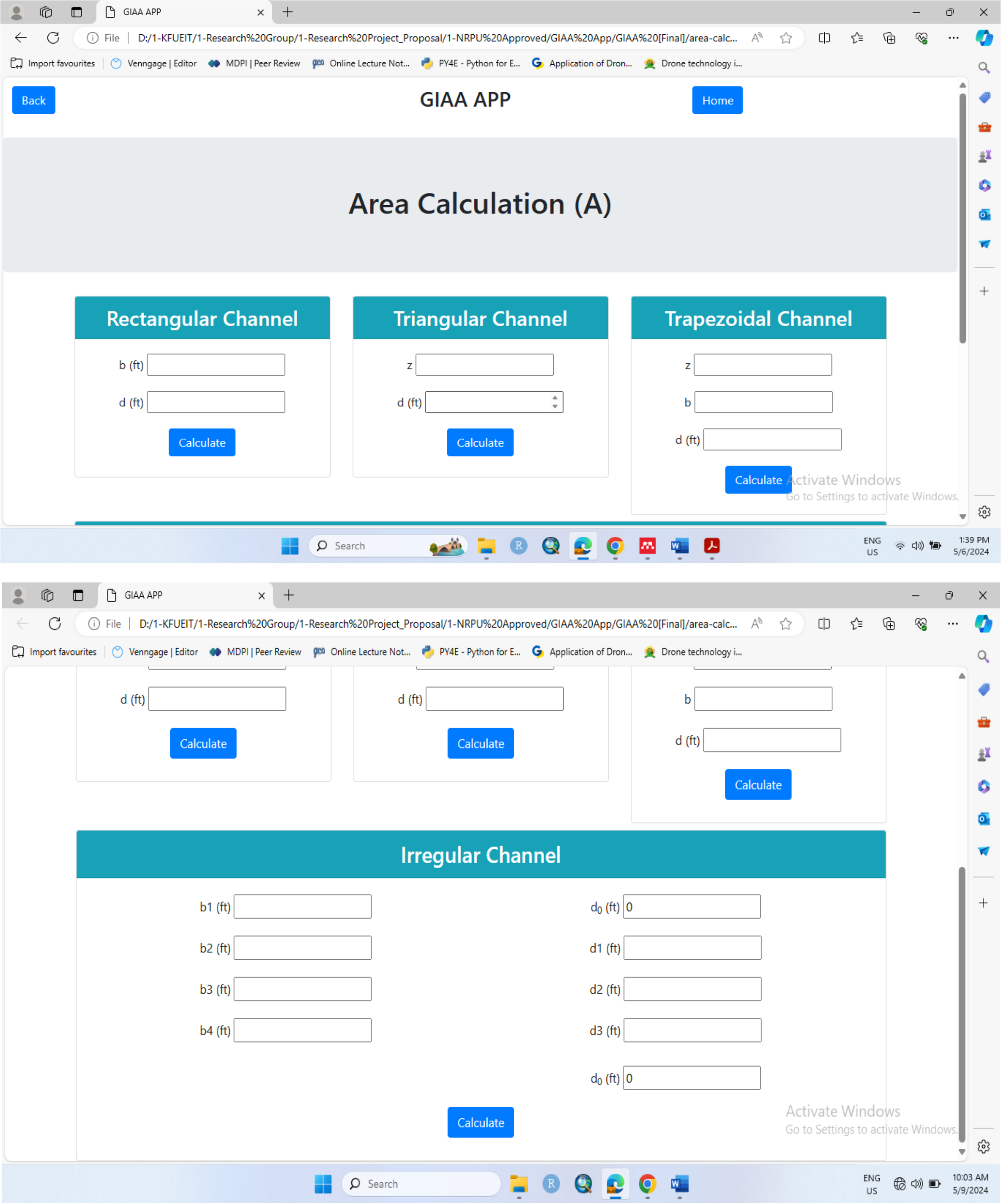


Figure 5: Channel Area Calculation Tab

4.2.3 *Discharge Calculation*

The methodology for discharge measurement in an open channel involves several crucial steps to accurately assess the flow rate of water. First, the cross-sectional area (A) of the channel is determined, typically by measuring the dimensions of the channel geometry, such as width and depth. Next, the velocity of the water (V) is measured using appropriate methods, such as the floating body method or velocity sensors. Once these parameters are obtained, the discharge (Q) can be calculated using the equation Q = A * V. This equation encapsulates the fundamental relationship between the flow rate, cross-sectional area, and velocity of water in an open channel.

