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"CROPWAT 8.0 in Irrigation Management: A Review of Methods and Applications"

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ABSTRACT

When it comes to effective farming, irrigation management is an important factor due to the increasing climate changes and scarcity of water. The Food and Agriculture Organization developed CROPWAT 8.0, a decision support tool which enables the user to calculate the needs of a crop and set up the best timing for the irrigation. This review paper describes the methods and the workings of CROPWAT 8.0 in regard to irrigation scheduling, giving special attention to innovations and developments registered after its launch. Important issues include the combination of CROPWAT with remote sensing and climate models, regional studies showing its practical usefulness and its contribution in the development of water management strategies Researchers identify crucial hurdles like data scarcity and necessity for real-time apps they discuss potential future paths. Recent research synthesis underscores CROPWAT 8.0's crucial impact on water use efficiency globally through myriad sustainable agricultural practices.

Introduction:

Agriculture is a critical sector for the economy of India, with more than 60% of the population depending on it for their livelihoods (Kumar *et al*., 2018). However, the diverse agro-climatic conditions of the country make sustainable agricultural development very challenging. Water management is especially very difficult due to erratic distribution of rainfall and over-extraction of groundwater. Of groundwater, it has become one of the most serious concerns for Indian agriculture (Chand *et al*., 2020). This problem is more severe in regions like Gujarat, a state in the western part of India, characterized by a semi-arid climate with intensive agricultural activity. Gujarat is known for growing a wide variety of crops, including cotton, groundnut, wheat, and maize, but faces increasing challenges of water shortages and inefficient water use in agriculture (Patel *et al*., 2017). The importance of irrigation, therefore—even though it accounts for about 80% of the country's total water use—becomes very essential in ensuring that the crops get an adequate amount of water during these dry periods. Efficient irrigation scheduling—that decides on the right time and amount of water to be given to crops—is very fundamental in improving Water use efficiency and ensuring sustainable agricultural production (Sharma *et al*., 2019). In India, with both surface and groundwater under pressure, the need for precise and efficient irrigation practices has never been more critical. Overexploitation of groundwater for irrigation, particularly in regions like Gujarat, has resulted in declining water tables, making it increasingly difficult to maintain crop yields and sustain livelihoods (Rao *et al*., 2020) With the increasing need for accurate tools and techniques that

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will empower farmers to estimate crop water requirements (CWR) for effective scheduling of irrigation, the CROPWAT model from the Food and Agriculture Organization has been gaining enormous popularity in India. The newest version, 8.0, offers a decision-support system that not only estimates the water requirement of crops but also designs irrigation schedules, and assists in optimizing water use for various cropping systems. The model uses climatic, soil, and crop-specific data to estimate reference evapotranspiration (ETo) and crop water requirements; hence, the model is an excellent tool to manage irrigation and especially in Gujarat, where the state is severely water-scarce (FAO, 1998). By integrating all these data, CROPWAT 8.0 assists in designing Schedules that are in consonance with the local climate and crop needs, thus avoiding excess water use and enhancing water use efficiency in agriculture. In Gujarat, where agriculture is highly dependent on irrigation, CROPWAT 8.0 has been applied in several studies to optimize the management of irrigation. Gujarat's agro-climatic conditions, characterized by high temperatures, limited rainfall, and varied soils types, thus being the most ideal case to apply CROPWAT 8.0 in developing solutions to water shortages (Patel *et al.*, 2017).. Types, thus stands as an excellent case for the application of CROPWAT 8.0 to solve the problems related to water shortage (Patel *et al.*, 2017).

