

Research Article

# Review on Crop Water Requirements in Ethiopia

Girma Tadesse Bekele\* 

Department of Water Resources and Irrigation Engineering, Gambella University, Gambella, Ethiopia

## Abstract

Agriculture in Ethiopia, which is predominantly dependent on smallholder rain-fed production systems, remains highly vulnerable to climatic variability, recurrent droughts, and increasing water scarcity. Accurate estimation of crop water requirement (CWR)- the volume of water required to satisfy crop evapotranspiration (ET<sub>o</sub>) for optimal growth is fundamental for irrigation design, crop planning, and sustainable manage net of limited water resources. In the Ethiopian context crop water requirement (CWR) coupled with crop coefficient (K<sub>c</sub>) approaches, operationalized through decision support models such as CROPWAT and Aqua-Crop. However, substantial spatial and temporal heterogeneity in climatic variables, soil properties, and cropping systems creates high uncertainty in current estimations. Additionally, inadequate meteorological coverage, insufficient temporal data resolution, and the scarcity of locally calibrated K<sub>c</sub> values constrain the accuracy and applicability of results across diverse agro-ecological zones. Recent climate projections under moderate emission pathways (e.g., RCP4.5) indicate a significant rise in temperature and altered rainfall distribution, potentially intensifying evapotranspiration and shifting seasonal irrigation demand. Emerging studies utilizing satellite-based evapotranspiration retrievals, downscaled climate models, and GIS-integrated hydrological simulations have improved crop water requirement (CWR) mapping and spatial analysis. Nevertheless, the integration of green-water (rain-fed) and blue water (irrigation) components into comprehensive water balance frameworks remains underdeveloped, limiting the translation of findings into actionable adaptation strategies. Bringing the methodological and data gaps through advanced spatial analysis tools, remote sensing technologies, and climate smart irrigation modeling is imperative for strengthening Ethiopia's food and water security and ensuring resilient agricultural development under climatic conditions.

## Keywords

CWR, Penman-Monteith, CWR, CROPWAT, IRRIGATION, RCP, Water Stress, Ethiopia

## 1. Introduction

### 1.1. Background

Agriculture remains the backbone of the Ethiopian economy and the primary means of livelihood for the vast majority of its population. More than 80% of Ethiopians derive their income, food security, and employment or indirectly from

agriculture [1]. The sector contributes approximately 35-40% to the national Gross Domestic Product (GDP), accounts for over 70% of export earnings, and provides the largest share of employment nationwide [2]. Its immense contribution notwithstanding, Ethiopian agriculture is predominantly rain-fed and hence highly susceptible to climate variability, prolonged dry spells, and recurrent droughts [3].

\*Corresponding author: [tadessegirma84@gmail.com](mailto:tadessegirma84@gmail.com) (Girma Tadesse Bekele)

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The sector is dominated by stallholder farmers who usually operate on fragmented plots characterized by low productivity, narrow access to modern technologies, weak irrigation infrastructure, and poor market linkages, hence constraining growth and general resilience in the sector [4]. Therefore, agricultural production continues to vary on a yearly basis, directly impacting food prices, rural livelihoods, and national economic stability [5].

Yet, the sector has great potential for economic transformation if strategic interventions are put in place. Expanding irrigation development, better water management, supporting climate-smart agricultural practices, and improving access to inputs and technologies can greatly improve productivity and food security [6]. Strengthening the agricultural sector is thus necessary not only for national food self-sufficiency but also for continued economic growth, poverty reduction, and building resilience to climate shocks [5].

## 1.2. Statement of the Problem

Ethiopian agriculture is predominantly rain-fed and relies heavily on rainfall, which is highly variable in both space and time; this, in turn, makes the sector extremely vulnerable to drought and climate variability [3, 7]. The unpredictability in precipitation patterns has resulted in frequent crop failures, erratic yields, and increased food insecurity [4]. In such conditions, efficient irrigation planning and sustainable water resource management are critically dependent on the correct estimation of crop water requirements [8].

However, the existing approaches to crop water requirement (CWR) estimation in Ethiopia are faced with several methodological and data related challenges. Most studies are heavily reliant on the FAO-56 Penman-Monteith method, with generic crop coefficient ( $K_c$ ) and the use of the CROPWAT model without proper local calibration or validation. This introduces considerable uncertainties in  $ET_c$  and crop water demand estimation under different agro-ecological conditions [9]. Besides, the scarcity, uneven distribution, and incompleteness of meteorological data across the country severely limit the accuracy of reference evapotranspiration ( $ET_o$ ) calculations [10].