$$Q = A \times V \tag{10}$$

Where:

Q is discharge (cusecs)

A is cross-sectional area of the channel (ft^2)

V is the velocity of the water (ft/s)

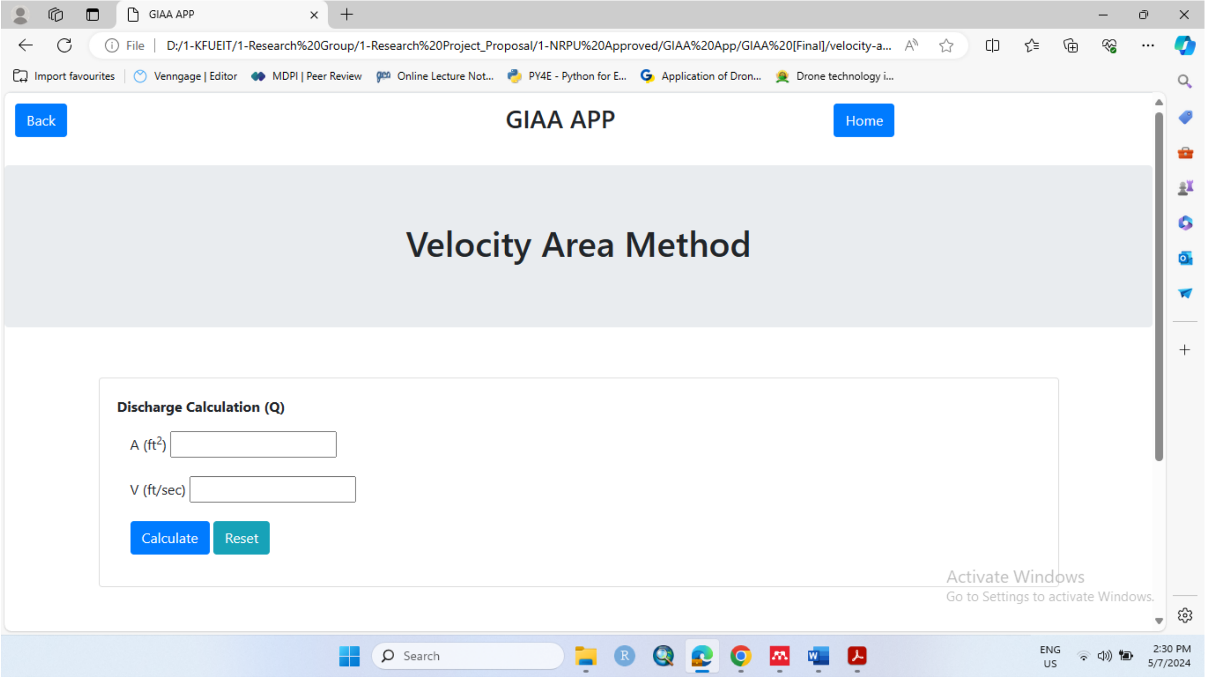


Figure 6: Discharge Calculation

4.3 Irrigation Water Demand

In assessing irrigation water demand, various methods are employed to gauge the needs of agricultural fields accurately. The direct method relies on soil moisture conditions to determine water requirements, providing insights into the immediate needs of crops. Conversely, the indirect method leverages meteorological data to estimate water demand, considering factors such as evapotranspiration rates and climatic patterns. Additionally, irrigation water demand can be inferred from the water requirements of major crops cultivated in the region, taking into account farmer practices and the adoption of deficit irrigation strategies within systems like the Indus Basin Irrigation System. These diverse approaches enable a comprehensive understanding of irrigation water demand, catering to the specific needs of different crops and agricultural practices.

