



Assessment of suitable land for surface irrigation development in an Ardy watershed, Upper Blue Nile Basin, Ethiopia

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Abstract

Despite its abundant water and land resources, Ethiopia has not fully harnessed its potential for irrigation development. This study assessed suitable land for surface irrigation in the Ardy watershed, Ethiopia, with the goal of utilizing the country's abundant yet underexploited water resources to increase agricultural productivity and sustainability. The data used in this study included soil, land use/land cover, meteorological, and streamflow data. The methodology integrates the Food and Agriculture Organization (FAO) land evaluation framework with Geographic Information Systems (GIS) and multicriteria analysis (Analytic Hierarchy Process, AHP) techniques. Land suitability was determined using factors such as slope, soil, land use/land cover, and proximity to water sources, with slope identified as the most influential parameter (47.09% weight). The Soil and Water Assessment Tool (SWAT) model was used to analyze surface water potential and demonstrated strong reliability during calibration ($R^2 = 0.90$, $NSE = 0.86$, $PBIAS = -18.9\%$) and validation ($R^2 = 0.85$, $NSE = 0.84$, $PBIAS = -14.9\%$). The results indicated that 99% (21,509 ha) of the watershed is suitable for surface irrigation, with 53% classified as moderately suitable. However, CROPWAT 8.0 modeling revealed that during peak irrigation demand periods (December, January, and February), the gross irrigation water requirement for the total suitable land exceeds the available river flow. On the basis of minimum available flows, the critical command area that can be reliably irrigated ranges from 918 ha (maize) to 1,057 ha (potato) across the subbasins. These findings provide policymakers with valuable guidance for developing targeted and effective management strategies to ensure sustainable resource use in the Ardy watershed.

Keywords Ardy watershed · Investigation · Land suitability · Surface water potential · Irrigation potential

Introduction

Ethiopia is often referred to as the “water tower of East Africa’s substantial water resources,” which include an annual surface runoff of 122–124 billion cubic meters (BCM) and an estimated groundwater flow of 30–40 BCM (Yonas et al. 2022; Kidanewold et al. 2014, 2018; Gedam et al. 2020). Despite this abundance, Ethiopia has utilized only a fraction of these resources for irrigated agriculture, resulting in an underdeveloped sector (Yimere 2022; Mola and Ping 2021). The country’s economy heavily depends on agriculture, which employs 75% of the population, contributes 40% to GDP, and generates 80% of export income (Yimere 2022).

However, the sector’s heavy reliance on rainfed agricultural systems makes it vulnerable to unpredictable rainfall, resulting in frequent crop failures and worsening food insecurity for the country’s population of more than 120 million (Yonas et al. 2022). Climate change has exacerbated

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these challenges, causing droughts that reduce crop yields and threaten farmers' livelihoods (Ahmed et al. 2024; FAO 2015). Over the past four decades, Ethiopia has experienced severe droughts that have led to massive crop losses, livestock deaths, and the displacement of millions of livestock (Matiwos et al. 2022; Shapiro et al. 2015), particularly in highlands where rainfall variability is especially pronounced (Yimere 2022). Therefore, effective management of water resources is crucial for addressing water scarcity in these highland regions.

In response to these challenges, expanding irrigation infrastructure is essential for the long-term improvement of agricultural productivity and sustainability (Asukala et al. 2024). Research indicates that techniques such as flood-water harvesting and stream diversion can significantly increase food security by increasing agricultural output and improving soil moisture (Tesfay et al. 2021). Although the Ethiopian government and NGOs have implemented irrigation schemes, many of these projects have encountered difficulties due to technical problems and inadequate site selection (Matiwos et al. 2022). A substantial portion of the country's irrigable land remains underutilized, primarily because insufficient assessments are needed to identify suitable areas for surface irrigation development (Ahmed et al. 2024; FAO 2015; Matiwos et al. 2022; Shapiro et al. 2015).

To address this critical need, various methods are commonly employed to identify suitable land for surface irrigation, including the use of Geographic Information Systems (GIS), the Analytical Hierarchy Process (AHP), and other techniques, either individually or in combination (Worku et al. 2024). The integration of GIS and remote sensing technologies, often combined with multicriteria evaluation (MCE) methods, is becoming increasingly prevalent for locating appropriate irrigation sites (Alene et al. 2022). This integrated approach not only supplements rainfed crops during dry spells but also has proven effective in stabilizing and increasing crop yields (Wubalem 2023; Alene et al. 2022; Aimée et al. 2017).

Nevertheless, research focused on identifying suitable areas for surface irrigation, particularly in the Ethiopian highlands, remains limited. This lack of comprehensive assessment is a significant issue in the Ardy watershed. Located in the Upper Blue Nile Basin of Ethiopia, the Ardy watershed has not yet been thoroughly evaluated for its potential in surface irrigation development. Therefore, this study aims to identify and assess potential sites for surface irrigation development within the Ardy watershed.

The research employed Geographic Information Systems (GIS) geographic information systems (GISs) integrated with multicriteria evaluation techniques to assess land suitability. The key factors analyzed included soil properties, land use and land cover, topography, and proximity to water sources.

Additionally, the SWAT model was used to simulate river flow and evaluate surface water potential, whereas the CROPWAT 8.0 software was used to estimate the irrigation water requirements for major crops such as wheat, potato, and maize.

The identification of suitable land for surface irrigation in the Ardy Watershed provides crucial information to local communities and decision-makers, enabling them to implement targeted irrigation schemes that increase agricultural production. This assessment offers valuable insights aimed at optimizing resource use and improving agricultural productivity and sustainability within the Ardy Watershed. Additionally, it serves as a useful reference for future studies exploring surface irrigation potential in the region and comparable areas worldwide.

Materials and methods

Description of the study area

Location of the study area

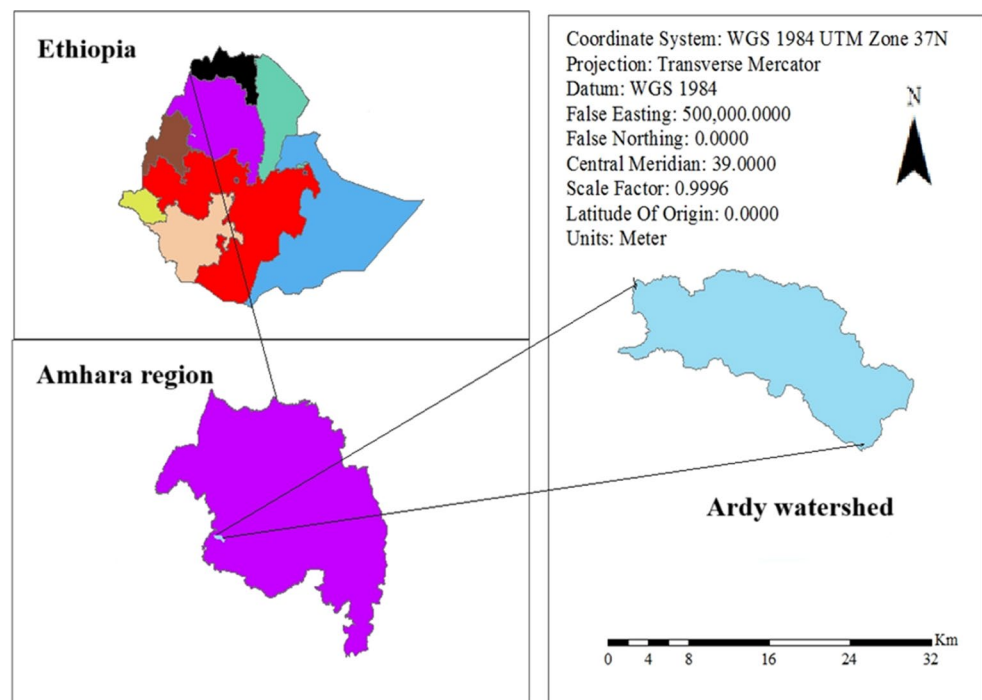
The Ardy watershed is located in the Awi Zone (Upper Blue Nile Basin) of the Amhara National Regional State in Ethiopia, as shown in Fig. 1. It spans three districts: Ankesha, Banja, and Guangua. Geographically, the watershed lies between latitudes 10°55'0" N to 10°57'48" N and longitudes 36°33'52" E to 36°46'34" E. Covering an area of 217.3 square kilometers at its gauging station outlet, the watershed serves as a tributary to the Abay Basin. With an average elevation of 2,235.5 m above sea level, it exhibits distinct highland characteristics.