Although both recent advances in remote sensing and hydrological modeling provide promising alternatives, their integration with ground-based observations and local datasets remains weak [11]. Most of the literature up to date has focused entirely on blue water requirements for irrigation purposes, with little consideration for green water (rain-fed) contributions, despite the latter being the dominant contribution in Ethiopian agricultural systems [12]. This dearth of knowledge results in an incomplete estimate of the total crop water requirement and carries enormous implications for holistic water management approaches.

Irrigation planning and water allocation decisions, as well as national climate adaptation policies, often rely on incomplete or uncertain data. Consequently, addressing these gaps

through the use of locally calibrated models that consider improved data integration with both green-water and blue-water components is paramount for ensuring sustainable water usage, improving crop productivity, and enhancing the food and water security of Ethiopia within a changing climate [13, 14].

## 2. Methods of Estimating Crop Water Requirement

### 2.1. Reference Evapotranspiration ( $ET_o$ )

It is considered one of the most basic elements of crop water requirement estimation, representing the rate at which a well-watered reference crop—generally grass—would transpire under prevailing climatic conditions [8]. For the estimation of reference evapotranspiration ( $ET_o$ ), in general, the FAO-56 Penman-Monteith method is recognized as the standard in Ethiopia owing to its strong physical basis and high accuracy. This method integrates key meteorological variables such as air temperature, relative humidity, solar radiation, and wind speed to quantify the atmospheric demand for water.

However, the reality of the FAO-56 method is extremely dependent on the continuity and quality of meteorological data. In case such data are incomplete or irregularly recorded, approximate reference evapotranspiration ( $ET_o$ ) estimates can be obtained by empirical methods such as the Hargreaves or Blaney-Criddle formulas. While these empirical approaches have fewer input requirements and may easily be applied in areas lacking sufficient data, they generally result in a loss of accuracy when compared to FAO-56 [15]. Thus, data quality and local calibration must be considered very carefully while choosing an appropriate method of reference evapotranspiration estimation.

### 2.2. Application of CROPWAT Model

The most commonly applied tool for estimating crop water requirements and irrigation scheduling in Ethiopia is the FAO CROPWAT model. In this model, climatic, crop, and soil data are integrated to calculate crop evapotranspiration, irrigation need, and effective rainfall, thus allowing both field-level and scheme-level planning. Due to its flexible nature, the output can be obtained for each crop type and at each growth stage for different types of soils, making it practical for use in smallholder and commercial farming systems.

Various Ethiopian studies have applied CROPWAT to understand the crop-water dynamics. For example, [16] conducted research in the central highlands for modeling seasonal irrigation demands of wheat and maize. The study identified high seasonal variability in the water requirement driven by local agro-ecological conditions, hence carrying out site-specific irrigation planning. Despite its general application, the performance of CROPWAT depends on the accuracy

of the local climatic records, crop coefficients, and soil characteristics that form the input data of the model; hence proper calibration remains indispensable to reduce uncertainty.

### 2.3. Remote Sensing and Modeling Innovations

Recent advances in both remote sensing and spatial modeling have presented many new opportunities to surmount the limitations related to the sparseness of meteorological networks. Satellite-derived evapotranspiration products like MODIS, GLEM, and SEBAL provide a basis for continuous, spatially explicit monitoring of water use in extended agricultural landscapes [17]. These tools allow the estimation of actual evaporation, the pattern of crop stress, and water productivity within field, watershed, and basin scales.

Integrating remote sensing with hydrological and crop

growth models offers a powerful framework for the assessment of both blue-water and green-water requirements, specifically in regions where ground measurements are unavailable.

Such approaches enhance basin-level planning, inform irrigation scheduling, and support climate-resilient water management strategies. However, remote sensing-based methods require validation by ground observations and consideration of specific crop characteristics in order to ensure reliable estimates of crop water demand.