4.4 Direct Method

This method involves collecting soil samples from the root zone depth both before and after irrigation. These samples are then dried to determine the moisture content on a weight basis (MC) within the root zone. Subsequently, irrigation scheduling is based on maintaining 15 to 20% of available moisture in the soil to prevent moisture stress. Given that the aim of irrigation is to elevate soil moisture content to field capacity, the crop's water requirement at the root zone is calculated using the equation:

$$D = \frac{(FC - CSM) \times B \times R}{100} \tag{11}$$

Where:

D is the water requirement on the day of soil moisture sampling (cm)

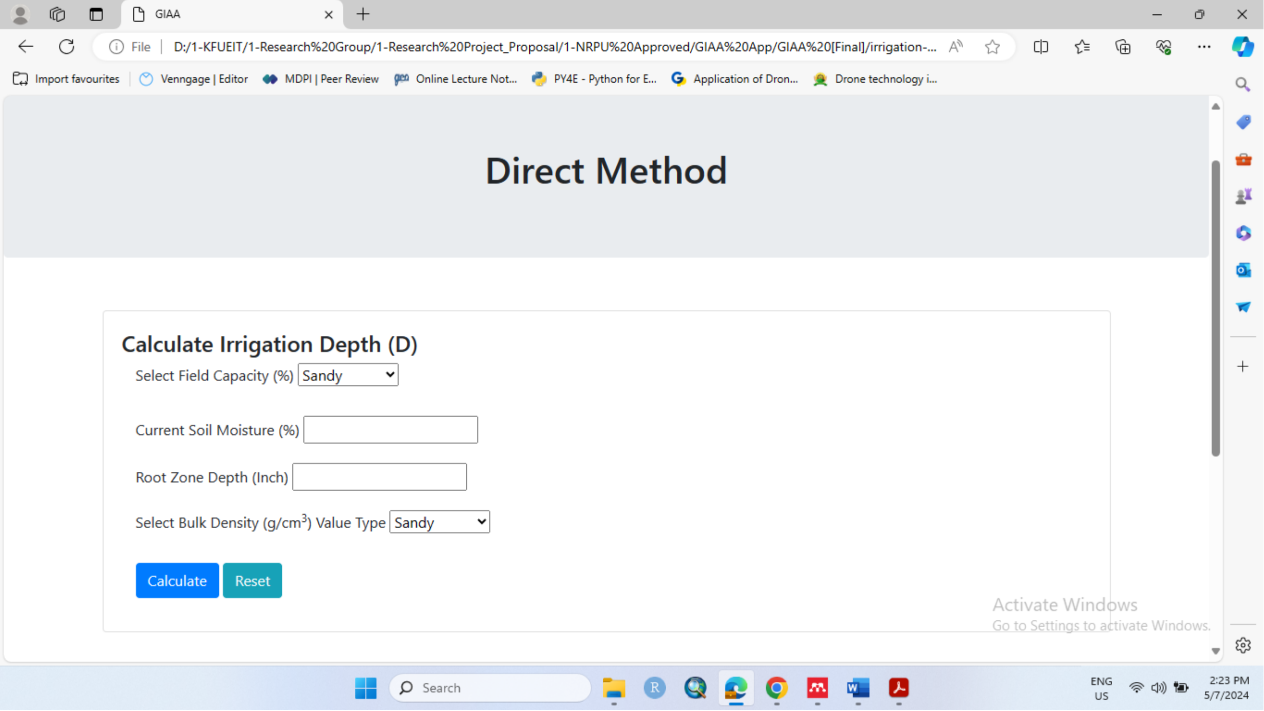
FC is the field capacity

CSM is the current soil moisture on the day of sampling

B is the bulk density of soil (in g/cm^3)

R is the root depth of the root zone (in cm)