The state has been under severe water stress, especially in regions like Saurashtra and Kutch, where over extraction of ground water for irrigation purposes has led to drastic declines in waterresources (Sharma *et al.*, 2019). For example, in Saurashtra, which is an area prone to droughts and also over-exploitation of groundwater, CROPWAT 8.0 has been found to be greatly effective in estimating the irrigation requirement of crops such as groundnut, cotton, and wheat so that less water is applied but crop yields can be maintained (Garg *et al.*, 2015). Usage of CROPWAT 8.0 in Gujarat has been very highly useful that proper irrigation scheduling can result in significant gains in water use efficiency. In areas where surface water resources are scarce, the software has been used in designing efficient crop irrigation schedules under sprinkler and drip irrigation systems, both of which are increasingly becoming popular as water-saving techniques in Gujarat (Khan *et al.*, 2020). These systems, when coupled with Optimized irrigation schedules from CROPWAT 8.0 help to reduce the losses of water by evaporation and deep percolation, ensuring water is used efficiently and crop yields are sustained even under water-scarce conditions. The following are some of the challenges to the application of CROPWAT 8.0 in Gujarat: The accuracy of the model's predictions highly depends on good quality and availability of data. For example, estimating crop water requirements correctly depends on the availability of good quality meteorological data along with detailed soil profile and crop-specific parameters. In some parts of the Gujarat state, however, the lack of extensive data leads to incorrect or sub-optimal irrigation schedules (Raza *et al.*, 2020). Further, while CROPWAT 8.0 is a great tool for estimating Irrigation needs; it needs to be calibrated to the local conditions. The regional crop coefficients and soil characteristics have to be adapted, addressing the diverse agro-climatic zones of Gujarat (Patel *et al.*, 2017). Also, the adoption of CROPWAT 8.0 in Gujarat has barriers like low awareness of the farmers on the profitability of using the tool and the challenges associated with its implementation. Most of the developing countries' farmers in rural areas still depend on traditional methods of irrigation scheduling that result in waste of water, and reduced yields in agriculture productivity. There is a need to have better extension programs that inform farmers about the merits of modern scheduling irrigation techniques; this includes making use of software like CROPWAT 8.0 and training associated with how to use the model effectively for their local farming conditions (Kumar *et al.*, 2018). Integrating CROPWAT 8.0 with emerging technologies, such as Geographic Information Systems (GIS) and remote sensing, will further increase the potential for this model's accuracy and applicability in changing environments of farming (Raza *et al.*, 2020). GIS can be used for mapping field characteristics such as soil types, elevation, and available water. Moreover, remote sensing provides real-time data regarding the condition of crops and soil moisture, which may further improve the scheduling of irrigation. In recent times, Gujarat has registered significant progress in Adoption of micro-irrigation systems, such as drip and sprinkler irrigation, helps in improving water use efficiency. Integration of these systems with tools like CROPWAT 8.0 would help farmers in Gujarat to a large extent in the reduction of water consumption and increase crop yields in the regions that experience chronic conditions of water shortage. For instance, Raza *et al.* (2020) studied integration of Integration of CROPWAT 8.0 with remote sensing data for optimized scheduling of irrigation in Gujarat helped decrease water use by 20-30% while maintaining or even increasing crop yields. Such studies show the potential of CROPWAT 8.0 in improving irrigation practices in the water-scarce regions of Gujarat, where every drop count.

Methodology:

The methodology is tailored to support effective management of the irrigation practices under the prevailing condition in the regions like Gujarat where water resource is scarce and crop productivity must be maximum.

1. Set-up and initialization of the model: Effective use of CROPWAT 8.0 in management of irrigation depends upon the proper initialization of the model; thus, inputs in the model entail precise climatic, soil, and crop information for defining water management parameters.

a. Input of Climate Data: First, the input of climate data is done. It includes temperature, wind speed, relative humidity, and solar radiation. All these are the main input variables in computing reference evapotranspiration (ETo) by the FAO Penman-Monteith method, which is a standard method for determining crop water requirements (Allen *et al.*, 1998). The reference evapotranspiration (ETo) serves as the baseline for crop-specific evapotranspiration (ETc) calculation, which adjusts the ETo using crop coefficients (Kc).

b. Setting up soil parameters: The soil characteristics, such as texture, field capacity, wilting point, and root depth, are input to estimate the water-holding capacity of the soil. These parameters have effects on the calculation of soil moisture and, consequently, determine the frequency of the irrigation events (Zhang *et al.*, 2016). Using these parameters on the soil, CROPWAT simulates how much water can be stored and when irrigation is needed.

c. Crop parameter setup: crop parameters are needed for modelling crop water requirements.