Climate

The Ardy watershed receives an average annual precipitation of 1,737.5 mm, which is based on data collected from the Ayehu, Chagni, Injibara, Kidamaja, and Tilili climate stations. The primary rainy season occurs from June to September, following a unimodal rainfall pattern that begins in late May and extends through early October. The rainfall distribution across the watershed exhibited considerable variability.

Between 1990 and 2019, the average monthly rainfall at individual stations fluctuated between 1 mm and 511 mm, whereas the overall average monthly rainfall for the watershed ranged from 5 mm to 395 mm. The temperature data indicate that the maximum temperatures vary from 23.2 °C to 31.6 °C, with April identified as the warmest month and July the coldest month. The minimum temperatures range from 11.3 °C to 16.1 °C.

Fig. 1 Location map of the study area



Data collection and sources

This study utilized both primary and secondary data sources. Primary data were collected via GPS to record Ground Control Points (GCPs), supplemented by personal observations and consultations with experts. Field surveys were conducted to gather ground truth data on land cover for accuracy assessment, ensuring a comprehensive evaluation of local conditions.

The secondary data included rainfall records, Landsat satellite imagery, (DEMs), and soil information, as these datasets are essential for obtaining accurate research results. After field data and existing maps were acquired, the data were prepared, processed, and analyzed via ArcGIS 10.8 software. These datasets enabled the creation of various thematic maps, including slope, flow direction, flow accumulation, precipitation, soil, land use/land cover (LU/LC), elevation, drainage density, and climatic variables such as daily precipitation, temperature, relative humidity, wind speed, and solar radiation. Agronomic data were obtained from the Awi Zone Agriculture Office, whereas climate data were sourced from the National Meteorological Agency. A summary of the datasets, software/models used, their sources, and their relevance to the study is provided in Table 1.

Data analysis

Identification of suitable land for surface irrigation

The analysis of land suitability for surface irrigation was conducted using GIS software, which focuses on factors such as slope, soil characteristics, land use/land cover, and proximity to water sources (Yalew et al. 2016). Each factor was assessed individually and assigned a weight to identify suitable areas for irrigation. The ArcSWAT model was employed to delineate the watershed and estimate surface water availability. The CROPWAT 8 model evaluated the water requirements of the dominant crops using climatic data from the SWAT weather database.

Slope suitability: To create the slope suitability map for the study area, a Digital Elevation Model (DEM) from the Shuttle Radar Topography Mission (SRTM) was clipped to a 30-meter resolution using the mask layer of the study area. The slope map was generated via the ArcGIS Spatial Analyst tool. Following the classification system outlined in reference (Wubalem 2023), the extracted slope data were categorized into suitability classes via the “Reclassification” and attribute generalization tools in ArcGIS.

Soil suitability: The evaluation of soil suitability for surface irrigation focused on key physical parameters,

Table 1 Summary of the data and software/models used in the study

Data and software	Sources	Purpose
Hydrological data	Abay Basin Authority	For sensitivity analysis, calibration, and validation
Meteorological data	National Meteorological Agency of Ethiopia (NMAE)	The input of Arc SWAT and CROPWAT 8.0
30mx30m DEM	USGS(SRTM)	The input for ArcGIS and Arc SWAT to determine proximity to the water supply
Soil data	Ministry of Water, Irrigation and Electricity	The input of ArcGIS, Arc SWAT & CROPWAT Models
LU/LC data	Ministry of Water, Irrigation and Electricity	The input of ArcGIS and Arc SWAT
Agronomic data	Zone of Agriculture office	The input of the CROPWAT8.0 model
GIS10.1	Environmental Systems Research Institute (ESRI)	For data visualization and map layout
Arc SWAT	https://swat.tamu.edu/software/	For watershed delineation and Simulation
SWAT-CUP	https://swat.tamu.edu/software/	For sensitivity analysis, calibration, and validation
CROP WAT 8.0	Food and Agricultural Organization (FAO)	For an estimation of irrigation water demand
Weather Generator	https://swat.tamu.edu/software/	To generate a realistic daily sequence of weather variables

including soil texture, depth, and drainage characteristics within the watershed. These factors are crucial in determining the soil's capacity to support surface irrigation. The suitability ratings for these attributes were used to assess the land's potential for irrigation development.

Land Use and Land Cover Suitability: Land use and land cover are critical factors in assessing the suitability of land for surface irrigation. The study area was classified into various land use and land cover types, with each category assigned a specific suitability level on the basis of its capacity to support surface irrigation.

Proximity: The distance from the command area to a surface water source is critical for evaluating land suitability for surface irrigation. A Digital Elevation Model (DEM) with a pixel size of 30×30 m was used to calculate the straight-line (Euclidean) distance from irrigable areas to the nearest surface water source, such as a river. This distance was then reclassified for inclusion in the weighted overlay analysis, which incorporates additional suitability factors.

Weighted overlay analysis to find potential irrigable sites

The weights assigned to the factors in this study were determined using the pairwise comparison method within the Analytical Hierarchy Process (AHP) (Ozgur 2024). This approach minimizes individual biases in weighting the

factors. Each factor exerts varying degrees of influence on the suitability evaluation, with higher weights indicating a greater impact on the overall assessment of land suitability for surface irrigation (Vanessa et al. 2023). The weighting of decision factors was informed by expert knowledge of the area's natural conditions, local characteristics, and relevant literature. According to (Hagos et al. 2022), slope is a critical factor in irrigation activities, particularly for surface irrigation. Similarly (Worku et al. 2024), identified the distance from the water source as the most important factor in determining a watershed's suitability for irrigation, even more so than soil properties. While land use/land cover is a relatively less significant factor for surface irrigation, slope, proximity to the water source, and soil characteristics were considered major influences in the suitability evaluation for this study on the basis of expert judgment. The pairwise comparison and definitions of the weighting process (Aimée et al. 2017) are presented in Table 2 below.

