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Satellite *ET*-based irrigation performance: Strategies to increase rainfed crops production in the lower Baro watershed, Ethiopia

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Abstract: Satellite-based irrigation performance is a valuable tool for improving yields in irrigated areas across the world and requires adequate land for long-term development. This study aimed to increase irrigation performance and yield gap variation of rainfed crops using the database of FAO's Water Productivity Open Access Portal (WaPOR) and the Global Yield Gap Atlas. The evapotranspiration (*ET*) performance of irrigation is expressed in equity *(CV* of *ET*), reliability, adequacy (*CV* of *ET)*, and water productivity (kg·m^{-3}). The rainfed crops are interpreted in terms of metric tonnes/ha. Specifically, 20,325 km^2 of suitable pastoral land across eight sub-classes was converted to rainfed rice, sugarcane, maize, and vegetable crops. Results showed that the R^2 value was 0.97 at Baro Itang and –0.99 at Sor Metu, with the Baro Gambella sub-catchment having the largest yield gap of 4.435.2, 8.870.4, and 10.080·10^6 kg when the yield increased by 1/3, 2/3, and 3/4. On the other hand, Gumero Gore had the smallest yield gap of 10,690, 29,700, and 33,750 kg, respectively. The management regime was 2.87, 0.87, and 0.35 kg·m^{-3} for growers in the estate, farmer association, and individual, respectively. The study concludes that no single irrigation technique can be considered the best, and a thorough analysis of spatiotemporal variation of the irrigation performance indicators and the yield gap in the water-scarce lower Baro watershed is required.

Keywords: crop water productivity, evapotranspiration, irrigation performance, lower Baro, yield gap

INTRODUCTION

*The Food and Agriculture Organization (*FAO) portal that manages Water Productivity Open-access Portal Database (WaPOR) performance indicators play a crucial role in improving water use efficiency, assisting performance-oriented management, identifying constraints, and comparing system performance with other products. Additionally, agricultural land and water resource strategies are increasingly utilised to provide information on these variables at various spatial and temporal scales. To enhance irrigation performance, remote sensing (RS) technology offers high-resolution measurements in agricultural production (Bwambale *et al*., 2022). However, the integration of the RS technology in agriculture, water, and energy management is still in its fledgling stage. RS provides realistic information for assessing the effectiveness of WaPOR in agriculture planning and water resources management (Sheffield *et al*., 2018). Climate change has disrupted interactions between Earth, atmosphere, and land systems, resulting in a gap between freshwater supply and demand in many regions, leading to environmental concerns such as rising energy usage and declining groundwater levels (Salem, Yahaya and Yohannes, 2022).

Agricultural water consumption comprises 22% of blue water and 78% of grey water resources (Giri, Arbab and Lathrop, 2018). Effective surface water distribution management has been suggested as a key approach to improve groundwater resources quality and quantity. Soil texture is an essential factor affecting soil quality and agricultural productivity, enabling water transport from high potential to low potential regions. Transpiration from irrigated crops accounts for only 13–18% of global water use, which is closely linked to crop yield and production (Nesru, 2021). The United Nations Sustainable Development Goals (SDGs) call for a significant improvement in water consumption efficiency and a doubled agricultural productivity by 2030 SGD2.3 and SDG6.4 (Moisa, Merga and Gemeda, 2022). An effective watershed sustainability indicator must be evaluated from the point of view of integrated water resource management and various disciplines, thus providing a framework for comparison and identifying bottlenecks that hinder watershed sustainability (Zare Bidaki *et al.*, 2023).

In sub-Saharan Africa, small landholder farmers, the majority of whom are women, face a yield gap in crop production, which needs to be reduced by two to four times (Giller *et al.*, 2021). In Ethiopia, 5 mln farmers cultivate a total of 2023.4 km^2 across 12 river basins, facing variable rainfall and requiring irrigation water demand of around 6 km^3 per ha, while the potential is 6.5 km^3 (Mekonen, Gelagle and Moges, 2022). However, in Ethiopia, the expected beneficiaries of irrigation receive up to 46.8%, even though 86.5% of irrigation systems are in operation and 74.1% of the command area is under cultivation (Awulachew and Ayana, 2011). By 2050, Ethiopia aims to increase the area of irrigation from 0.12 Mha to 2.05 Mha by gravity and 0.04 Mha by pressured irrigation (Multsch *et al.*, 2017). However, the improvement from increasing irrigation has slowed recently due to increasing temperature. This translates into a challenge to improve water productivity through the extension of irrigation (Yimere and Assefa, 2022).