Crop type, planting and harvest dates, crop development stages and crop coefficients (Kc) are needed. TheKc values change with the life cycle of the crop, and CROPWAT adjusts them so that good estimates of crop water requirements are achieved (Hassan *et al.*, 2017).

2. Evapotranspiration and Crop water requirement calculation: After model initialization, the next step is the estimation of crop water requirement that involves estimating reference evapotranspiration (ETo) and then using crop specific parameters to get the actual evapotranspiration (ETc).

a. Reference Evapotranspiration Estimation: ETo is determined through the Penman-Monteith method that integrates various climatic parameters in determining ETo: temperature humidity solar radiation and wind speed (Allen *et al.* 1998). It forms the basic value required for attaining crop-evapotranspiration (ETc).

b. Crop Evapotranspiration (ETc) Estimation: Crop-specific actual evapotranspiration (ETc) can be achieved by multiplying the reference evapotranspiration (ETo) by the crop coefficient (Kc) at each growth stage. The Kc is a function of the crop's growth stage, and the model modifies the water requirement accordingly. This step is very critical in computing the total water demand during the growing season (Khalil *et al.*, 2020).

3. Irrigation Scheduling: Once the crop water requirements are determined, then irrigation schedules can be generated using two major methods in CROPWAT: the soil moisture balance method and the fixed interval method.

a. Soil Moisture Balance Method: The soil moisture balance method is a dynamic approach where the model calculates soil moisture levels and compares them with crop water needs. If the soil moisture is inadequate, it schedules irrigation to fill the water deficit (Molden *et al.*, 2010). This method is highly suitable for regions having fluctuating rainfalls, as in the case of Gujarat where irrigation scheduling needs to be done by crop type and soil type

b. Fixed Interval Method: Under this approach, the time interval between applications of irrigation remains fixed. Such a simple way of irrigation management is apt where water availability in the area never varies significantly. Alternatively, simple irrigation schedules provide comfort to many farmers as stipulated by Chawlaet al., 2020). However, this method may not be as good as the soil moisture balance method, mainly for water-scarce regions.

4. Water Use Efficiency (WUE) Optimization: Water use efficiency (WUE) is among the most main performance indicators to irrigation scheduling. WUE is the ratio of crop yield to the amount of water used. Optimizing the WUE is of great importance to ensure that irrigation systems are working effectively under water-scarce regions. a. Water Use Efficiency EvaluationCROPWAT compares different irrigation scheduling scenarios to determine the most water-efficient methods. It considers crop yield and water use under different scheduling techniques and irrigation methods, for example, drip, sprinkler, and surface irrigation, with the aim of maximizing crop yield with minimal water use (Wani *et al.*, 2017).

b. Integration of Irrigation Systems CROPWAT 8.0 has a feature to integrate advanced irrigation systems, such as drip and sprinkler irrigation, in the scheduling process. These systems allow more precise application of water and reduce water losses through evaporation and runoff. The model determines the influence of the irrigation system on the WUE in order to find the most suitable way of optimization of the irrigation practice (Abou-Hadid *et al.*, 2011).

5. Model Validations and Refinement: From the development of the irrigation schedules, the model goes on validate the results either by field trials or through historical data comparison. Validation of the model is necessary to ensure that the irrigation schedules resemble real world conditions.

a. Model Validation: Often, field trials are carried out to validate the irrigation schedules as generated by CROPWAT 8.0. A comparison is made between model's predicted irrigation requirements and crop yields to actual field data, which gives insight into the accuracy of the model (Sharma *et al.*, 2019). This step is helpful in fine tuning the model so that it can give reliable and accurate irrigation schedules.

b. Model Refinement: The input parameters may be refined based on the results of model validation. This may involve the adjustment of crop coefficients, irrigation depths, or soil characteristics. Refining the model improves its predicting capability and assures a better fit to the real conditions, further enhancing water use efficiency (Feng *et al.*, 2018).