The factors listed in the columns were compared with those in the rows to assess their significance in surface irrigation. A pairwise comparison matrix was then constructed via the scoring methodology proposed by (Aimée et al. 2017), as shown in Table 3.

The normalized decision matrix for the irrigation suitability factor was created by dividing each element in a column by the total sum of that column. These normalized

Table 2 Pairwise comparison scale and definition

Intensity of importance	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective.
3	Somewhat more importance	Experience and judgment slightly favor one over the other.
5	Much more importance	Experience and judgment strongly favor one over the other.
7	Very important	Experience and judgment very strongly favor one over the other.
9	More important	The evidence favoring one over the other is of the highest possible validity.
2,4,6,8	Intermediate values	When compromise is needed

Table 3 Pairwise comparisons of all factors

Factors	Soil	Slope	River	LU/LC
Soil	1.00			
Slope	3.00	1.00		
River	2.00	0.50	1.00	
LU/LC	0.33	0.20	0.25	1.00
Sum	6.33	2.03	3.75	13.00

values were obtained from the pairwise comparison matrices (Aimée et al. 2017) via the following equation.

$$N = \frac{\sum j}{C} \quad (1)$$

where N is the normalized value, j is the column of the matrix, and c is the sum of the values of the column factors.

To assign weights to each irrigation suitability factor, Saaty's technique employs the principal eigenvector of a square reciprocal matrix derived from pairwise comparisons of the criteria. In this study, four factors for evaluating irrigable land were weighted via these comparisons. After completing the pairwise comparison matrices, the weighting module was used to calculate the consistency ratio (CR) and determine the optimal weights. A CR value below 0.1 indicates acceptable consistency within the pairwise comparison matrix, whereas a value above 0.1 signifies inadequate consistency, requiring the comparison process to be repeated until the CR falls below 0.1 (Saaty 2008). The consistency ratio is calculated via Eq. (2).

$$CR = \frac{CI}{RI} \quad (2)$$

Here, the RI refers to Saaty's random index, which varies according to the number of factors in the matrix, as shown in Table 4. In this study, with four parameters, the RI is 0.89. The consistency index (CI) is calculated via Eq. 3 (Aimée et al. 2017).

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (3)$$

where n is the number of factors being compared and $\lambda_{\max}$ is the largest eigenvalue of the pairwise comparison matrix.

The spatial analysis and weighted factors were integrated into a multicriteria evaluation by overlaying them within the GIS environment. The final suitability map for surface irrigation was generated via the weighted overlay tool in

ArcGIS. Each land suitability criterion was rasterized, and an evaluation scale from 1 to 5 was applied: 1 for highly suitable areas, 2 for moderately suitable areas, 3 for marginally suitable areas, and 4 and 5 for unsuitable areas (N).

Surface water availability assessment

Data from the Ardy watershed gauging station, combined with climatological data, were used to estimate the current surface water availability in the study area. Simulated streamflow values generated by the ArcSWAT model were employed to assess the available surface water in the watershed. Additionally, a sensitivity analysis was conducted for model calibration and validation using river flow data obtained from the Abay Basin Authority.

The Arc-SWAT model is a semidistributed hydrological tool integrated into the ArcGIS platform. It simulates various components of watershed systems, including hydrology, sedimentation and erosion, weather patterns, plant growth, nutrient cycles, land management practices, channel routing, and pond/reservoir dynamics. The model allows for the subdivision of subbasins into smaller subwatersheds, which are further divided into Hydrological Response Units (HRUs) on the basis of variations in soil types, land use/land cover, and topography. Additionally, the model features a built-in weather generator that produces daily data for precipitation, temperature, solar radiation, wind speed, and relative humidity. The SWAT model requires a daily meteorological time series, including precipitation, maximum and minimum air temperatures, daily daylight hours, wind speed, and relative humidity.

Land use/land cover plays a pivotal role in influencing runoff, evapotranspiration, and surface erosion within the study area. The land use and land cover maps were reclassified to categorize areas on the basis of specific land use or cover types, ensuring accurate representation in the model. Similarly, soil data are vital for the SWAT model, which requires detailed physical properties such as texture, depth, and drainage characteristics. To facilitate analysis, the soil maps were reclassified to group the soils into defined types

Table 4 Saaty ratio index value of consistency (Saad et al. 2025)

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.89	1.12	1.24	1.32	1.41	1.45	1.49

suitable for the model. Complementing these inputs, a DEM with a resolution of 30×30 m was utilized to delineate watersheds and analyze surface drainage patterns. This DEM served as a crucial input for HRU analysis, providing the foundation for spatial modeling. Accurate weather data further strengthened the modeling process. The Weather Generator application was employed to fill gaps in the data by incorporating relevant parameters and location information. Finally, river flow data were critical for SWAT model simulation, calibration, and validation. The observed daily river flow data from 1990 to 2004 supported a model warm-up period of two years, followed by eight years for calibration and five years for validation. This comprehensive dataset ensured robust hydrological predictions across the study area.

HRUs After the watershed was delineated, the subbasins were further divided into HRUs, which represent areas characterized by distinct combinations of land use/land cover, soil types, and slopes. Individual patches of land use, soil, and slope were aggregated to form HRUs. The datasets for land use/land cover, soil, and slope were reprojected to align with the projection of the DEM. These data were then reclassified, overlaid, and linked to the SWAT database in preparation for defining the HRUs. A multifaceted approach was employed to determine the distribution of HRUs within the watershed. Threshold values for land use/land cover, soil, and slope were established to specify the number of HRUs per subbasin and across the entire watershed.

SWAT model simulation, sensitivity analysis, calibration, and validation After all necessary input data were incorporated, the SWAT model was executed to generate simulation outputs. However, these outputs cannot be directly used for further analysis. To ensure accurate streamflow predictions, the results must be refined through sensitivity analysis, calibration, and validation (Das et al. 2024). Sensitivity analysis evaluates how variations in model parameters influence simulation results (Borgonovo et al. 2022), identifying critical parameters that significantly impact outputs (Xiao et al. 2025). Using t statistics and p values, parameters with higher sensitivity and statistical significance are prioritized for calibration, whereas nonsensitive factors are excluded to streamline the process. The sensitivity parameters are then adjusted to align the simulation outputs with the observed streamflow data, ensuring accuracy and reliability. This adjustment can be performed manually or automatically, depending on the methods employed, and iterates until the model's performance meets acceptable standards (Abbaspour et al. 2018). In this study, historical streamflow data from 1992 to 1999 were used for calibration, enabling

parameter fine-tuning on the basis of real observations (Hussein and Baylar 2023). Subsequently, validation tests the model's predictive ability via independent data not utilized during calibration. By running the model with calibrated parameters and comparing predictions to observed data, validation ensures robustness and applicability to real-world scenarios. Streamflow data from 2000 to 2004 were used for validation, confirming the model's reliability and predictive accuracy.

Measure of model performance efficiency The accuracy, consistency, and adaptability of the SWAT model are critical factors in evaluating its performance. This study assessed the model's efficiency by visually comparing observed and simulated hydrographs and by utilizing objective statistical metrics. The primary evaluation metrics included the coefficient of determination (R^2), percentage bias (PBIAS), and Nash-Sutcliffe efficiency (NSE), which collectively quantify the accuracy and reliability of the model simulations relative to the observed values.