Global sugar consumption is expected to continue increasing, albeit at a slower pace, by 2027 (Oort van *et al.*, 2017). Water productivity potential (*WPP*), water productivity actual (*WPA*), yield potential (*Yp*), actual yield (*Ya*), and water-limited yield (*Yw*) are affected by topography and water availability. Although these measurements are based on benchmark rainfed crops, they determine the appropriate inference domain for specific *WPP*, *WPA*, *YP*, and *YW* yield gap estimates can be challenging and require us to translate knowledge into action. Therefore, this study aims to explore strategies for enhancing the production of rice, sugarcane, maize, and small vegetables through land use change and yield improvement in the lower Baro watershed, Ethiopia.

MATERIALS AND METHODS

STUDY AREA

The lower Baro watershed (Fig. 1) is located in Ethiopia's South-Western part of Gambella State. The basin, which covers parts of the Oromia region, has a minimum elevation of 390 m and a maximum elevation of 3,240 m, and an area of 20,325 km^2. The watershed coordinates are 8°28'40" latitude and 34°20'36" longitude. The Baro, Alwero, Gilo, Birbir, and Akobo are the principal rivers in the Baro-Akobo Basin. The basin's large wetland is one of its peculiar features (Alemayehu *et al.*, 2017). The total area of Saudi stars under lease in Gambella is 0.14–500 Mha. Still, only 10,000 ha are under the production of the Alwero Dam; which is one of tributaries of the Baro River. From a hydro-geological point of view, the basin is dominated by mining, and less surface water resource development (Halefom *et al.*, 2020). The tributaries of the watershed are shown in Figure 1.

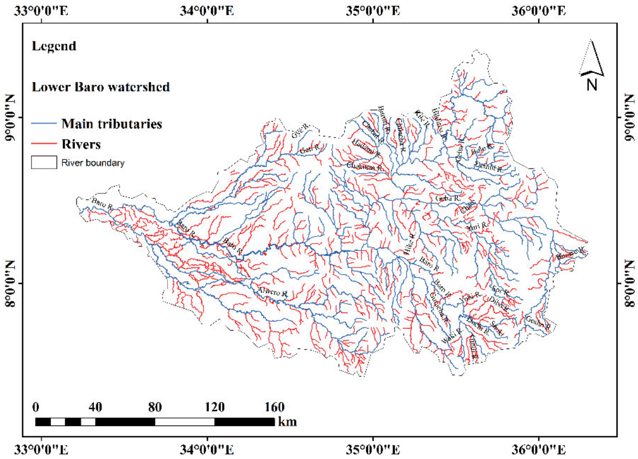

Fig. 1. Lower Baro watershed drainage system; source: Ministry of Water and Energy of Ethiopia data

AGRO-CLIMATE ZONE

Ethiopia's landscapes vary with climatic zones. The annual average rainfall in the catchment is indicated based on Trewartha's classification for each sub-catchment to show temperature and precipitation data from the National Meteorology Agency (NMA). Table 1 shows the climatic zone and land use types for the eight sub-catchments of the lower Baro watershed.

LAND SUITABILITY FOR RAINFED CROPS

The digital elevation model (DEM) based slope maps between 0–2, 16–30, 2–8, 30–50, 8–16, and >50% were used. In this study, the actual *ETa* is the water lost from a surface whereas the potential *ETp* is the water lost from the vegetated surface (*ETa*/*ETp)* using a combination of the *Eta-WaPOR*, slope classification map, and land use map, the optimal land conversion area for rainfed crops yield is further categorised. The major slope classes and land use map of the lower Baro watershed are shown in Figures 2 and 3. When water supplies are scarce, agricultural productivity influences how land is used.

The quality assessment of the *ETa*-WaPOR product is enhanced by combining multiple evaluation methods. The real-time satellite *ET*-based irrigation performance and strategy for the rainfed crop at spatial and temporal variation were very crucial. The following assessments were used in the methodological study to implement the anticipated approach.

IMPROVED AGRICULTURAL PRACTICE

In this study, four irrigation performance monitoring criteria were selected, namely equity, adequacy, reliability, and crop water productivity (*CWP)* in lower Baro tributaries. Increasing *CWP* is vital regardless of prospects for growth or the demand, according to *ET*-based WaPOR statistics. Previous studies have used a top-down spatial framework for the yield gap analysis (Deng *et al.*, 2019). A framework for evaluating the performance of irrigation systems using WaPOR has been represented as the water productivity and the *ETa* in seasonal water consumption. To achieve the irrigation performance in terms of water productivity, the following indicators are used: equity, adequacy, reliability, and crop water productivity.

