Developing a Novel Remote Sensing-Based Framework for Sustainable Irrigation Water Use

Wickramasinghe D.C. [1*], Leh M.[1], Velpuri N.[1], Dembélé M.[2] and Schmitter P.[1]

[1]International Water Management Institute (IWMI), Colombo, Sri Lanka

[2]International Water Management Institute (IWMI), Accra, Ghana

* d.wickramasinghe@cgiar.org

1. Introduction

Global extreme events threaten vulnerable populations in unstable regions, disrupting food chains. Strengthening local food systems is critical for steady nutrition during crises. Vegetable production enhances food security and economic gains. Irrigated agriculture, crucial for crops facing water deficits worsened by climate change, must expand sustainably to meet future demand without harming natural ecosystems (Falkenmark and Lundqvist, 1998, de Fraiture and Wichelns, 2010, Bouraima et al., 2015, Darko et al., 2020). Sustainable groundwater use is crucial to avoid depletion but may reduce yields in areas of current unsustainable extraction, necessitating sustainable expansion in new areas (Rosa, 2022). This project is focused on developing a robust data-driven tool that can accurately identify areas suitable for irrigated vegetable production and expansion while ensuring sustainable water usage. The primary objective is to create an evidence-based irrigation investment tool tailored for humanitarian organizations. Initially piloted in Mali and Ethiopia, the tool is built to scale in other countries with minimal in situ data and calibration. The framework comprises mapping regions for optimal vegetable production considering bio-geophysical variables, and socio-economic factors. The tool also, assesses sustainable irrigation thresholds integrating water availability and crop water requirements, and identifies appropriate water abstraction technologies. This study focuses developing a novel remote sensing approach integrating surface water availability, groundwater recharge, and crop water requirements to derive sustainable irrigation water use limits/thresholds.

2. Methodology

The analysis includes understanding both surface water availability and groundwater potential (within the sustainable safe yield of annual groundwater recharge) using a new hydrologic framework. This framework combined hydrologic data sources from the water accounting plus (WA+) framework (Karimi et al., 2013) for understanding surface water availability and a global hydrological model (PCR-GLOBWB) based groundwater recharge potential maps (Sutanudjaja et al., 2018).The assessment of water resources for agricultural use involves several key components, including surface water yield, groundwater recharge, crop water requirements, and the estimation of utilizable groundwater. Here's a summary of these elements and their integration into irrigation sustainability analysis.

2.1 Surface Water Yield

Surface water yield is derived from the difference between precipitation (P) and total actual evapotranspiration (ET). Positive values indicate areas where precipitation exceeds ET, typically representing rainfed croplands. Negative values signify regions where ET surpasses precipitation, often corresponding to irrigated lands, wetlands, or areas with significant groundwater withdrawal. For the period 2003-2022, long-term average water yield maps were created to illustrate these dynamics.

2.2 Groundwater Recharge

Groundwater recharge estimates were obtained from the PCR-GlobWB model, which integrates hydrological and groundwater modeling. This model provides annual recharge potentials from 1959 to 2015, reflecting the safe yield of groundwater for different locations. These estimates help identify areas with potential for sustainable groundwater use.

2.3 Crop Water Requirements

To understand the availability and limits of surface and groundwater irrigation, the water needs of common vegetable crops were analyzed. Crops were categorized into high (approximately 800 mm/season), medium (600 mm/season), and low (400 mm/season) water requirements. The total irrigation water requirement (TIWR) was calculated using a formula accounting for conveyance and application efficiencies. With conveyance efficiency assumed at 80% and application efficiency at 60%, an additional 52% of water beyond the crop water requirement is needed for irrigation.

2.4 Estimating Utilizable Groundwater

While groundwater recharge maps indicate the safe yield, actual groundwater availability for irrigation must account for existing usage. By subtracting current groundwater use from the safe yield, the utilizable groundwater is estimated. This considers areas suitable for vegetation and adjusts for current irrigation demands to determine the remaining groundwater available for future use.

2.5 Estimating Irrigation Potential

Surface water yield for both wet and dry seasons was calculated and compared to the TIWR to assess irrigation needs. In Mali, the wet season spans June to November, while Ethiopia has two wet seasons: Kiremt (June to September) and Belg (March to May). If TIWR exceeds surface water yield, additional irrigation is needed, typically supplied by groundwater. The deficit in water supply was compared with the utilizable groundwater to determine if it meets crop requirements. Areas where the combined surface water yield and utilizable groundwater exceed crop needs are classified as suitable and sustainable. Conversely, if the available water resources fall short, the area is marked as suitable but unsustainable.