The Nash–Sutcliffe Efficiency (NSE) is a normalized statistic that quantifies the relative magnitude of the residual variance compared with the variance of the observed data (Nash and Sutcliffe 1970; Moriasi et al. 2014). It measures how well the simulated data correspond to the observed data, ideally resulting in a 1:1 relationship. The NSE is calculated using the following formula (Eq. 4):

$$NSE = 1 - \sum_{i=1}^N \left(\frac{[Q_o - Q_s]^2}{[Q_o - \bar{Q_o}]^2} \right) \quad (4)$$

where Q_o is the observed flow, Q_s is the simulated flow, $\bar{Q_o}$ is the mean observed discharge, and N is the total number of time steps.

An NSE of 1 indicates perfect agreement; an NSE=0 suggests that the simulations are as accurate as the mean of the observations, and an NSE<0 implies that the model is less reliable than the mean (Awa et al. 2018).

The coefficient of determination (R^2) quantifies the proportion of variance in the observed values that the model explains (Gupta and Sorooshian 2014). It is calculated as shown in Eq. 5:

$$R^2 = \frac{\sum_{i=1}^n [Q_s - Q_{sm}] (Q_o - Q_{om})^2}{\sum_{i=1}^n [(Q_s - Q_{sm})^2 * (Q_o - Q_{om})^2]} \quad (5)$$

where Q_s and Q_{sm} are the simulated and observed discharges, respectively; Q_o and Q_{om} are their means; and n is the number of observations.

An R^2 value approaching 1 indicates excellent model performance, whereas values below 0.5 indicate poor performance. Typically, R^2 values above 0.6 are considered acceptable (Gupta and Sorooshian 2014).

The percentage bias (PBIAS) evaluates whether the model systematically overestimates or underestimates the observed values (Nakagawa et al. 2017). It is calculated using the following formula (Eq. 6):

$$PBIAS = \frac{\sum_{i=1}^n (Q_{o,i} - Q_{s,i})}{\sum_{i=1}^n (Q_{o,i})} * 100 \quad (6)$$

where $Q_{o,i}$ and $Q_{s,i}$ are the observed and simulated flows at time i . A PBIAS of 0 indicates perfect agreement; positive values suggest underestimation bias, whereas negative values indicate overestimation. Model performance was categorized as unsatisfactory, satisfactory, good, or very good on the basis of these statistical indicators (Nakagawa et al. 2017).

Computing irrigation water requirements for crops

To estimate the irrigation water requirements for crops in the study area, the most widely cultivated crops, i.e., wheat, potato, and maize, were selected on the basis of factors such as farming practices, direct sowing methods, their role in ensuring food security, and their economic significance in improving farmers' livelihoods and income. These crops are vital to local agriculture because of their adaptability and economic value. Wheat is cultivated primarily at mid-to-high altitudes in Ethiopia, ranging from 1,700 to 2,800 m above sea level, with optimal growth occurring between 1,800 and 2,400 m. However, with irrigation, wheat can be successfully grown at elevations below 1,700 m. It thrives in black, red, or brown soils and has an average daily temperature of 15–25 °C. Wheat generally performs well in regions receiving 800–1,000 mm of annual crop water, with a critical depletion range of 0.55–0.8. The growing period for wheat spans 120–150 days (Yongliang et al. 2022).

The potato is a globally important crop, especially in high-altitude regions. It is also adaptable to lowland areas and can thrive under irrigated conditions (Devaux et al. 2021). The optimal growing altitude for potatoes ranges from 1,500 to 2,800 m. Potato growth requires soil temperatures between 15 °C and 25 °C and can be cultivated in various soil types, except saline and acidic soils. Sandy clay loam or silty loam soils with good drainage are preferred for optimal yields. The critical depletion range for potatoes is between 0.25 and 0.5, with a growing period of 105 to 145 days, depending on the variety, such as the Belete variety.

Maize, one of the most widely cultivated cereal crops, thrives in well-aerated, well-drained loamy soils with temperatures ranging from 15 to 35 °C (Dejene et al. 2024). It is adaptable to various altitudes but performs optimally at elevations between 1,000 and 2,000 m. The growing period for maize typically ranges from 125 to 180 days.

The study area is supported by five meteorological stations, Ayehu, Chagni, Enjibara, Kidamaja, and Tilili, with the Ayehu and Chagni stations providing comprehensive climate data. The majority of the Ardy watershed is located near the Chagni station. These stations were used to assess the irrigation water requirements for the selected crops in the study area. The planting dates for the crops were aligned with the local cropping calendar obtained from the Awi Zone Agriculture Office, ensuring synchronization with the meteorological station data. The crop coefficients for each selected crop were determined according to FAO guidelines and the irrigation agronomy manual. The irrigation water requirements were then estimated via the CROPWAT 8 model. A summary of the methodology flowchart is presented in Fig. 2.

Results

Identification of suitable land for surface irrigation

Slope suitability

Slope plays a crucial role in evaluating land suitability for surface irrigation. The FAO land suitability classification guidelines define four slope suitability classes for the development of surface irrigation, as shown in Fig. 3; Table 5.

According to Tables 5 and 95.2% (20,688 hectares) of the total area is classified as highly to marginally suitable for surface irrigation, whereas the remaining 4.8% (1,042 hectares) is considered unsuitable.

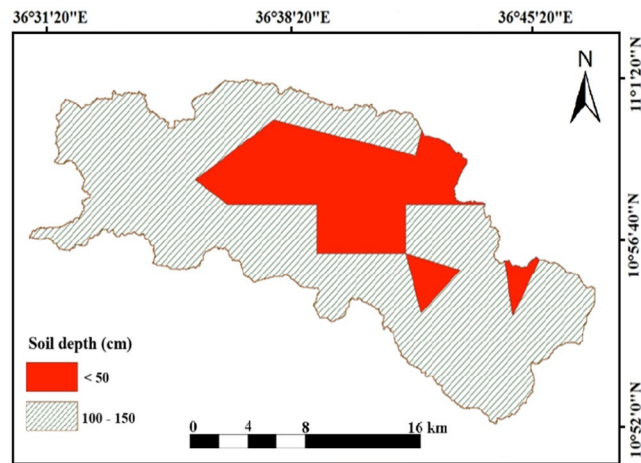
Soil suitability

The soil texture, depth, and drainage were analyzed via overlay analysis. These factors significantly influence plant root growth, water infiltration, and crop productivity.

Soil texture suitability: The soil texture in the study area was classified into three categories: clay, sandy clay loam, and silty loam (Wubalem 2023). The analysis indicated that silty loam was the predominant soil type in the region. The assessment of soil texture suitability revealed that 25.5% of the total area was highly suitable, 37.9% was moderately suitable, and approximately 36.6% was marginally suitable for surface irrigation. Notably, no areas were classified as unsuitable, as shown in Fig. 4; Table 6.