Table 1. Basic information on the river catchments (1986–2018) and the land use types of the lower Baro watershed

Catchment name	Climatic zone (Trewartha's classification)	Area (km²)	Annual average rainfall (mm)	Area of land use types (ha)		
				agricultural	pastoral	other
Alwero	humid	4,696.0	195.3	14,000	22,000	143,086
Gilo Fugnido	humid	1,716.5	190.8	1,315	460	1000
Birbir Yibdo	tropical	1,563.0	104.4	634,415	8,115,000	14,280
Gog	humid	3,025.0	82.0	1,650	25000	29.3
Baro Gambella	humid	2,978.3	176.0	280,000	81,000	600,000
Baro Itang	humid	325.25	173.0	1914	33	1499
Gumero Gore	tropical	1,249.0	208.0	25	3000	538
Sor Metu	tropical	1,622.0	213.0	78	234	120

Source: own elaboration based on MoWE data from 1976–2020, NMA data from 1986–2018, and various literature.

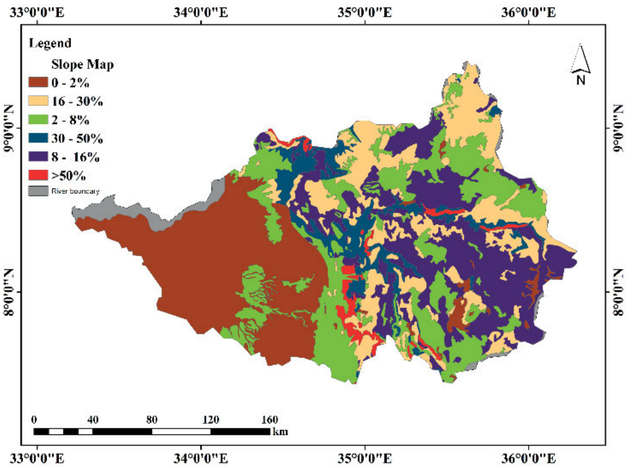

Fig. 2. The major slope classes of the lower Baro watershed; source: own elaboration based on MoWE data from 2016

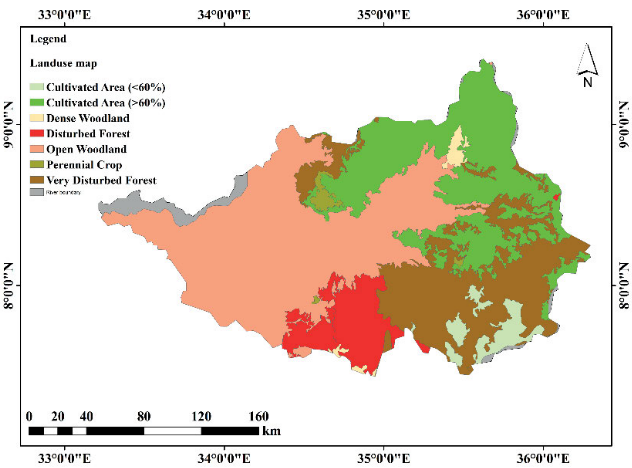

Fig. 3. The land use map of the lower Baro watershed; source: own elaboration based on MoWE data from 2017

APPROPRIATE LAND AREA CONVERSION

In addition to the performance in irrigation, a coefficient of determinants is used for the rainfed crops to select the function from among a set of linear and nonlinear functions that most closely match the set of data (Nesru *et al.*, 2022). The average and maximum yields and the increase in yield gaps by 1/3, 2/3, and 3/4 were applied to estimate the increase in rainfed crop production in the lower Baro eight sub-catchments represented as A_1, A_2, A_3, A_4 A_5, A_6, A_7, and A_8 on the bases of coefficient of determinants as shown in Equation (1).

$$Y = A_1 + A_2 ETa + A_2 SR + \ldots + A_8 F \qquad (1)$$

where: Y = crop yield (kg·ha^{-1}), ETa = actual seasonal evapotranspiration (mm), SR = seed rate (kg·ha^{-1}), and F = fertiliser application rate (kg·ha^{-1}).

The operational range and acceptable range of relative *ET* were established using the target and critical crop production. Determined by land use, slope, radiation, temperature, planting date, and supply of water for *Yw* and 80% of *Yp* or *Yw* interpreted as yield level and exploitable yield gap.

The source of data for WaPOR were 30 m spatial and 10 days temporal resolution downloaded from in 01/07/2010–01/07/2022 from the FAO WaPOR portal. For rainfed the Global Yield Gap Atlas (GYGA) for rice, maize, and sugarcane high expert agronomist data and high-quality locally relevant in 1999–2017 were downloaded from https://www.yieldgap.org/. In addition, the annual average crop output, seed rate, and fertiliser application were taken from the Central Statistical Agency of Ethiopia.

Due to the linear relationship between *ETa* and yield, the irrigation main goal is to make sure that *ETa* can keep up with *ETc* throughout the growing season. In this study, the performance indicator equity (*E*) is represented by the coefficient of variation (*CV*), a measure of how widely data points in a data series *CV*(*ETa*) are distributed. Adequacy (*S*) is expressed as seasonal (Snl) *ETa* divided by seasonal *ETp*. Each performance indicator is shown in Equations from (2) to (5).

$$E = CV(ETa) \qquad (2)$$

$$R = CV\,\frac{ETa}{ETp} \qquad (3)$$

$$S = \frac{Snl\ ETa}{Snl\ ETp} \qquad (4)$$

$$RWD = 1 - \frac{ETa}{ETx} \tag{5}$$

where: R = reliability, S = adequacy, RWD = relative water deficit.