The final results in the application are converted into inches to main the harmony in the units of the application and for the ease of the farmers.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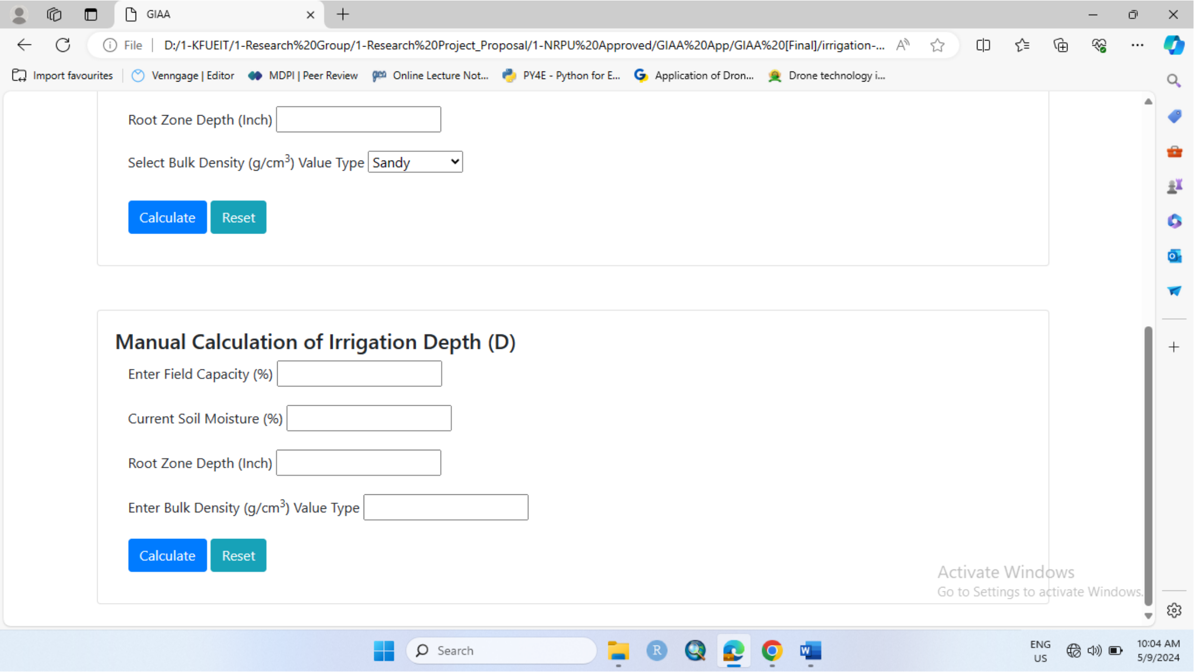


Figure 7: Direct Method Tab

4.5 Indirect Method

In the Pan Evaporation-based method for calculating irrigation water demand, the process involves utilizing evaporation data collected from a standard evaporation pan placed within the agricultural field. This method integrates the atmospheric demand for moisture with crop-specific factors to estimate the water requirements of the crops accurately. By following a systematic approach outlined in the following steps, this method enables efficient irrigation scheduling tailored to the specific needs of the crops and prevailing environmental conditions.

The stepwise procedure as:

I. Place a standard evaporation pan within the agricultural field and measure the evaporation rates regularly.

II. Record the evaporation data collected from the pan over a specific period, typically on a daily or weekly basis.

III. Take into account factors such as crop type, growth stage, and local climatic conditions to estimate the water requirements of the crops.

IV. Use the evaporation rates and crop-specific factors to estimate the irrigation water demand for the crops.

$$ET_o = E_{pan} \times K_{pan} \quad (12)$$

Where:

ET_o is potential evapotranspiration

E_{pan} is the evaporation from the pan (inch)

K_{pan} is the pan coefficient

$$D = ET_o \times k_c \quad (13)$$

Where:

D is the irrigation water demand

Kc is the crop coeffect

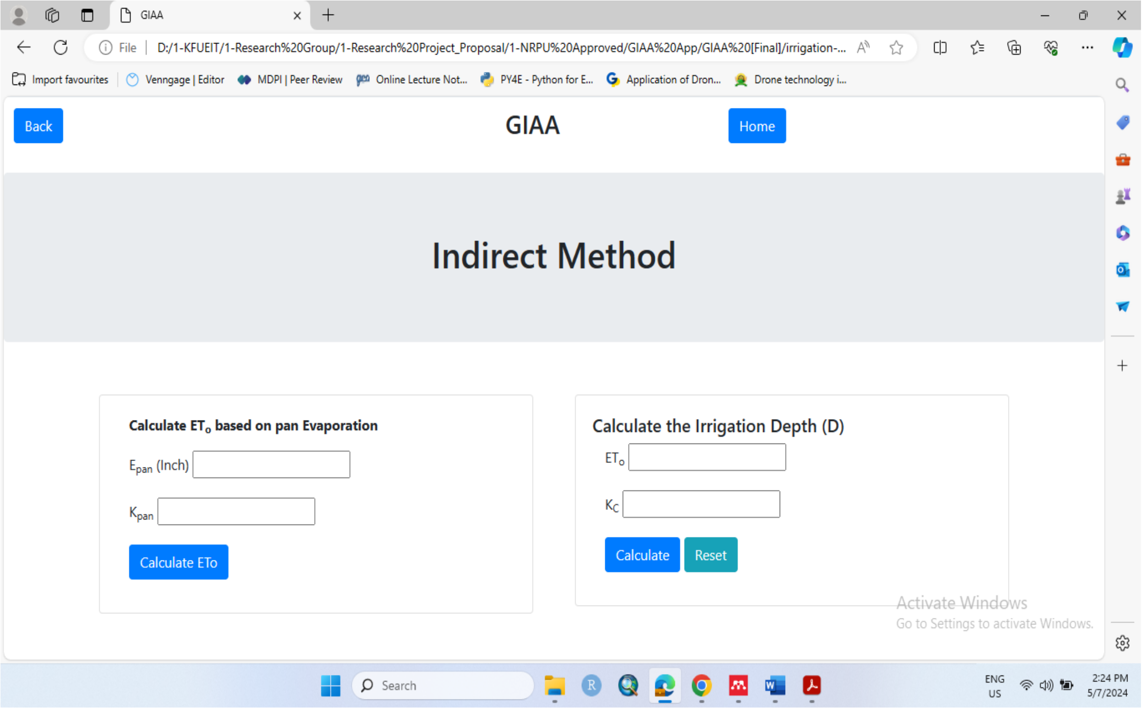


Figure 8: Indirect Method Tab

In this method, the direct value if ETo can be also used instead of ETpan based calculation. This option provides the assessment of irrigation water demand based on the advanced instrument used for the ETo estimation.

4.6 Major Crops Based

The major crops-based tab represents the farmer practices and deficit practices adopted in the irrigated Indus basin irrigation system. In the farmers practices the most widely adopted irrigation water demand is presented for soaking and all the next irrigation. Additionally, the deficit irrigation water practices are also presented.

4.7 Irrigation Methods

Effective irrigation plays a pivotal role in agricultural success, ensuring that crops receive adequate water for optimal growth and yield. Various irrigation methods, such as basin, border, furrow, sprinkler, and drip irrigation, offer distinct approaches to delivering water to crops. Each method has its own set of advantages, disadvantages, and performance efficiencies, catering to diverse agricultural landscapes and crop requirements. Whether it's the traditional simplicity of basin irrigation, the controlled precision of drip irrigation, or the versatility of sprinkler systems, the overarching goal remains the same: to provide crops with the right amount of water at the right time while maximizing water use efficiency and minimizing environmental impact.

4.7.1 Basin Irrigation

Basin irrigation, a traditional method, involves creating flat areas of land surrounded by low bunds to contain water. The simplicity of this method makes it one of the oldest and most common irrigation techniques in Pakistan. Fields are divided into smaller units, each with nearly level surfaces, enclosed by bunds. Water is filled to the desired depth within these basins and retained until it infiltrates the soil. This method is particularly effective for crops like rice, where water can be ponded for extended periods to leach salts from the soil.