Table 6 Soil textural suitability classes of the study area

Texture category	Area coverage(ha)	Area coverage (%)	Suitability
Clay	5542	25.5	Highly Suitable
Silty loam	8240	37.9	Moderately suitable
Sandy clay Loam	7948	36.6	Marginally Suitable

**Fig. 5** Soil depth of the study area

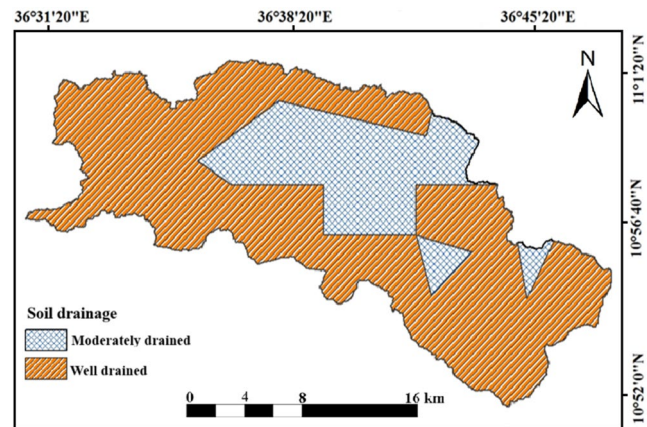
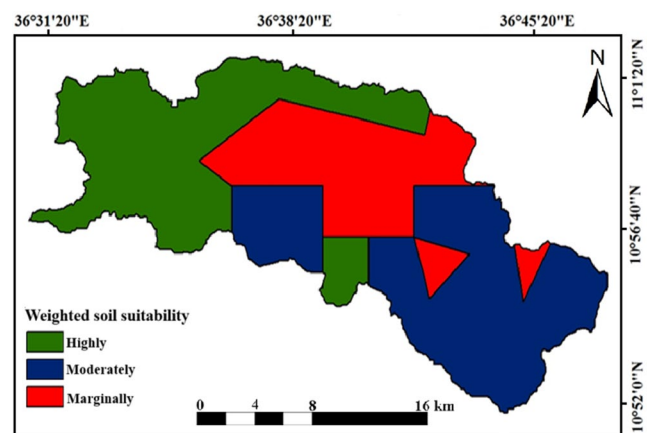
summary, 25.5% of the entire study area was determined to be unsuitable on the basis of the soil depth analysis.

Soil drainage suitability The soil drainage conditions in the study area were classified into two categories: well drained and moderately drained. A suitability map for soil drainage, along with the corresponding area coverage, is presented in Fig. 6. The analysis revealed that approximately 74.5% (16,187 ha) of the watershed is highly suitable for surface irrigation development, whereas the remaining 25.5% (5,542 ha) is moderately suitable. These findings indicate that the soil drainage conditions in the study area are favorable for surface irrigation.

A weighted overlay analysis was conducted to assess soil suitability, assigning equal importance to each soil parameter. The results indicated that 36.57% (7,947.6 ha) of the area is highly suitable, 37.97% (8,250 ha) is moderately suitable, and 25.46% (5,532.7 ha) is marginally suitable for surface irrigation development, as shown in Fig. 7.

Land use/land cover suitability

The suitability of land for surface irrigation was assessed on the basis of land use/land cover in the study area. Five land use/land cover types were identified: cultivated land, shrubland, forest, urban areas, and dense woodland. Among these areas, cultivated land was the most prevalent, comprising 80.66% (17,528.49 ha) of the total area, and was classified

**Fig. 6** Soil drainage suitability of the study area**Fig. 7** Soil suitability map for surface irrigation

as highly suitable. Dense shrubland and open forest areas accounted for 17.6% (3,825.93 ha) and were deemed marginally suitable, whereas urban and dense woodland areas, comprising 1.74% (375.58 ha), were considered unsuitable for surface irrigation development (Fig. 8).

Proximity to the river

The straight-line horizontal distance from the river was calculated, and the proximity to water sources was analyzed via GIS-based three-dimensional layers to identify areas suitable for surface irrigation. To evaluate the impact of distance on land suitability, features were extracted and converted into raster format. These features were then reclassified into suitability categories, as illustrated in Fig. 9.

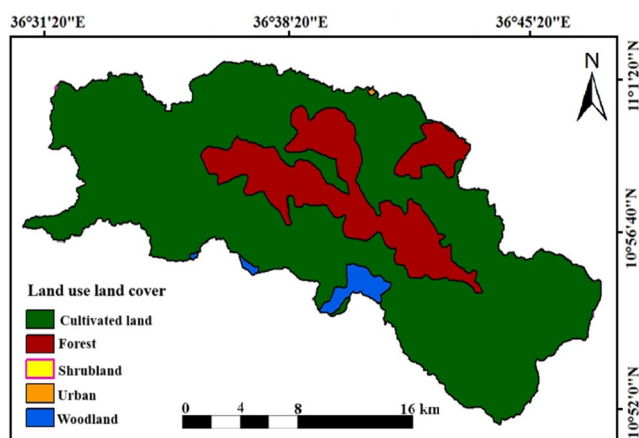


Fig. 8 Land use/land cover suitability map of the study area

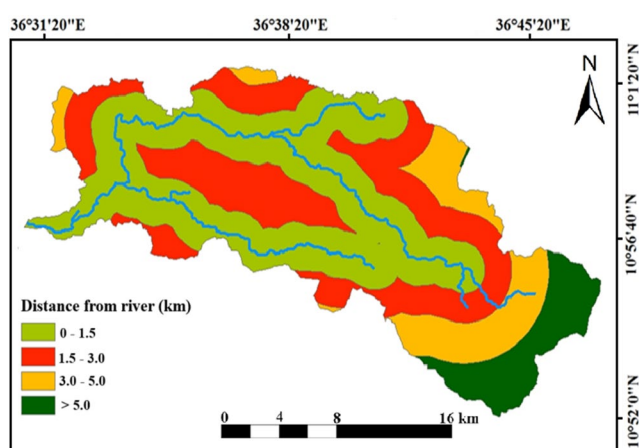


Fig. 9 Proximity to the water supply map of the study area

Table 7 summarizes the Euclidean distance analysis, detailing the suitability classifications and their corresponding area coverage. The proximity analysis revealed that 45.4% of the total area was classified as highly suitable, 31.3% as moderately suitable, 13.8% as marginally suitable, and 9.5% as not suitable. Overall, 90.5% (19,667 ha) of the study area was categorized as highly to marginally

suitable for surface irrigation, whereas the remaining 9.5% (2,063 ha) was deemed unsuitable.

Weighting of factors and suitable areas for surface irrigation

On the basis of expert knowledge of the natural environment and local characteristics of the study area, which is supported by previous literature (FAO 2015, Wubalem 2023; Alene et al. 2022; Nakagawa et al. 2017), factors such as slope, distance to water sources, and soil were identified as highly relevant for the analysis. In contrast, land use and land cover were considered less critical. Consequently, an Analytical Hierarchy Process (AHP) using a pairwise comparison approach was employed, as detailed in Tables 8 and 9.

The normalized pairwise matrix was created by dividing each element in a column by the sum of that column, and the criteria weights were determined by averaging the values in each row.

After normalizing the matrix, consistency was evaluated to ensure the accuracy of the computed values, as shown in Table 10. The weighted sum values were calculated by summing the corresponding values in each row of the normalized matrix.