Reliability is the degree to which water delivery conforms to prior expectations of users and is expressed as $CV(ETa/ETp)$. Irrigation performance indicators are proposed based on operational activity and resource utilisation. Table 2 illustrates various clusters employed in lower Baro tributaries.

RESULTS AND DISCUSSION

WATER PRODUCTION FUNCTION

It was observed that the watershed temperature increased from 35 to 45°C while *ET* was fluctuating due to climate variability. This shows that high temperatures do not increase *ET*. Based on the coefficient of determinants (R^2), a set of linear and nonlinear functional forms has been checked, and the function that most closely resembles the set of data has been selected. As a result, the crop yield, seed rate, and fertiliser R^2 for each of the eight sub-catchments was 0.96, –0.46, –0.30, 0.86, 0.76, 0.97, 0.96, and –0.99. The value of the R^2 maximum of 0.97 was observed at Baro Itang and a minimum of –0.99 was observed at Sor Metu as compared to the other six sub-catchments. The highest attained value indicated the highest level of equitable distribution of water.

Table 2. Summary of all the various clusters employed in Lower Baro from 2010–2022

Category	Cluster name	Command area	Type of management grower
Land holding	growers on a small scale	<50 ha	run modern business line
	grower of moderate size	50–1000 ha	farmer-managed and commercial
	grower on a large scale	>1000 ha	farmer-managed and commercial
Management type	estate managed	>1000 ha	run along modern business lines
	farmers association	50–500 ha	farmer managed communally
	individual growers	3–100 ha per farm	farmer managed individually
Location area (km^2)	Alwero	4696	farmer's associations and commercial
	Gilo Fignido	1716.5	run along modern business lines
	Birbir Yibdo	1563.0	farmer managed individually
	Gog	3,250	farmer managed individually
	Baro Gambella	2978.3	farmer's associations and commercial
	Baro Itang	325.25	farmer managed communally
	Gumero Gore	1,249	farmer's associations and commercial
	Sor Metu	1622	farmer managed individually
Irrigation method	center pivot	5%	–
	sprinkler	10%	–
	furrow	25%	–
	drip	20%	–

Source: from various literature published specifically on *ET*-based irrigation.

CROP WATER PRODUCTIVITY

While determining the dependability of remotely sensed *ET* products, one of the issues is the lack of *ET* spatial layer validation as well as the cost and complexity of such analysis. The WaPOR database enhances the agricultural water sector by 25%, because it helped to tackle water stress in a wet and dry areas. However, the combination of multiple evaluation methods improves how the quantity of the *ETa* WaPOR product is assessed. In this study, the harvest index (*HI*) shows how much biomass production contributes to harvestable fraction of a crop. It is expressed as the ratio of dry grain weight over the above-ground dry matter. In 2008–2018, the average estimated wheat yield was 3,203 kg·ha^{-1}, and the average estimated potato yield was 31,495 kg·ha^{-1}. This was comparable to the reported wheat yield of 3,000 kg·ha^{-1} (Safi *et al.*, 2022).

LAND PRODUCTIVITY

In this study, the moisture content ratio (θ) allows for converting fresh yield into summer (Bega) dry yield by accounting for water content in the harvested product. In the Awash zone, the WaPOR data estimation shows that sugarcane grows for an average of 585 days during 0.8–2.8 years (Mersha *et al.*, 2018). The light use efficiency (*LUE*) was a coefficient by which vegetation converts energy into biomass. As regards rice, the *LUE* was 1 for C3, and

C4 crops, the *HI* was 0.43, the above-ground biomass (*AoT*) was 0.75, and the θ was 0.15. As regards sugarcane, the *LUE* was 1.8 for C3 and C4 crops, the *HI* was 1, *AoT* was 1, and the θ was 0.7. In the case of maize, the *LUE* was 1 for C3 crops and 1.8 for C4 crops, the *HI* was 0.35, AoT was 0.93, and θ was 0.26. For small vegetables, the *LUE* was 1 for C3 and C4 crops, the *HI* was 1, *AoT* was 1, and θ was 0 in the sub-catchment of the lower Baro. According to past calculations, this would increase the world food calorie production by 54% kcal per year (Rockström *et al*., 2017). As a result, the study evaluated the WaPOR biomass product under the crop classification. Additionally, a linear association between sugarcane crop production and *ET* was discovered, with a slope of around 10 kg·m^{-3} and a corresponding value of 1.3 kg·m^{-3} (Karimi *et al*., 2019). The typical annual *ET* for a different producer cluster of crops was 1.5 Mg, compared to the typical annual value of 1.3 Mg for a crop, such as wheat or maize (Chukalla *et al*., 2022). A fixed value of 2.7 was applied to cropland in WaPOR and, through this interface, the value was multiplied by 1.8 for C4 crops, which had a higher *LUE* as shown in Table 3.