2.6 Scenarios Analysis

Three scenarios were analyzed for vegetable crops with varying water demands:

a) High-water demanding crops (800 mm/season irrigation).

b) Medium-water requirement crops (600 mm/season irrigation).

c) Low-water demanding crops (400 mm/season irrigation).

These scenarios were evaluated for both wet and dry seasons in Mali and Ethiopia, assessing sustainability based on the available surface water and groundwater resources. This comprehensive analysis helps in understanding the capacity of different regions to support vegetable irrigation and guides decisions on water resource management for sustainable agricultural practices.

2.7 Estimating Irrigation Expansion Limits for Vegetable Production

To evaluate the potential for expanding irrigated vegetable production, we summarize suitable areas for cultivation in each administrative district and assess the sustainability of these areas. This analysis is conducted for 569 Woreda/districts in Ethiopia and 288 Cercles in Mali, with a focus on understanding the limits of irrigation expansion for high, medium, and low water demanding vegetables.

3. Results and Discussion

Tables 1 and 2 present the distribution of sustainable areas in Ethiopia and Mali for various seasons, based on differing crop water requirements. Meanwhile, Figures 1 and 2 depict the geographical spread of these sustainable areas in each country.

Table 1:The sustainable limits of irrigating vegetable crops under high, medium, and low water requirement categories for Ethiopia.

Total Suitable Area (million ha)	Category	Suitable and Sustainable (million ha)		
		Kiremt	Dry	Belg
18.1	High	2.31	0	0
18.1	Medium	6.57	0	0.03
18.1	Low	10.69	0.4	2.8