4.7.2 Border Irrigation

In border irrigation, narrow strips of land are utilized, often guided by parallel ridges to direct the flow of water down slopes. These strips, known as borders, can be either level or graded, depending on topographic conditions. The flow of irrigation water down the slope is controlled by bunds, ensuring uniform distribution across the field. Borders are typically irrigated independently, with each strip receiving water for a specified duration at a predetermined flow rate. The width and length of border strips are carefully considered to optimize water use efficiency and minimize costs.

4.7.3 Furrow Irrigation

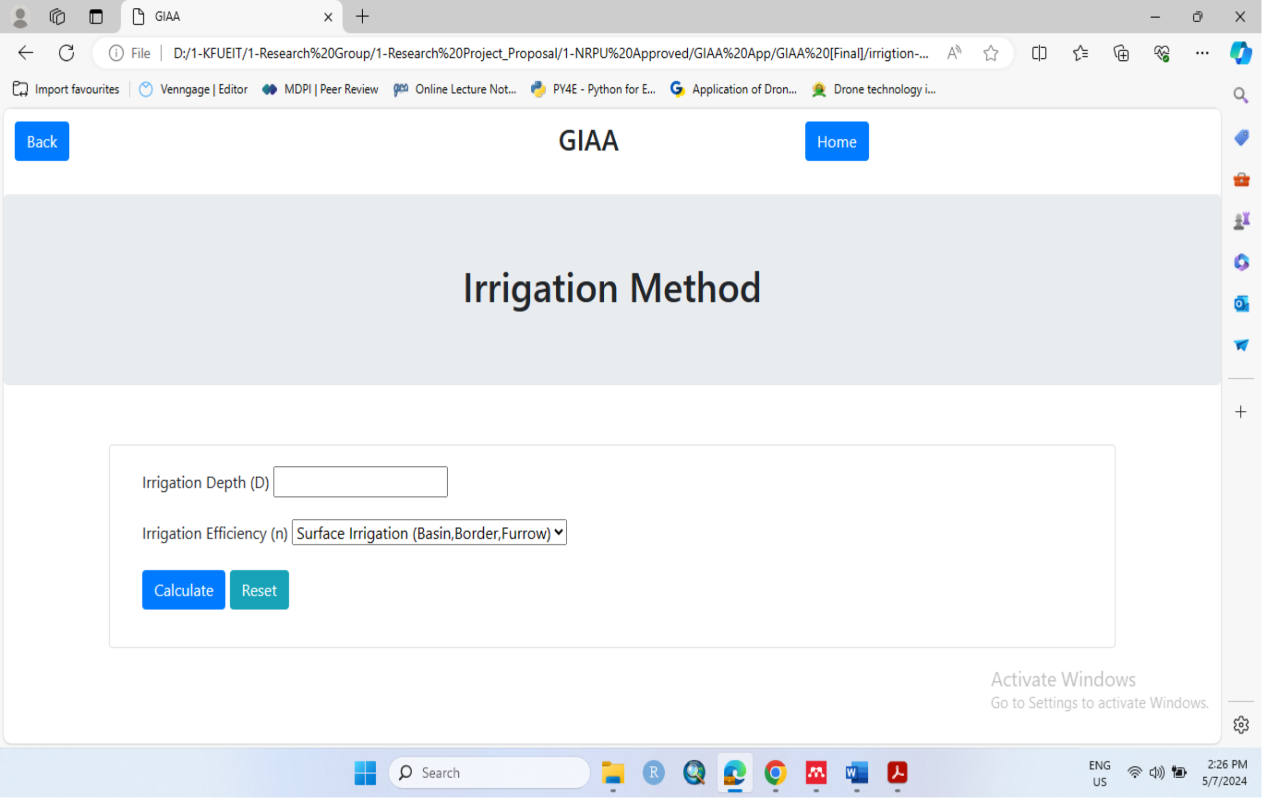
Furrow irrigation involves the creation of small channels, or furrows, between crop rows, allowing water to flow downhill. Crops are often planted on ridges or raised beds between the furrows. Water is delivered to the furrows either by opening the bank of an irrigation channel, using siphons, or gated pipes. As water moves along the furrows, it infiltrates into the soil, irrigating the areas between rows. The duration of water flow in furrows is determined by factors such as crop water requirements and soil infiltration rates. This method is adaptable to various crops and can accommodate different irrigation stream sizes.