The WaPOR for 10-year real data shows that for each sub-catchment of Baro Gambella, Gog, Gilo Fugnido, Birbir Yubdo, Baro Gambella, Gumero Gore, Sor Metu, and Baro Itang was 2.54, 1.3, 1.21, 0.96, 0.96, 0.96, and 0.95 kg·m^{-3}. The 4-year seasonal average WaPOR-based yield was 89 Mg·ha^{-1} (86 Mg·ha^{-1} for regions with furrow irrigation, 88 Mg·ha^{-1} for areas with sprinkler irrigation, and 93 Mg·ha^{-1} for areas with center pivot irrigation) (Chukalla *et al*., 2022). The average *CV* for metrics was determined as the performance of various clusters. The Saudi Star irrigation project had better *CV* of 5% than medium-scale and individual farmers' *CV* of 65%. Compared to other climate zones, tropical zone-based agricultural yield and crop water productivity estimates showed greater variation of 1–10 Mg·ha^{-1} and 1.0–12.5 kg·m^{-3}, respectively (Mohanasundaram *et al*., 2022). As a result, the number of growers in the estate, farmer association, and the individual was 2.87, 0.87, and 0.35 kg·m^{-3}, respectively. The result was comparable with standard ranges of the global *WP* from 0.62–11 kg·m^{-3} (Safi *et al*., 2022). As regards lower Baro farmers who produce crops, the average water adequacy could be impacted by factors other than general water availability as shown in Table 4.

In this study, the analysis covers the eight sub-catchments, including Alwero *ETa* (less than 28), Gilo Fugnido (28–43), Birbir Yubdo (43–48), Gog (48–53), Baro Gambella (53–58), Baro Itang (58–60), Gumero Gore (60–63), and Sor Metu (63–67) mm. In the Awash and Koga watersheds in Ethiopia, the WaPOR was superior to other *ET* products (Blatchford *et al*., 2020). As a result, in the case of Sor Metu the *ETa*/*ETp* was 7.12 in the range of 63–67 and the average yield *CWP* was 120 kg·m^{-3} (highest), *ETa*/*ETp* was 3.73 (lowest) in the range of 28–43 and the average yield *CWP* was 590 kg·m^{-3} of *ETa*. Covering the gap in rainfed agriculture, the analysis showed the maximum seed rate 985 kg·m^{-3}. Fertiliser application was 165 kg·ha^{-1} with the corresponding maximum number of householders of 70,490.56. Moreover, the highest yield was 5600 kg·ha^{-1} in the sub-catchments. The amount of crop *ET* had a direct relation to crop yield as shown in Table 5.

As a result, in comparison to the other six sub-catchments, the Baro Gambella sub-catchment had the highest yield gap of 443.52·10^{6}, 887.04·10^{6}, and 1,080·10^{6} kg, while the Gumero Gore sub-catchment had the lowest yield gap of 10,690, 29,700, and 33,750 kg. In December, Gambella got 67.61 mm of rain approximately 3 rainy days in the month and humidity was close to 68% (Hailu, Tolossa and Alemu, 2019). This led to an increase in rainfed crop output throughout the entire lower Baro watershed, as stated in Table 6.

The major cereal crop production *YA* in rain-fed agriculture was as follows: rice 6, maize 12, sugarcane 9, and small vegetables 7 in terms of Mg·ha^{-1}. Comparing the *YW* and *YA*, the crop production shows a significant difference in rice 1.5, maize 8.5, sugarcane 5.5, and vegetables 3.5 Mg·ha^{-1}, whereas for *WPA:* rice 2.5, maize 4.5, sugarcane 3.5, and small vegetables 4.5 Mg·ha^{-1}. However, the use of fertilisers and modern seeds become a challenge. The current potential world yields of wheat, maize, and rice are 7.7, 10.4, and 8.5 Mg·ha^{-1}, respectively (Rong *et al*., 2021). The exploitable yield gap explains the unusual convergence of necessary conditions to attain water-limited yield. As a result, feeding the future population that was closing the gap in lower Baro tributaries to the selected crops showed a significant trend variation in terms of Mg·ha^{-1} as shown in Figure 4.