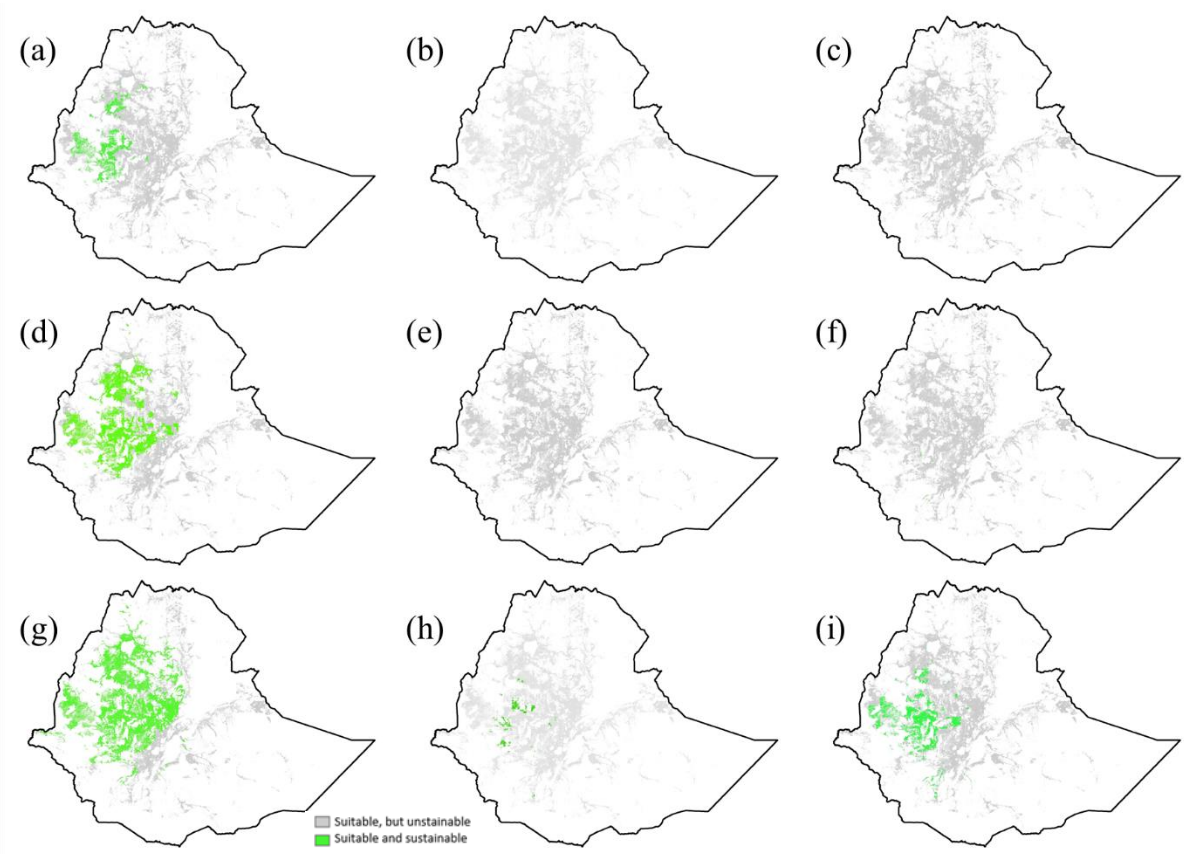

Figure 1: Location and distribution of suitable and sustainable areas for high-water-demanding vegetables during a) Kiremt, b) dry season, and c) Belg season; medium-water-demanding vegetables during d) Kiremt, e) dry season, and f) Belg season; and low-water-demanding vegetables during g) Kiremt, h) dry season, and i) Belg season in Ethiopia.

3.1 Ethiopia

During the Kiremt season (June to September), suitable and sustainable areas for high-water demanding vegetables are primarily found in the high mountainous regions of western Oromiya, totaling approximately 2.31 million hectares. This area represents about 12% of the total suitable land identified. Both the dry and Belg seasons are unsuitable for high-water demanding crops due to insufficient water availability.

For medium-water demanding vegetables, suitable areas are located in the highlands of western Oromiya, Benishangul-Gumuz, and Amhara during the Kiremt season, amounting to around 6.6 million hectares (36% of the total suitable area). During the dry season, these regions are not suitable, but the Belg season allows for approximately 25,000 hectares of medium-water demanding crops.

Low-water demanding vegetables can be cultivated in a significant portion of Ethiopia. During the Kiremt season, approximately 10.7 million hectares (59% of the total suitable area) are identified as suitable and sustainable. In the dry season, about 0.4 million hectares are suitable, and during the Belg season, around 2.84 million hectares are identified as suitable for low-water demanding vegetables.

Table 2: The sustainable limits of irrigating vegetable crops under high, medium and low water requirement categories for Mali.

Total Suitable Area (million ha)	**Category**	**Suitable and Sustainable (million ha)**	
		Wet	**Dry**
6.7	High	0	0
6.7	Medium	0.18	0
6.7	Low	1.2	0

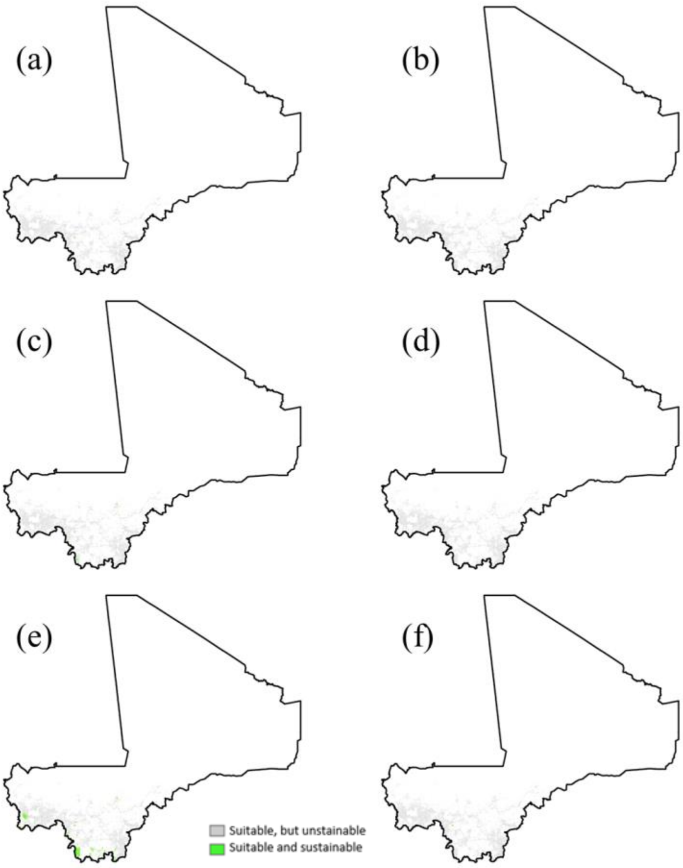

Figure 2: Location and distribution of suitable and sustainable areas for high-water-demanding vegetables during a) wet and b) dry season; medium-water-demanding vegetables

during c) wet and d) dry season; and low-water-demanding vegetables during e) wet and f) dry season in Mali.