6. Impact Assessment: The last step in the methodology is the evaluation of the impact of the irrigation schedules on water use and crop productivity. This is done by comparing water usage and crop yields before and after using CROPWAT-generated schedules

Application of CROPWAT 8.0 in Irrigation Management: CROPWAT 8.0 is a software package by FAO to help in managing irrigation, estimating crop water requirements (CWR), and designing optimal irrigation schedules in conditions where water is a scarce resource. Estimation of Crop Water Requirements (CWR): This is one of the most important features of CROPWAT, as it estimates the water requirements of crops—an essential component in effective irrigation management. The model uses climate, soil, and crop data to estimate crop evapotranspiration (ETc), which tells us how much water the crops need to thrive. The simple formula is given as:

$$ET_c = ET_o \times K_c$$

Where ETc is the crop water requirement, ETo is the reference evapotranspiration based on climate data, and Kc is the crop coefficient that varies with the development of the crop. This makes planning of irrigation easy and assures that crops get just the right amount of water without waste.

Irrigation Scheduling: CROPWAT offers two main ways to schedule irrigation:

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oil Moisture Balance Approach: This involves estimation of soil water balance including precipitation, irrigation, crop water needs, and soil moisture. It applies when the soil moisture level drops to a certain threshold hence very useful for areas with unpredictable rainfall patterns some parts of India (Rana *et al.*, 2008).

$$SMB = P + I - ETc - D$$

Fixed Interval Method: It involves predetermination of time intervals between water applications, independent of soil moisture status. Very often, it is used for irrigation systems where the discharge is fixed or the rainfall is in a more homogeneous pattern than in areas characterized by erratic weather conditions (Sangha *et al.*, 2019).WUE and Sustainability: One of the most important objectives in irrigation management is to achieve high WUE—maximum crop yield with minimum application of water. CROPWAT helps to schedule irrigation optimally so that it can enhance water use efficiency. It assures optimal use of available water while harvesting maximum crop. It also compares different methods of irrigation, including drip and sprinkler systems, to find out the most efficient option for specific crops in specific regions (Allen *et al.*, 2019).

Case Studies of CROPWAT Application:

India: In the water-scarce regions similar to Gujarat, CROPWAT has proved instrumental in bringing about improvements in water use efficiency for a multitude of crops, including cotton, wheat, and rice. The tool has therefore enabled farmers to lower water applications in their fields while maintaining crop yields in the face of erratic rainfalls and over-exploited groundwater's (Sharma *et al.*, 2019).

Arid and Semi-arid Regions: Water shortage is becoming a serious problem in Egypt and sub-Saharan countries of Africa; in these regions, CROPWAT has been found effective. The optimization of the irrigation schedule could result in a reduction in water use but an increase in crop yield, thus making the practice of irrigation sustainable (Abou-Hadid *et al.*, 2011; Nicolás *et al.*, 2017).Challenges and Limitations: CROPWAT, although a very good tool in managing irrigation, does not come without its challenges. Its predictions are based on the goodness of input data, so where reliable data is scanty, results may not be that precise. The use of CROPWAT also does not put into consideration other important factors like soil salinity or pest problems, which may equally have an effect on water requirements (Molden *et al.*, 2010).

Result and discussion:

Methods and Algorithms in CROPWAT 8.0 for Irrigation Scheduling:

CROPWAT 8.0 for irrigation:

CROPWAT 8.0 is a powerful decision-support tool for scheduling irrigation, water resources management, and crop water requirement estimation. The methods and algorithms used in CROPWAT have their basis in various scientific models related to evapotranspiration, crop growth stages, and soil-water balance relevant to the scheduling of optimum crop irrigation. Further in the succeeding section will detail some major methods and algorithms applied by the tool CROPWAT 8.0.including the FAO Penman-Monteith method for estimating reference evapotranspiration, crop coefficient adjustments, soil moisture balance, and various irrigation scheduling methods

1. Evapotranspiration Estimation (ET): Estimation of evapotranspiration is one of the core elements of CROPWAT 8.0 since it has a direct consequence on the irrigation scheduling. The model makes use of a few methods for estimating both the reference and crop evapotranspiration.

a. Reference Evapotranspiration (ET_o)

CROPWAT 8.0 uses the FAO Penman-Monteith method (Allen *et al.*, 1998), for the estimation of the reference evapotranspiration (ETo) being the water amount that gets evaporated from standardised reference crop (grass) under standard conditions. The FAO Penman-Monteith equation is generally considered the most accurate method of determining ETO and includes the effects of climate variables such as temperature, solar radiation, relative humidity, and wind speed. The formula is as follows:

- ETo is the reference evapotranspiration (mm/day),
- Δ is the slope of the temperature-based vapor pressure curve (kPa/°C),
- Rn is the net radiation at the crop surface (MJ/m^2/day),
- G is the soil heat flux density (MJ/m^2/day),
- γ is the psychometric constant (kPa/°C),
- T is the mean daily air temperature (°C),
- U_2 is the wind speed at 2 meters height (m/s),
- e_s is the saturation vapor pressure (kPa),
- e_a is the actual vapor pressure (kPa).

b. Crop Evapotranspiration (ET_c): The crop evapotranspiration, ET_c, is calculated by multiplying the reference evapotranspiration (ET_o) by the crop coefficient (K_c) at every growth stage:

$$ET_c = ET_o \times K_c$$

The crop coefficient, Kc is not constant for the whole growth period of the crop and expresses the changes of water need of the crop with the progress of growth, like, initial growth, development, mid-season, and late season. The Kc values are empirical and are locally calibrated and crop class adjusted (Raes *et al.*, 2009).

2. Soil Moisture Balance Algorithm: Soil moisture balance (SMB) is used to estimate the soil water content considering the precipitation, irrigation, crop water requirement and the losses by evaporation and drainage. CROPWAT uses a dynamic algorithm to account for the change in soil moisture over time.

3. Irrigation Scheduling Methods: CROPWAT 8.0 provides for the following multiple irrigation scheduling methods that optimize water applications while, at the same time ensuring an adequate water supply by crops. This program includes;
Soil Moisture Balance Method- Dynamic Approach –This, indeed is CROPWAT major and by far the most versatile irrigation schedules being used presently by the models, which on soil moisture dynamic conditions, dictates/decides/trigger and provide for "SCHEDULE irrigation". Here algorithm Continuously updates soil moisture based on rainfall, irrigation, evapotranspiration, and drainage; it triggers the irrigation when soil moisture falls below the crop threshold level (Allen *et al.*, 1998). The approach is very flexible in terms of irrigation and thus quite useful in areas with erratic rainfalls

b. Fixed Interval Method: This method does irrigation at fixed, pre-determined interval regardless of soil moisture content. It is a simpler approach to irrigation, and among the common methods applied where the rainfall can be predicted, or the irrigation systems are of fixed delivery rate. The former is though easier to put into practice, but has lower efficiency since the periods of high rainfall may result in over-irrigation while the spells may result in under-irrigation (Molden *et al.*, 2010)

4. Water Use Efficiency Optimization Algorithms: water

use efficiency referred to here as WUE is the amount of crop yield produced per unit of water consumed. CROPWAT uses optimization algorithms to maximize WUE by adjusting irrigation depths and scheduling. These optimization algorithms focus on the minimization of water use while maintaining or increasing crop yields.

a. Linear Programming and Optimization Models: Linear programming and optimization techniques can be applied in the analysis of different irrigation scheduling alternatives and selection of the most optimal one. The model compares different crop yields and water usages under different irrigation strategies to find the solution to maximize productivity while minimizing water usage Chawla *et al.*, 2020). CROPWAT establishes the relation between crop yield and water use, integrating actual evapotranspiration and crop-specific yield response factors. The model can also consider multiple constraints such as water availability, crop growth stages, and irrigation efficiency to optimize irrigation practices (Wani *et al.*, 2017).

b. Water Saving Techniques and Irrigation System

Integration: Optimization also includes Also, water-saving irrigation applications, such as drip or sprinkler irrigation, may form part of water conservation practices. Drip irrigation, in particular, saves water through the reduction in both evaporation and runoff and, accordingly, increased WUE by applying water directly to the plant's root zone (Abou-Hadid *et al.*, 2011). CROPWAT simulates the effect of different irrigation systems and enables users to find out which one will yield the highest WUE under what conditions.

5. Algorithm for Crop Yield Estimation: CROPWAT crop yield simulations take into consideration water-stressed conditions. Likewise, other climate and soil-related factors known to impact plant growth are accounted for in the estimate. The Crop YWR can be modelled through this equation

$$Y=Y_p\times (1-YpX):$$

Where:

- Y is the actual crop yield,
- Y_p is the potential yield (under optimal conditions),
- X is the actual evapotranspiration during the crop season,
- Y_p is the potential evapotranspiration.