The study finds that the implementation of irrigation management systems in the lower Baro watershed in Ethiopia can increase production and bring more land under irrigation. The potential to raise production and bring more land under irrigation, with increased yield and irrigated area of 20 and 140% respectively (Mandal *et al*., 2020). The research shows that the current rainfed systems without irrigation in the region demonstrate a small *CWP*. To increase crop yield, additional water needs to be made available for *ET*. However, crop management improvements and secured irrigation supplies during dry years have raised crop yields and increased water productivity. As a result, the maximum potential water

Table 3. Sub-catchment area based on crop type

Crop type	Sub-catchment area (ha)							
	Alwero	Gilo Fugnido	Birbir Yubdo	Gog	Baro Gambella	Baro Itang	Gumero Gore	Sor Metu
Rice	22,000	460	8,115,000	25,000	81,000	33	3,000	234
Sugarcane	10,000	14	2,028,754	513,438	148,610	37,161	10,040	2,568
Maize	6,001.69	23	507,194	255,158	100,942	34,526	11,141	3,427
Small vegetables	280,000	70,000	35,000	17,500	8,750	4,375	2,188	1,093

Source: own study.

Table 4. A summary of seasonal indicator average values for all clusters in lower Baro tributaries

Category name	Cluster name	*ET*	*ETp*	Equity *CV* of *ET*	Adequacy *CV* of *ET*	Water productivity (kg·m^{-3})
		mm per month				
Grower scale	small scale	45.3	29.4	0.98	1.54	0.99
	medium scale	54.3	35.2	1.17	1.54	0.53
	large scale	64.9	3.25	0.10	19.97	2.52
Management regime of grower	estate managed	66.5	3.32	0.11	20.03	2.87
	farmers associations	54.3	35.2	1.17	1.54	0.87
	individual growers	64.9	42.1	1.40	1.54	0.35
Location of growers	Alwero	66.5	3.32	0.11	20.03	0.78
	Gilo Fignido	3.73	2.42	0.08	1.54	1.21
	Birbir Yibdo	3.87	0.19	$6.45 \cdot 10^{-3}$	20.37	0.96
	Gog	4.54	0.22	0.09	20.64	1.30
	Baro Gambella	4.70	0.23	$7.8 \cdot 10^{-3}$	20.43	2.54
	Baro Itang	6.76	0.33	0.01	20.48	0.95
	Gumero Gore	6.16	0.30	0.13	20.53	0.96
	Sor Metu	7.12	4.62	0.15	1.54	0.96
Irrigation method	center pivot	3.32	0.16	$5.5 \cdot 10^{-3}$	20.75	0.96
	sprinkler	0.66	0.03	$1.1 \cdot 10^{-3}$	22.00	0.96
	furrow	16.62	10.8	0.36	1.54	0.97
	drip	13.3	0.66	0.02	20.15	0.99

Explanations: *ET* = evapotranspiration, *ETp* = potential evapotranspiration, *CV* = coefficient of variation. Source: own study.

Table 5. Average and highest rainfed crops yield, actual seasonal evapotranspiration (*ETa*), seed rate, and fertiliser in the sub-catchment

ETa (mm)	*ETa*/*ETp*	Average yield		Highest yield	Seed rate	Fertiliser rate	No. of holders
		CWP (Mg·m^{-3})	yield				
			Mg·ha^{-1}				
<28	–	–	1.73	5.6	–	0.033	–
28–43	3.73	0.59	2.45	5.6	0.985	0.123	155.60
43–48	3.87	0.58	2.43	5.6	0.432	0.121	14,611.1
48–53	4.54	0.57	1.42	4.8	0.325	0.123	70,490.56
53–58	4.7	0.41	1.29	4.8	0.225	0.140	18,333.3
58–60	6.76	0.39	2.71	2.7	0.345	0.165	28,000.0
60–63	6.16	0.17	0.73	2.2	0.412	0.146	2,777.7
63–67	7.12	0.12	0.65	2.2	0.314	0.120	1,555.6

Explanations: *ETp* as in Tab. 3, *CWP* = crop water productivity. Source: own study.

productivity was found to be 25 Mg·ha^{-1}, but the (*YA*) from 1999–2017 was very low as shown in Figure 5. Differently how atypical years farms can distort estimates of potential and water-limited production harvest time. In 1985-2002, the study on the Baro River and projected data from 2023 to 2040, the *ET* increased by 12% while the surface runoff decreased by 42% (Mengistu *et al.*, 2023).

This suggests that limited water resources in the region were not properly used for required rainfed crops. The study also notes that the *ETa*-WaPOR value is often overestimated in irrigated areas due to various factors, such as quality layers input, local advection effects, and relative soil moisture content. Overall, findings suggest that the implementation of efficient irrigation management systems can improve water productivity and crop yields in the lower Baro watershed.