### 2.4. Comparative Discussion of Methods

Different methods of estimating CWR have distinct strengths, weakness, and appropriate applications, summarized in Table 1:

**Table 1.** Comparison of CWR Estimation Methods.

| Methods                             | Data Requirements                                           | Accuracy              | Advantages                                         | Limitations                              | Recommended Applications                 |
|-------------------------------------|-------------------------------------------------------------|-----------------------|----------------------------------------------------|------------------------------------------|------------------------------------------|
| FAO-56<br>Penman-Monteith           | Temperature, Relative Humidity, Wind Speed, Solar Radiation | High                  | Standard, globally validated, accurate             | Requires full meteorological data        | Reference ETo, Irrigation Scheduling     |
| Hargreaves                          | Temperature, Extraterrestrial radiation                     | Moderate              | Simple, minimal data requirement                   | Less accurate, needs local calibration   | Data-scarce areas                        |
| Blaney-Criddle                      | Temperature, day length                                     | Low- Moderate         | Simple, widely known                               | Low accuracy, site-specific limitations  | Preliminary estimates                    |
| CROPWAT                             | Climate, crop coefficients, soil data                       | High (if calibrated)  | Integrates crop, soil, climate for ET <sub>c</sub> | Sensitive to input errors                | Field and scheme-level irrigation        |
| Remote Sensing (MODIS, SEBAL, GLEM) | Satellite imagery, climate data                             | High spatial coverage | Spatially explicit, monitors large areas           | Requires validation, technical expertise | Basin-level planning, climate adaptation |

## 3. Findings from Ethiopian Studies

### 3.1. Spatial and Crop-specific Variability

Crop water requirements in Ethiopia exhibit significant spatial and crop-specific variability due to diverse agro-ecological conditions. Highland regions, characterized by cooler temperatures and higher humidity, generally show lower reference evapotranspiration (ETo) and crop water requirements (CWR). Conversely, arid and semi-arid lowland areas, such as the Rift valley, experience higher ETo and seasonal crop water demand, reflecting the combined effects of elevated temperatures, strong solar radiation, and low humidity [16].

In addition to regional variability, crop specific water demand varies with growth duration, rooting depth, and evapotranspiration characteristics. Cereals such as wheat and teff typically require 350-500mm per growing season, whereas maize and sorghum demand 500-700mm, depending on the location and seasonal climatic conditions [16]. These variations underscore the necessity of site-specific and crop-specific irrigation planning to optimize water use and maximize yield.

### 3.2. Impacts of Climate Change

Climate change is projected to increase reference evapotranspiration (ETo) across Ethiopia, primarily due to rising temperatures and shifts in precipitation patterns. Model simulations suggest that irrigation demand could increase by

10-20% by mid-century under high emission scenarios [18]. Such changes are particularly concerning for major river basins such as the Awash and Abay. Where water is shared among agricultural, domestic, and hydropower sectors. Rising demand may exacerbate competition for water resources, potentially leading to shortages during dry periods and affecting both food security and energy production.

Moreover, climate change might shift the seasonality of rainfall, prolong crop water deficits, and increase the reliance on supplemental irrigation, specifically in the lowlands, which indicates the need to incorporate climate projections into irrigation planning and management to increase resilience to such changes.

### 3.3. Data Limitations

Despite the importance of accurate crop water requirement (CWR) estimation, meteorological networks in Ethiopia remain sparse and unevenly distributed, especially in rural and lowland areas. Critical variables such as wind speed, solar radiation, and relative humidity often have gaps or are unavailable, leading to the use of empirical methods such as Hargreaves or Blaney-Criddle in place of FAO-56 Penman-Monteith [15]. While these methods provide practical alternatives, they introduce uncertainty into CRW estimates, particularly for planning irrigation systems where a precise water allocation is required. Incomplete data also constrain the calibration of crop coefficient (Kc), further reducing the reliability of model-based irrigation planning. Enhancing meteorological coverage and establishing continuous observation networks is therefore essential for accurate water demand assessment.

### 3.4. Green vs. Blue Water

A significant characteristic of Ethiopian agriculture is its reliance on rain-fed systems, with over 70% of cropland depending primarily on rainfall [15]. In such systems, green water- the soil moisture from rainfall is the dominant source supporting crop growth. However, most studies and irrigation planning efforts focus predominantly on blue water (surface or groundwater irrigation), often neglecting the contribution of rain fed water.

The underrepresentation of green water in crop water requirement (CWR) studies leads to incomplete assessments of water availability, potentially overestimating irrigation needs and misguiding resource allocation. Integrating green and water assessments is therefore critical for holistic water resource planning, ensuring efficient use of available water and supporting climatic- resilient agricultural strategies.

## 4. Gaps and Challenges

Despite substantial research, several gaps and challenges limit the effectiveness of crop water requirement (CWR)

estimation and irrigation planning in Ethiopia.