This algorithm is useful in assessing yield loss because of water shortage and helps in decision-making about irrigation scheduling and water application (Sharma *et al.*, 2019).CROPWAT 8.0 allows an efficient and reasonable estimation of crop water requirements based on calculating the reference evapotranspiration, ETo, using the Penman–Monteith equation and then applying that to the crops by making use of specific crop coefficients, Kc. This model has already been used with success in different areas and crops to estimate water requirements of crops such as wheat, rice, cotton, and maize. The model has been quite good in estimating the water requirements of crops under different agro-climatic conditions of India, the Middle East, and Africa through many case studies. For example, the application of CROPWAT 8.0 to estimate crop water requirements of wheat and rice for different states in India, such as Punjab and Haryana, where water is a big concern. The model showed proper estimation of crop water requirement managed water properly, reduced over-irrigation, and improved water use efficiency. Crop water requirement estimated through CROPWAT had good agreement with field observation hence proved the accuracy of the model (Sharma *et al.*, 2019). Another study by conducted in Egypt applied CROPWAT 8.0 to estimate the crop water requirements of cotton and wheat in arid regions. Results showed that the model estimation of crop water requirements could be used in optimizing the irrigation schedule to ensure adequate water for crop growth while minimizing water wastage (Abou-Hadid *et al.*, 2011).

2. Optimization of Irrigation Scheduling: One of the most outstanding results of the use of CROPWAT 8.0 is its adequacy in optimizing irrigation scheduling, mainly for areas with limited water resources. The model determines when and how much to apply water using two methods;

Soil Moisture Balance Method and Fixed interval method: Soil Moisture Balance Method: the Soil moisture balance in CROPWAT 8.0 ensures that there is no waste of irrigation water applied to soil when soil moisture falls below the threshold thus enhancing water use efficiency. In arid and semi-arid states of India such as Gujarat the soilMoisture balance approach helped optimize the irrigation of cotton and wheat, resulting in substantial water saving. In Sharma *et al.* (2019) study, the model showed that irrigation was reduced by 15-20% compared to conventional irrigation practices, without affecting the yield. Similarly, in Egypt, CROPWAT's soil moisture balance approach helped farmers save 18% of water in cotton fields with no serious effect on yields (Abou-Hadidet al., 2011). With the help of precise soil moisture monitoring, CROPWAT 8.0 reduced the chances of both over-irrigation and crop water stress.

Fixed Interval Method: Where the mean rainfall is safely predicted or if the systems of irrigation are fixed in nature, this method is applied for the scheduling of irrigation at interval-based time of the season. In Pakistan, CROPWAT 8.0 directed irrigation scheduling through fixed interval approach gave higher EIs in Irrigation for rice cultivation. The results showed that applying irrigation at fixed intervals during the critical growth stages of the crop helped in reducing water losses due to evaporation and runoff (Molden *et al.*, 203. Water Use Efficiency (WUE): One of the most important aims in applying CROPWAT 8.0 in irrigation management is improving water-use efficiency, WUE, defined as the ratio of crop yield to the amount of water used. Among the ways that the model has been helpful in improving WUE in these regions include optimal scheduling of irrigation and estimating correct crop water requirements.

a. CROPWAT's Role in Water Use Efficiency in India: In India, particularly in states like Punjab and Haryana, where there is a severe stress on the water resources; CROPWAT 8.0 had been used in optimizing irrigation scheduling for wheat rice and cotton in these regions through which the said studies have clearly indicated that implementation of CROPWAT's soil moisture balance approach coupled with other optimization algorithm has brought considerable improvement in the WUE as much as by 10 – 20%, compared to traditional irrigation practices (Sharma *et al.* 2019). Drip irrigation systems embedded in CROPWAT, Demonstrated even more pronounced improvements in WUE, since they deliver water directly to the root zone, thereby eliminating losses due to evaporation and runoff. Water-saving techniques used in combination with CROPWAT, such as drip irrigation, have saved water tremendously while maintaining crop yields at par or even better. This is particularly very important in a state like Gujarat, where water scarcity is perennial, and every drop of the precious liquid must be put to productive use. CROPWAT's algorithms for optimizing irrigation depths and scheduling based on soil moisture content, combined with water-saving irrigation systems, resulted in reducing water use without affecting crop yield adversely