The calculated weights were evaluated for consistency to ensure accuracy. The consistency ratio (CR) was found to be 1.92% (0.0192), with a consistency index (CI) of 0.0171. These results indicate that the judgments derived from the pairwise comparison matrix were satisfactory and consistent (Vanessa et al. 2023). Consequently, the calculated consistency ratio was deemed acceptable for weighting the factors used to assess the physical land capability of the Ardy watershed. This analysis facilitated the creation of an irrigation suitability map, as presented in Table 11.

Using these weights, ArcGIS was employed to identify potentially irrigable land in the Ardy watershed by integrating factors such as slope, soil type, land use/land cover, and proximity to water sources. As illustrated in Fig. 10, the

Table 7 Proximity of river flow to the study area

Euclidean distance (km)	Area coverage(ha)	Area coverage (%)	Suitability
0.0–1.5	9859	45.4	Highly suitable
1.5–3.0	6804	31.3	Moderately suitable
3.0–5.0	3004	13.8	Marginally suitable
>5.0	2063	9.5	Not suitable

Table 8 Pairwise comparison matrix

Function	Soil	Slope	River	LU/LC
Soil	1.00	0.33	0.50	3.00
Slope	3.00	1.00	2.00	5.00
River	2.00	0.50	1.00	4.00
LULC	0.33	0.20	0.25	1.00
Sum	6.33	2.03	3.75	13.00

Table 9 Normalized Pairwise Matrix

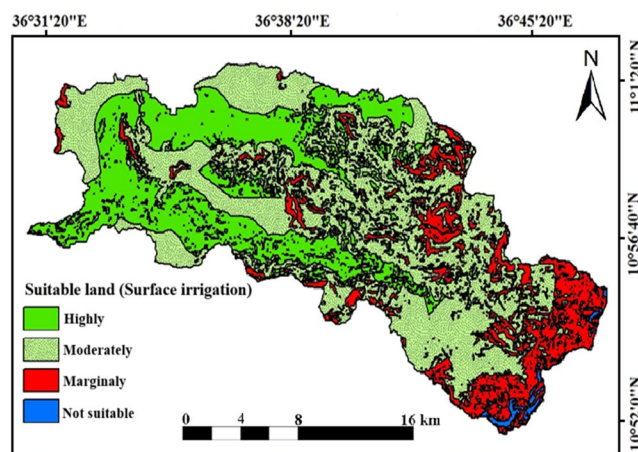
Function	Soil	Slope	River	LULC	Weighted sum value	criteria weight
Soil	0.1579	0.1639	0.1333	0.2308	0.6859	0.1715
Slope	0.4737	0.4918	0.5333	0.3846	1.8834	0.4709
River	0.3158	0.2459	0.2667	0.3077	1.1361	0.2840
LULC	0.0526	0.0984	0.0667	0.0769	0.2946	0.0736

Table 10 Matrix Consistency

Function	Soil	Slope	River	LU/LC	Weighted sum value(W.S)	Criteria weight(C.W)	W.S/C.W
Soil	0.1715	0.1570	0.1420	0.2209	0.691	0.1715	4.0318
Slope	0.5144	0.4709	0.5680	0.3682	1.922	0.4709	4.0810
River	0.3430	0.2354	0.2840	0.2946	1.157	0.2840	4.0737
LU/LC	0.0572	0.0942	0.0710	0.0736	0.296	0.0736	4.0190

Table 11 Percentage of influence for each parameter

Parameters	% of influence
Soil	17.15
Slope	47.09
River	28.40
LU/LC	7.36

**Fig. 10** Suitable land for surface irrigation map of the study area

weighted overlay analysis indicated that 30% (6,446 ha) of the area was highly suitable, 53% (11,533 ha) was moderately suitable, 16% (3,530 ha) was marginally suitable, and only 1% (221 ha) was unsuitable for surface irrigation development. This distribution of suitability reflects the combined effects of the assessed factors, with 99% of the study area classified as highly to marginally suitable, with the majority being moderately suitable.

Water availability assessment

The assessment of water availability in the Ardy watershed utilized simulated river flow values generated by the ArcSWAT model. The model was successfully executed, using

observed flow data for calibration and validation after identifying sensitive parameters.

Sensitivity analysis

In the sensitivity analysis, ten parameters were identified as the most influential for model calibration and validation. The SUFI-2 algorithm ranks these parameters on the basis of their *t* statistics and *p* values. Compared with the other parameters, the initial SCS runoff curve number for moisture condition II (CN2.management) was the most sensitive parameter, with the lowest *p* value and the highest *t* statistic, followed by the baseflow alpha factor and groundwater delay.

Model calibration, validation and performance evaluation

The SWAT model was calibrated and validated via daily streamflow data from the Ardy River. Calibration was conducted from 1992 to 1999, followed by validation from 2000 to 2004, with no further parameter adjustments made during validation. Model performance was assessed by comparing time series plots of observed and simulated flow values. The model's goodness-of-fit and performance were evaluated via several objective functions, including R^2 , NSE, and PBIAS, all of which fell within acceptable ranges for both the calibration and validation periods. Although some years showed underestimations or overestimations in daily flow estimates due to varying conditions, the overall model performance remained satisfactory, as illustrated in Fig. 11 and summarized in Table 12.

Crop water requirements analysis via the CROPWAT8.0 model

Climate data, crop types, planting dates, and soil textures (silty loam) were input into the CROPWAT 8.0 model to estimate reference evapotranspiration (ET_o), effective

Fig. 11 Observed and simulated daily flows for both calibration and validation

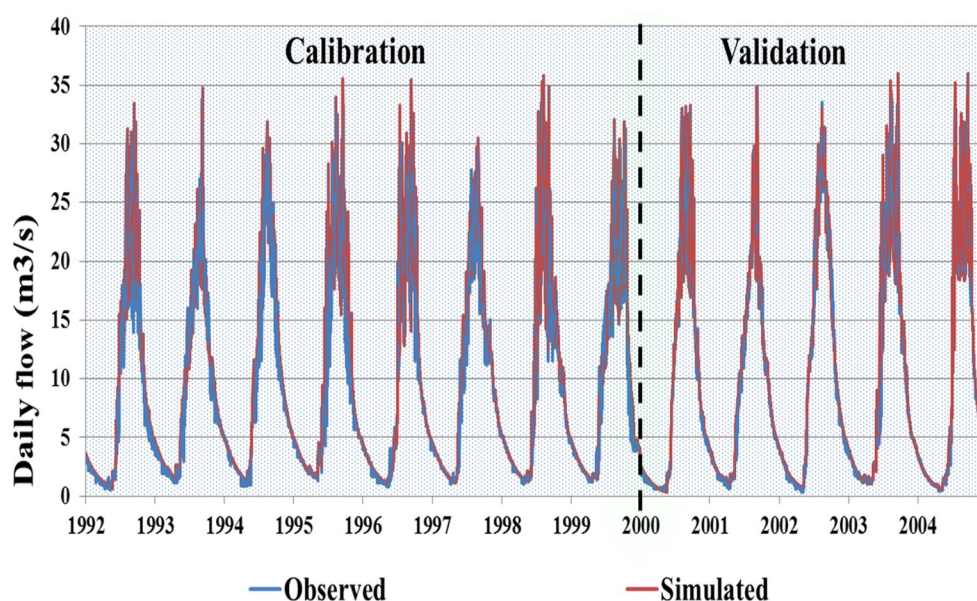


Table 12 Model performance

Objective function	Calibration	Validation
R ² (Coefficient of determination)	0.90	0.85
NSE (Nash Sutcliffe Efficiency)	0.86	0.84
PBIAS (Percent of bias)	-7.4	-3.1

rainfall, crop water requirements (CWRs), and irrigation needs for the selected crops.