- 1) Lack of locally calibrated crop coefficients (Kc): most studies use generalized FAO Kc values, which may not reflect local crop varieties, management practices, and growing conditions.
- 2) Inadequate meteorological data: limited station density and incomplete datasets reduce the reliability of reference evapotranspiration (ET<sub>o</sub>) estimation, particularly in lowland and remote areas.
- 3) Limited integration of climate scenarios: Few studies systematically integrate CMIP6 climate projections with crop water and irrigation models to anticipate future changes in water demand.
- 4) Neglect of rain-fed agriculture: Rain-fed crop water requirement (CWR) assessment remain underexplored despite dominating Ethiopian farming systems, leaving a significant gap in understanding total water use.

## 5. Recommendations

Based on the findings and identified gaps in Ethiopian studies on crop water requirements (CWR), the following recommendations are proposed to improve the reliability of water demand estimates and support sustainable agricultural water management;

- 1) Conduct Field-Based Crop Coefficient (Kc) Experiments
  - a) Locally calibrated crop coefficients are essential for accurate CWR estimation, as generalized FAO Kc values may not reflect local crop varieties, management practices, or agro-ecological conditions.
  - b) Field experiments for major Ethiopian crops- including teff, sorghum, maize and wheat- should be conducted across different agro-ecologies. These experiments would provide stage-specific Kc values, enabling precise irrigation scheduling and reducing water use inefficiencies.
- 2) Invest in Meteorological Infrastructure and Data Integration
  - a) The current meteorological network in Ethiopia is sparse and unevenly distributed, leading to gaps in critical data such as wind speed, solar radiation, and humidity.
  - b) Expansion of ground-based meteorological stations, combine with the integration of satellite-derived datasets (e.g., MODIS, SEBAL, GLEAM), can provide continuous, spatial explicit data. This hybrid approach enhances the accuracy of reference evapotranspiration (ET<sub>o</sub>) calculations and supports model calibration in data-scarce regions.
- 3) Mainstream Climate Projection Analysis into Irrigation Planning
  - a) Climate change is expected to increase reference evapotranspiration (ET<sub>o</sub>) and seasonal irrigation demand by 10-20% under high-emission scenarios [19].

- b) Incorporating CMIP6 or other climate model projections into irrigation and water allocation planning allows stakeholders to anticipate future water stress.
- 4) Integrating Green and Blue Water Accounting
  - a) Over 70% of Ethiopian agriculture relies on rain-fed systems, yet most studies and irrigation planning focus predominantly on blue water (Irrigation).
  - b) Accounting for both green water (soil moisture from rainfall) and blue water (irrigation supply) in crop water assessments will provide a comprehensive picture of water availability, improve resource allocation, and inform sustainable, integrated water management strategies.
- 5) Capacity Building and Knowledge Transfer
  - a) Training of agricultural extension workers, water managers, and researchers on crop water requirement (CWR) estimation methods, remote sensing, and integrated water accounting is critical.
  - b) Strengthening local capacity ensures the practical application of research findings to irrigation scheduling, water policy, and climate- resilient agricultural planning.

## 6. Conclusions

Ethiopian research on crop water requirement (CWR) has progressed significantly through FAO-56, CROPWAT, and remote sensing, improving understanding of water use in diverse agro-ecologies. However, critical challenges persist, including lack of localized Kc values, sparse meteorological data, neglect of green- water contributions, and limited integration of climate projections.

Addressing these challenges through field experiments, improved monitoring, remote sensing, green-blue water accounting, and climate-informed planning is essential for climate-resilient agriculture, sustainable water management, and food security in Ethiopia.

The integration of advanced methods with local calibration and holistic water management offers a pathway toward efficient, resilient, and sustainable agricultural water use, supporting both smallholder livelihoods and national development goals.

## Abbreviations

|                 |                                               |
|-----------------|-----------------------------------------------|
| CWR             | Crop Water Requirement                        |
| ET <sub>o</sub> | Reference Evapotranspiration                  |
| ET <sub>c</sub> | Crop Evapotranspiration                       |
| K <sub>c</sub>  | Crop Coefficient                              |
| FAO             | Food and Agriculture Organization             |
| GDP             | Gross Domestic Product                        |
| RCP             | Representative Concentration Pathway          |
| MODIS           | Moderate Resolution Imaging Spectroradiometer |

|       |                                               |
|-------|-----------------------------------------------|
| GIS   | Geographic Information System                 |
| SEBAL | Surface Energy Balance Algorithm for Land     |
| GLEAM | Global Land Evaporation Amsterdam Model       |
| CMIP6 | Coupled Model Intercomparison Project Phase 6 |

## Author Contributions

Girma Tadesse Bekele is the sole author. The author read and approved the final manuscript.

## Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this review article. The research was conducted independently, without any financial, personal, or institutional relationships that could have influenced the work presented.

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