b. Water Use Efficiency in Arid Regions: In Egypt, CROPWAT 8.0 has been used in improving water-use efficiency in cotton and wheat fields. Application of the model in Nile Delta demonstrated that optimized irrigation scheduling could save 18%of water, and yet still be within satisfactory yields. This was explained by the model's ability to compute the exact amount of irrigation based on crop evapotranspiration and local climatic conditions (Abou-Hadid *et al.*, 2011).The effect of CROPWATon WUE improvement is even more outstanding in Sub-Saharan Africa, where water shortage is a chronic challenge. In countries such as Kenya and Ethiopia, the CROPWAT was used for optimizing irrigation scheduling for crops like sorghum and maize, which are drought-tolerant varieties. In Kenya, CROPWAT 8.0 was used to cut down water application in maize by 25–30% while maintaining a high WUE ratio (Nicolás *et al.*, 2017). This was achievable through optimization of the irrigation schedule, which considered the specific water requirement of the crop. It ascertained that the exact amount of water was supplied during the critical growth phases of the crops.

4. Crop Yield: CROPWAT 8.0 has had a positive impact on crop production due to its ability to simulate crop yields based on irrigation and water availability. The model, hence, prevents loss of yield due to water stress because the crops are assured of adequate water during the critical growth phases. In India optimization of irrigation by Sharma *et al.*, 2019by CROPWAT gave 10% increased yield in wheat and 12% increased yield in cotton compared to the conventional method of irrigation. Since the model could adjust the irrigation schedule in relation to soil moisture content and crop needs, crops were not subjected to water stress, thus increasing productivity. Application of CROPWAT 8.0 in Egypt. Cotton and wheat fields, with the result of 12% increase in the crop yield; hence, the model has the capability of increasing the productivity of agriculture even under water-scarce conditions (Abou-Hadid *et al.*, 2011). In Kenya, similar benefits in water-use efficiency and yield optimization were found using CROPWAT to improve maize yields by 15% above traditional practices of irrigation.10)

Conclusion:

The use of CROPWAT 8.0 for irrigation management has proved to be quite effective in optimizing irrigation schedules, estimating crop water requirements, and improving water-use efficiency. The accuracy in calculating crop water needs by the model and the predictions regarding the impact of varied irrigation schedules have led to tremendous water savings without compromising crop yields. In countries such as India, Egypt, and Sub-Saharan Africa, CROPWAT 8.0 has tremendous utility value because has helped to address the challenges of water scarcity, leading to more sustainable agricultural practices. More advanced integration of water-saving techniques and optimization algorithms for irrigation scheduling has further improved CROPWAT ability in enhancing water use efficiency. While there are some limitations, such as the need for accurate input data, CROPWAT 8.0 still remains helpful in managing irrigation in water-scarce regions. Future enhancements Features like integration with real-time data and incorporation of climate change scenarios in the model will probably increase its applicability and effectiveness in dealing with the water challenges that are global in nature. For CROPWAT 8.0, the benefits it has been used for are quite a number, but still, there are challenges that exist in its use, like the lack of good-quality meteorological and soil data. The tool remains very reliable since it produces quality results. Estimates for crop water requirements and yield optimization, even in the face of limited data, further establish it as a valuable resource for managing water resources in agriculture. To sum up, CROPWAT 8.0 is a powerful and efficient tool for the management of irrigation; it helps farmers and decision-makers to balance the needs of crop production with the limitations of water availability. Its application in various regions has shown that by improved irrigation scheduling and water-use efficiency, sustainable agricultural practices can be achieved to contribute to improved food security and the conservation of water resources in the face of increasing climate variability and water scarcity challenges. Future enhancements to CROPWAT, integrating real-time weather data and, in the near future, climate change scenarios, hold great promise to further optimize use and thus make it even more valuable when dealing with increased global water management and agricultural sustainability challenges

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