Reference evapotranspiration (ET_o) for the study area

To calculate the reference evapotranspiration (ET_o), the CROPWAT model uses data on solar radiation, maximum and minimum temperatures, relative humidity, sunshine duration, and wind speed. Generally, as the temperature, solar radiation, and wind speed increase, evapotranspiration also increases. According to the CROPWAT 8.0 calculations, the ET_o values for the watershed ranged from 3.32 mm/day to 5.48 mm/day, with the highest value occurring in April and the lowest in August. Higher evapotranspiration values correspond to increased evaporation, resulting in greater crop water requirements. Conversely, lower evapotranspiration values lead to reduced crop water demands. Therefore, crop water requirements are highest in April and lowest in August.

Crop water requirements for wheat

Wheat thrives in frost-free conditions, requiring cool temperatures during early growth for flowering and a dry period for ripening. The wheat growing season lasts 120 days, beginning on November 1st and ending on February 28th. The growth phases are divided into four stages: the initial

phase lasts 15 days, the development phase lasts 25 days, the midseason phase lasts 50 days, and the late season phase lasts 30 days.

The CWR for wheat varies at each growth stage and is influenced by the crop coefficient (K_c) and the duration of each phase. Water needs depend on factors such as climate, crop type, and soil characteristics. The highest water demand occurs between December and January during the midseason stage. In contrast, water requirements are lower during the initial and late-season phases, as the plants are smaller at the beginning and require less water toward the end of the growing season due to harvesting. The peak water demand coincides with the fruit formation stage, when the plants need more energy to produce fruit. The net irrigation water requirement for wheat throughout the growing season is 391 mm. Consequently, the gross irrigation water requirement for wheat during the entire growing season is 652 mm.

Crop water requirements for potato

The potato variety studied in the area, particularly the Belete crop, is well known. The growth cycle of potatoes, from planting to harvest, spans 110 days, beginning on November 1st and ending on February 18th. The growth phases of the potato crop commence in the early season and extend into the late season. The initial phase lasts for 25 days, followed by the development phase (30 days), the midseason phase (35 days), and the late season phase (20 days). The CWR, crop coefficients, and duration of each growth stage for potatoes vary depending on the soil type, climate, and crop characteristics. Significant water is required during the tuber formation process, as this stage demands more energy for tuber development. The net irrigation water requirement for

potatoes throughout the entire growing season is 352.8 mm. Consequently, the gross irrigation water requirement for potatoes during the growing period is 587.8 mm. January experiences a peak in irrigation water demand.

Crop water requirements for maize

Large-scale maize production can thrive in soils with less than 10% clay content (sandy soils) or more than 30% clay content (clay and clay-loam soils). Soil textures with clay contents between 10% and 30% provide optimal air and moisture conditions for healthy maize growth. The maize growth cycle consists of four phases: the initial phase, development phase, midseason phase, and late-season phase, which last 20, 35, 40, and 30 days, respectively. Like other crops, maize has varying CWRs, crop coefficients, and durations of each growth stage. The total water requirements are calculated for each stage and decade, with the highest crop water demand occurring in January. The lowest water demand is observed during the initial phase, as the maize plants are small and have minimal coverage, resulting in significant water loss through evaporation. As plants transition into the fruit-forming stage, water requirements increase due to the heightened energy demand for fruit development. As shown in Table 13, the net irrigation water

requirement for maize throughout the entire growing season is 364.5 mm, whereas the gross irrigation water requirement for the entire growing period is 607.4 mm.

Irrigation potential of the Ardy watershed

The irrigation potential of the Ardy watershed was evaluated by comparing the mean monthly flows available with the gross irrigation water requirements (GIR) for the land identified as suitable for surface irrigation. This analysis, which is based on the methodology proposed by (Yongliang et al. 2022; Devaux et al. 2021), revealed that in November, the GIR for all selected crops in subbasin 3 was lower than the corresponding mean monthly flows. However, in the other subbasins, the monthly GIR for the selected crops exceeded the available flows, as illustrated in Table 14. Specifically, the GIR for wheat, potato, and maize in subbasins 1 and 2 surpassed the available flow from December to February. This indicates that, with the exception of subbasin 3 in November, the existing water resources are insufficient to irrigate the entire irrigable land potential of the Ardy catchment. Consequently, critical command areas were calculated on the basis of (Dejene et al. 2024) for crop irrigation. According to Table 14, the minimum available flows in January for the subbasins were 0.187, 0.292, and 0.382 m³/s

Table 13 Gross monthly irrigation water requirements (Mm³) for three dominantly growing crops

Suitable land for surface irrigation (ha)	Crop type	Nov	Dec	Jan	Feb
21,509	Wheat	15.4	46.9	48.9	29.0
	Potato	14.0	39.2	45.4	27.9
	Maize	9.4	30.9	52.2	38.1

Table 14 Mean monthly simulated available flows and GIRs of suitable land for selected crops

No	Sub basins	Command area(ha)	Discharge(m ³ /s)	Mean monthly flow available in each sub basin and GIR for selected crops				
					Nov	Dec	Jan	Feb
1	Sub-Basin-1	6362	Available flow	Wheat	0.910	0.241	0.187	0.238
			GIR		1.760	5.357	5.581	3.310
2	Sub-Basin-2	13,360	Available flow		0.928	0.386	0.291	0.342
			GIR		3.696	11.249	11.721	6.951
3	Sub-Basin-3	1787	Available flow		1.192	0.593	0.382	0.400
			GIR		0.494	1.505	1.568	0.930
1	Sub-Basin-1	6362	Available flow	Potato	0.910	0.241	0.187	0.238
			GIR		1.597	4.469	5.176	3.180
2	Sub-Basin-2	13,360	Available flow		0.928	0.386	0.291	0.342
			GIR		3.354	9.385	10.870	6.677
3	Sub-Basin-3	1787	Available flow		1.192	0.593	0.382	0.400
			GIR		0.449	1.255	1.454	0.893
1	Sub-Basin-1	6362	Available flow	Maize	0.910	0.241	0.187	0.238
			GIR		1.068	3.529	5.960	4.351
2	Sub-Basin-2	13,360	Available flow		0.928	0.386	0.291	0.342
			GIR		2.242	7.410	12.516	9.137
3	Sub-Basin-3	1787	Available flow		1.192	0.593	0.382	0.400
			GIR		0.300	0.991	1.674	1.222

for the selected crops. Moreover, the gross irrigation water requirements for each subbasin were 0.0008772, 0.0008773, and 0.0008774 m³/s/ha for wheat; 0.000814, 0.0008136, and 0.00081365 m³/s/ha for potato; and 0.0009368, 0.0009368, and 0.00093677 m³/s/ha for maize. On the basis of these flows, the critical command areas that can be reliably irrigated with the minimum available flows in each subbasin were calculated to be 213 ha, 331.5 ha, and 435.5 ha (totaling 980 ha) for wheat; 230 ha, 357 ha, and 470 ha (totaling 1057 ha) for potato; and 199.64 ha, 310.36 ha, and 408 ha (totaling 918 ha) for maize.