4.7.4 Sprinkler Irrigation

Sprinkler irrigation involves the pressurized spraying of water over the field, simulating natural rainfall. This method is suitable for a wide range of crops and terrain types. Sprinklers distribute water evenly, reducing water loss due to evaporation and wind drift. However, the initial cost of equipment and energy consumption can be higher compared to other methods. Nonetheless, sprinkler irrigation offers greater flexibility and control over water application, making it a popular choice in many agricultural settings.

4.7.5 Drip Irrigation

Drip irrigation delivers water directly to the root zone of plants through a network of tubing and emitters. This precise method minimizes water waste by delivering water only where needed, thereby enhancing water use efficiency. Drip systems can be tailored to specific crop requirements, soil conditions, and topographies, making them highly adaptable. While initial installation costs may be higher, drip irrigation can result in significant water savings and improved crop yields over time. This method is particularly advantageous in arid regions or areas with limited water resources.



Irrigation Method

Irrigation Depth (D)

Irrigation Efficiency (n) Surface Irrigation (Basin,Border,Furrow)

Figure 9: Irrigation Methods

4.7.6 Time of Operation

Time to calculate the operation time for a tubewell to irrigate the desired land in Acres with the calculated irrigation water demand in inches and with the calculated discharge from the irrigation water source (tubewell).

$$T = \frac{AD}{Q} \tag{14}$$

Where, T is time of operation (hours) for the tubewell, to irrigate area A (acres) for the depth D (inches) with the discharge Q (cusec).

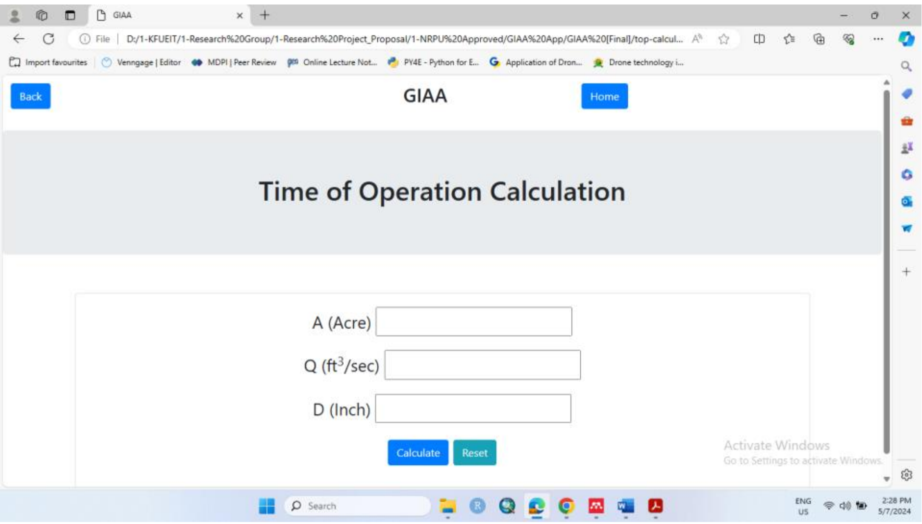


Figure 10: Time of Operation Calculation Tab

4.7.7 Frequency of Irrigation

Additionally, the time of next irrigation can be calculated based on the amount of water stored in the rootzone and the daily actual evapotranspiration. The projection of the root zone moisture budget extends into the future until reaching the desired soil moisture level for irrigation. This projection accounts for a linear rate of evapotranspiration. Additionally, determining the date of the next irrigation involves dividing the total consumable moisture by the average rate of evapotranspiration.

$$Number\ of\ days\ to\ next\ irrigation = \frac{Depth\ of\ Water\ Stored\ in\ Rootzone}{Daily\ ET_a} \qquad (15)$$