3.2 Mali

In Mali, the harsh dry climate and low groundwater yields severely limit the cultivation of high-water-demanding vegetables, with no suitable areas identified in the available data. Approximately 177,800 hectares, or 2.7 percent of suitable land, are considered suitable for medium-water-demanding crops, primarily in the southern regions. However, during the dry season, the potential for medium-water-demanding vegetable production is minimal. For low-water-demanding vegetables, around 2.84 million hectares, or 17.6 percent of suitable land, are available, concentrated along the southern borders. Yet, even this area sees a significant reduction in suitable land during the dry season.

3.3 Sustainable Limits

The sustainable limits for irrigation expansion are crucial to avoid overexploitation of water resources. In Ethiopia, the Kiremt season allows for the cultivation of high-water demanding vegetables on about 2.31 million hectares, medium-water demanding vegetables on approximately 6.57 million hectares, and low-water demanding vegetables on up to 10.69 million hectares. The dry season is generally unsuitable for extensive vegetable production due to water constraints, with only small areas suitable for low-water demanding crops during the Belg season.

In Mali, the potential for growing high-water demanding vegetables is very limited, with only a small portion of suitable land available for medium-water demanding crops and more substantial areas for low-water demanding vegetables. Expansion beyond these sustainable limits could lead to groundwater over-extraction and potential crop failures.

3.4 Distribution by Administrative Units

During the Kiremt season, many districts (about 500 out of 566) are not suitable for high-water demanding crops. However, 20-25 districts can support up to 50,000 hectares, and some districts can support up to 80,000 hectares. For medium-water demanding crops, about 450 districts are unsuitable, while 60-100 districts can support up to 100,000 hectares. Low-water demanding crops have a broader suitability, with around 100-150 districts able to support up to 150,000 hectares.

The outcome of Mali shows limited potential, with only about 5-10 Cercles supporting medium-water demanding crops and 20-25 Cercles capable of producing low-water demanding vegetables sustainably.

Overall, this assessment helps delineate the feasible boundaries for irrigation expansion and supports sustainable agricultural practices by highlighting areas where water resources are adequate and sustainable.

4. Conclusion and Recommendation

The identified areas for sustainable irrigation range from about 1.2 million hectares in Mali to over 10 million hectares in Ethiopia, supporting thousands of farmers during crises. Following sustainable irrigation practices can enhance water resource management in these regions.

This study highlights suitable areas for vegetable production, which are essential for Africa's agricultural future and food security. By integrating agricultural productivity with ecological conservation, it ensures that farming systems remain resilient and capable of meeting the needs of a growing population. This approach not only addresses current food security but also invests in the long-term viability of African agriculture.

References

Bouraima AK, Weihua Z, Chaofu W. 2015. Irrigation water requirements of rice using Cropwat model in Northern Benin. International Journal of Agricultural and Biological Engineering **8** (2): 58–64 DOI: 10.3965/j.ijabe.20150802.1290

Darko RO, Liu J, Yuan S, Sam-Amoah LK, Yan H. 2020. Irrigated agriculture for food self-sufficiency in the sub-saharan African region. International Journal of Agricultural and Biological Engineering **13** (3): 1–12 DOI: 10.25165/j.ijabe.20201303.4397

Falkenmark M, Lundqvist J. 1998. Towards water security: Political determination and human adaptation crucial. Natural Resources Forum **22** (1): 37–51 DOI: 10.1111/j.1477-8947.1998.tb00708.x

de Fraiture C, Wichelns D. 2010. Satisfying future water demands for agriculture. Agricultural Water Management **97** (4): 502–511 DOI: 10.1016/j.agwat.2009.08.008

Karimi P, Bastiaanssen WGM, Molden D, Cheema MJM. 2013. Basin-wide water accounting based on remote sensing data : an application for the Indus Basin. Hydrol. Earth Syst. Sci.: 2473–2486 DOI: 10.5194/hess-17-2473-2013

Rosa L. 2022. Adapting agriculture to climate change via sustainable irrigation: Biophysical potentials and feedbacks. Environmental Research Letters **17** (6) DOI: 10.1088/1748-9326/ac7408

Sutanudjaja EH, van Beek LPH, Drost N, de Graaf IEM, de Jong K, Peßenteiner S, Straatsma MW, Wada Y, Wanders N, Wisser D, et al. 2018. PCR-GLOBWB 2.0: a 5 arc-minute global hydrological and water resources model. Geoscientific Model Development **11** (6): 2429–2453 Available at: https://doi.org/10.5194/gmd-11-2429-2018