In this case, the result showed that the maximum *Yw* was 1200 kg·ha^{-1} with the corresponding minimum *YA* of 1300 kg·ha^{-1}. But the analysis of the trend's variation could lead to increasing

Table 6. Increase in the current rainfed yield of rice, sugarcane, maize, and small vegetable field

Sub catchment	Agricultural land (ha)	Average yield	Highest yield	Increase in yield production ($\cdot 10^6$ kg)		
		($kg \cdot 10^6 \cdot ha^{-1}$)		0.33 of yield gap	0.66 of yield gap	0.75 of yield gap
Alwero	14,000	$3 \cdot 10^{-3}$	$5.6 \cdot 10^{-3}$	13.86	27.72	31.5
Gilo Fugnido	1,315	$3.2 \cdot 10^{-3}$	$5.6 \cdot 10^{-3}$	1.38	2.77	3.15
Birbir Yubdo	634.4	$5.6 \cdot 10^{-3}$	$5.6 \cdot 10^{-3}$	1.17	2.34	2.66
Gog	1,650	$1.7 \cdot 10^{-3}$	$4.8 \cdot 10^{-3}$	0.92	1.85	2.10
Baro Gambella	280,000	$4.8 \cdot 10^{-3}$	$4.8 \cdot 10^{-3}$	443.52	887.04	1,008
Baro Itang	1,914	$2.7 \cdot 10^{-3}$	$2.7 \cdot 10^{-3}$	1.70	3.41	3.87
Gumero Gore	25	$1.8 \cdot 10^{-3}$	$2.2 \cdot 10^{-3}$	0.01	0.02	0.03
Sor Metu	78	$2.2 \cdot 10^{-3}$	$2.2 \cdot 10^{-3}$	0.05	0.11	0.12

Source: own study.

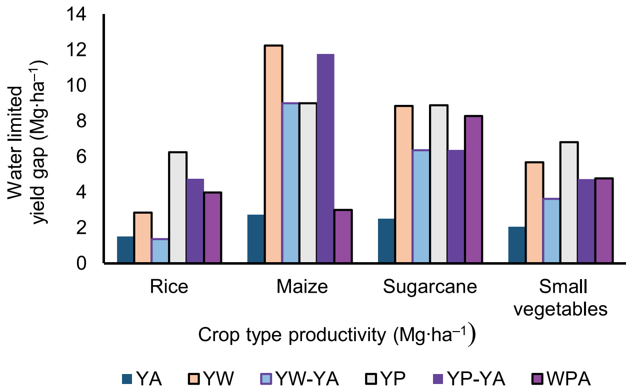

Fig. 4. Crop-type productivity versus water-limited yield gap ($Mg \cdot ha^{-1}$); *YA* = actual yield, *YW* = water limited, *YP* = yield potential, *WPA* = water productivity actual; source: own study

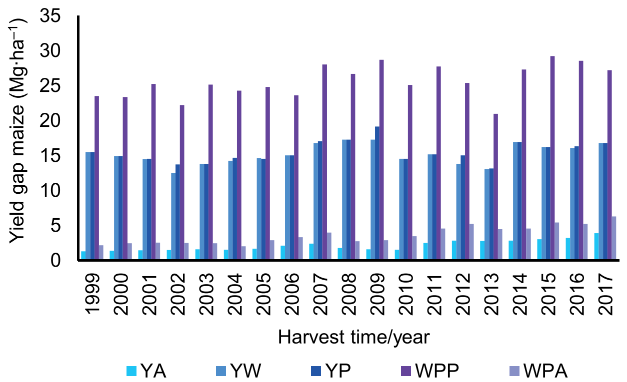

Fig. 5. Lower Baro tributary yield gap for maize crop in 1999–2017; *YA*, *YW*, *YP*, *WPA* = as in Fig. 4, *WPP* = water productivity potential; source: own study

and decreasing yield gaps. Maximum of 1.3 $Mg \cdot ha^{-1}$ in terms of *YA* and the corresponding *YW* variation 1.2 $Mg \cdot ha^{-1}$ for water-limited yield gap in the lower Baro watershed as shown in Figure 6. There were temporal scales that should be set to capture (eliminate) the environment-related dynamic aspects (soil, climate, and ecosystem components). The analysis time frame must be clear and in line with standards relevant for a critical evaluation of data. This cannot be determined without more thorough research utilising simulation models. South and South-

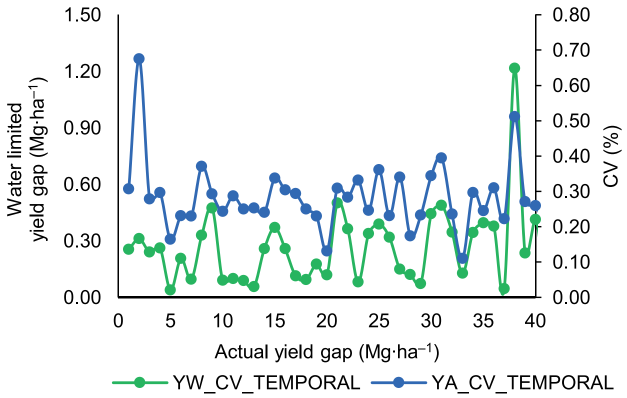

Fig. 6. Temporal variation (*CV*) of actual yield gap versus water-limited yield gap; *CV*, *YW*, *YA* as in Fig. 4; source: own study

west African regions have disproportionately high yields, whereas the North, Central, and Eastern regions have lower yields (Andersson *et al.*, 2009).