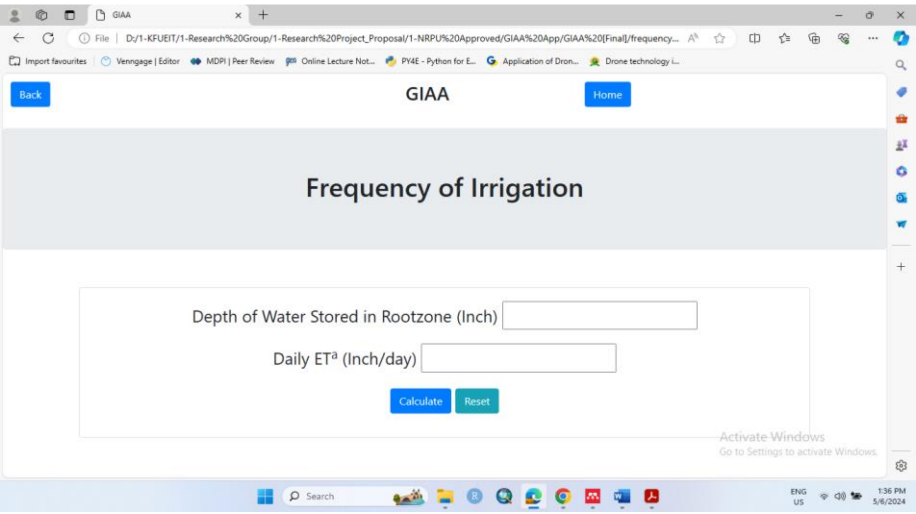


Figure 11: Frequency of Irrigation Calculation Tab

5. FUTURE DIRECTIONS AND ENHANCEMENTS

Moving forward, the development and implementation of the Groundwater Irrigation Advisory Application (GIAA) can benefit from several future directions and enhancements. These may include integrating advanced technologies such as remote sensing and artificial intelligence to improve real-time monitoring and predictive analytics capabilities. Additionally, enhancing the user interface and accessibility features of the application can ensure widespread adoption among farmers and water managers. Furthermore, incorporating feedback mechanisms to gather user input and continuously updating the application based on evolving needs and technological advancements will be crucial for its long-term effectiveness and sustainability.

The adoption of the Groundwater Irrigation Advisory Application (GIAA) holds significant implications for sustainable groundwater management. By providing farmers with accurate and timely information on groundwater availability, usage patterns, and efficient irrigation practices, GIAA empowers users to make informed decisions that optimize water use efficiency and minimize environmental impact. Moreover, GIAA facilitates compliance with regulatory frameworks governing water allocation and reporting, thereby promoting transparent and accountable groundwater management practices. Ultimately, the widespread adoption of GIAA has the potential to contribute to the preservation and sustainable use of groundwater resources, ensuring their availability for future generations.

The Groundwater Irrigation Advisory Application (GIAA) exhibits several strengths that contribute to its effectiveness in promoting sustainable groundwater management. These include its ability to provide real-time groundwater monitoring, tailored irrigation schedules, and educational support to farmers, thereby empowering them to optimize water usage and maximize agricultural productivity. Moreover, GIAA facilitates data-driven decision-making and enhances regulatory compliance, fostering transparent and accountable groundwater management practices. However, GIAA also faces certain limitations, such as the need for continuous updates and improvements to keep pace with evolving technology and user needs. Additionally, challenges related to data accuracy, accessibility, and user adoption may hinder its widespread implementation and effectiveness in certain contexts.

6. CONCLUSION

The development and implementation of the Groundwater Irrigation Advisory Application (GIAA) represent a significant step towards promoting sustainable groundwater management, agricultural productivity, and food security. By leveraging technology to provide farmers with timely and accurate information on groundwater availability and efficient irrigation practices, GIAA empowers users to make informed decisions that optimize water use efficiency and minimize environmental impact. While GIAA exhibits strengths in promoting transparent and accountable groundwater management practices, addressing its limitations and ensuring continuous updates and improvements will be essential for maximizing its effectiveness and impact in the long run. Overall, GIAA holds great promise in safeguarding groundwater resources and ensuring the resilience of agricultural systems in the face of increasing water scarcity and climate uncertainty.

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