Discussion

The surface irrigation suitability analysis for the Ardy watershed underscores the critical role of geographic and environmental factors in shaping surface irrigation-suitable lands. The integration of GIS and the AHP in this study provides a robust framework for evaluating areas suitable for surface irrigation, offering valuable insights for both scientific research and agricultural planning in the area. This study employs GIS-based MCDA to assess areas suitable for surface irrigation, leveraging AHP, a structured technique for weighting key parameters on the basis of their relative importance (Aniley 2025). This combined approach ensures scientifically rigorous and practically applicable surface irrigation suitable for land assessment (Worku et al. 2024). While previous studies have applied GIS and AHP separately or in combination, this research focuses on a streamlined selection of factors such as slope, soil, land use/land cover, and proximity to water sources tailored to the unique suitable land assessment of the Ardy watershed. This targeted approach enhances the model's precision, addressing gaps in localized suitable land for surface irrigation assessment.

The surface irrigation suitable land assessment factors identified in this study play critical roles in assessing the suitability of land for surface irrigation (Li and Chen 2020). The findings provide significant insights into the spatial distribution of suitable land for surface irrigation.

Among these factors, slope was identified as the most influential in the assessment of suitable land for surface irrigation. Low-gradient areas presented higher suitability ratings. The slope classes were categorized into four subgroups, with the dominant classes (0.0–2°) covering half of the study area (Hagos et al. 2022). This finding aligns with established hydrological principles where the slope gradient directly governs the surface runoff velocity and water accumulation potential. This large proportion of low-gradient zones highlights their increased suitability for surface irrigation, which is consistent with prior studies. The

identification of suitability factors for surface irrigation in the Ardy Watershed is consistent with established hydrological and geomorphological theories. These variables are widely recognized in the literature for their critical role in influencing factors for surface irrigation (Abawa et al. 2024; Bengal 2018; Beza 2024; Mamo et al. 2022). The dominant role of slope in our analysis corroborates previous flood vulnerability studies conducted in diverse geographical contexts (Al-Kindi and Alabri 2024; Ghanem and Zaifoglu 2024), confirming its universal importance in flood risk modeling. Steeper slopes facilitate rapid drainage, reducing flood risk, whereas flatter terrains promote water stagnation, exacerbating susceptibility (Abawa et al. 2024; Bengal 2018). This aligns with findings of (Beza 2024), where slope contributed more than 50% to flood risk in deltaic regions.

Soil depth is a critical factor in assessing land suitability for surface irrigation in the study area. The soil was categorized into two classes: 100–150 cm and <50 cm, which were highly to moderately suitable and not suitable, respectively. The soil depth suitability analysis revealed that approximately 74.5% of the total watershed area falls within the highly to moderately suitable categories, whereas the remaining 25.5% is deemed unsuitable for surface irrigation development. Overall, 25.5% of the entire study area was classified as unsuitable on the basis of soil depth analysis (Ozgur 2024). This underlines the importance of considering soil depth in suitable land assessments for surface irrigation, as areas with shallow depth are more suitable than areas with good soil depth.

Land use/land cover (LU/LC) is another crucial factor affecting the suitability of land for surface irrigation. Cultivated land was the most prevalent area, comprising 80.66% (17528.49 ha) of the total area, which is highly suitable. Dense shrubland/open forest, which accounts for 17.6% of the total area (3825.93 ha), is marginally suitable, and dense urban/woodland, which accounts for 1.74% (375.58 ha), is not suitable for surface irrigation development. These findings align with insights from various studies (Abawa et al. 2024; Bengal 2018; Beza 2024; Mamo et al. 2022).

The proximity to water sources (rivers) was analyzed via GIS-based three-dimensional layers to identify areas suitable for surface irrigation. To evaluate the impact of distance on land suitability, features were extracted and converted into raster format. These features were then reclassified into suitability categories. Euclidean distance analysis, detailing the suitability classifications and their corresponding area coverage. The proximity analysis revealed that 45.4% of the total area was classified as highly suitable, 31.3% as moderately suitable, 13.8% as marginally suitable, and 9.5% as not suitable. Overall, 90.5% (19,667 ha) of the study area was categorized as highly to marginally suitable for surface irrigation, whereas the remaining 9.5% (2,063 ha)

was deemed not suitable. These findings are consistent with those reported in (Abawa et al. 2024).

The overall suitability of land for surface irrigation via the combined effects of the assessed factors revealed that 99% of the study area was classified as highly to marginally suitable, with the majority being moderately suitable. These findings are consistent with various studies (Abawa et al. 2024; Bengal 2018; Beza 2024; Sebnie et al. 2020).

Conclusions and recommendations

The assessment of land suitability for surface irrigation was conducted via GIS, Arc SWAT, and CROPWAT 8.0 software. A multicriteria approach assigns influence weights of 47%, 28%, 17%, and 8% to slope, distance from the water source, soil, and land use/land cover, respectively. To estimate surface water potential, the Arc SWAT model, integrated with ArcGIS, was utilized to simulate streamflow.

The crop water requirements for the selected crops were calculated via the CROPWAT 8.0 model. Available streamflow data from Arc SWAT simulations were compared with the gross irrigation water requirements of the crops. This analysis identified potentially suitable irrigable areas within the watershed. During the months of December, January, and February, when the irrigation demand was high and the river flow was low, the gross irrigation demand for suitable land was greater than the amount of river water that was available.

The final assessment of land suitability in the watershed indicates that only a small portion of the land is highly suitable for surface irrigation, while the majority falls into the moderately suitable category. Therefore, it is crucial for policymakers and local communities to address specific land constraints and implement effective management strategies for sustainable use in the Ardy watershed. Marginally suitable land should be managed through advanced techniques to maximize its potential. Community engagement through awareness programmes is critical for empowering communities with knowledge. It is also important for the effective management of land and water resources for irrigation development. This study focused on land suitability and surface water availability for surface irrigation. However, further investigations into the suitability of alternative irrigation methods are necessary to explore additional irrigation development opportunities in the area. The land suitability assessment considered various factors, including slope, soil depth, soil texture, soil drainage, land use/land cover, and proximity to water sources. Future research could refine these findings by incorporating additional variables, such as land use/land cover and climate change projections, water quality, environmental impacts, groundwater resources, and

social considerations, as well as integrating machine learning models to ensure a comprehensive and reliable analysis.

The estimation of gross irrigation water requirements was based on three crops currently in demand in the area. Future research should encompass a broader selection of economically significant crops to better inform irrigation planning. Additionally, examining the surface irrigation potential of a watershed can provide valuable insights and serve as a reference for future studies in the region.

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Declarations

Conflict of interest The authors declare that there are no conflicts of interest.

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