In this study, as a result, the maximum temporal variation was 1.2 $Mg \cdot ha^{-1}$, *YW* with *YP* of 0.9 $Mg \cdot ha^{-1}$, and a *CV* value of 0.68. The corresponding minimum value was 0.1 ton/ha *YW* of 0.3 $Mg \cdot ha^{-1}$ of *YP* with a *CV* of 0.68. These patterns collectively may result in the widening of yield gaps in the lower Baro watershed as shown in Figure 7. A single prediction of potential production (water limitation) employed as a reference in the gap

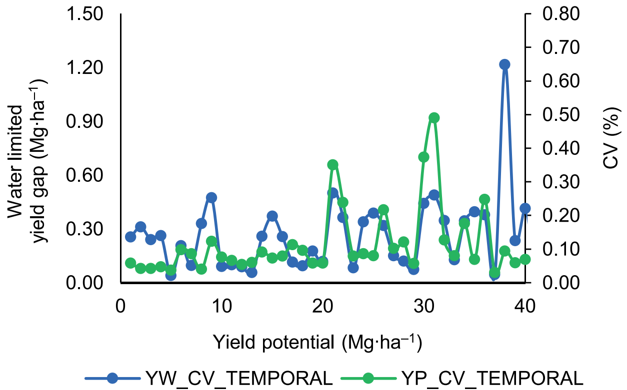

Fig. 7. Temporal variation (*CV*) of potential yield gap versus water-limited yield gap; *YW*, *YP* as in Fig. 4; source: own study

analysis does not accurately represent all of the circumstances that would exist within a cropping system and agroecological zone. Most farmers could not achieve the yield produced by a contest winner in the (highest-yielding fields) that would not benefit from the same climatic as well as soil conditions. Studies mention that the *CV* ranges from 0.1–0.05 based on the observed rainfall data (1972–2000) in the upper Baro River (Kebede, Diekkrüger and Edossa, 2017).

SUSTAINABLE YIELD GAP CLOSURE THROUGH IRRIGATION

Watershed management performance indicators have enhanced the water's long-term availability in rain-fed areas. In addition, effective irrigation management in these areas would lead to better use of water supply for irrigation in Lower Baro. The paramount importance of spatial and temporal inter-annual variation in environmental variables and their impact on yield is a significant finding of the entire inquiry. This has effects on how reliable yield estimates were produced from data used, especially those from region and the globe. This was made evident by databases from reporting districts, comparative yield studies, and specific commercial fields.

WaPOR DATABASE LIMITATIONS

The results in this study primarily depend on data from the WaPOR database. Additionally, over the 10 years, WaPOR data have fluctuated.

CONCLUSIONS

The purpose of this study is to enhance yield gaps and water productivity in the lower Baro watershed by utilising the Water Productivity Open Access Portal (WaPOR) and the Global Yield Gap Atlas (GYGA). A framework is developed to encompass various aspects of agricultural production and irrigation performance to categorise crop fields and enable comparative analysis using real yield and evapotranspiration (*ET*) estimates that reflect the heterogeneity at the crop-field level. Furthermore, land conversion is identified as a means to achieve the anticipated yield gap by 2050.

The WaPOR database offers 25% improvement in the agricultural water sector and increases crop yield gap output. The output of the current agricultural land is increased by expanding the area of rainfed crops and irrigation. The entire lower Baro watershed, increased the production of selected crops by 1/3, 2/3, and 3/4 of the yield gap. Regardless of a plot size, spatial resolutions of 250, 100, and 30 m are adequate for inter-annual and inter-scheme assessment of sufficiency, equity, and *CWP*. For adequacy, equity, and *CWP* within a scheme, spatial resolutions of 250 and 100 m show general spatiotemporal trends, but not the full amount of plot-to-plot variance. Water harvesting, effective irrigation techniques, modifying water allocation, and enhancing irrigation and water control reliability are all steps that can be taken to increase *WP* in a physical sense. A comprehensive analysis of the spatiotemporal variation of indicators and yield gap shows that there is no single irrigation technology that stands out to be the best. Further research is needed to understand the causes of this diversity, especially how spatial scale affects the estimates of the achievable/actual yield gap.

CONFLICT OF INTERESTS

The authors declare no potential conflicts of interest concerning the research, authorship, and/or publication of this article.

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