ORIGINAL ARTICLE

Suitable dam site identification using GIS-based MCDA: a case study of Chemoga watershed, Ethiopia

Yonas Gebresilasie Hagos[1] · Tesfa Gebrie Andualem[2,3] (iD) · Mequanent Abathun Mengie[1] · Workineh Tadesse Ayele[2] · Demelash Ademe Malede[4,5]

Abstract

Ethiopia is Africa's second-most populous country, after Nigeria, and is primarily a farming community with low productivity that is heavily reliant on rain-fed agriculture. Water scarcity, global warming, and rising population all necessitate more effective water conservation methods. As a result, the demand for dams is increasing dramatically in order to provide the community with safe drinking water, electricity, and irrigation to ensure food security. The goal of this study was to use remote sensing and geographic information system (GIS) techniques in conjunction with the dam suitability stream model and multi-criteria decision analysis to identify potential sites for multi-purpose dam construction. The study used six influencing factors to find suitable dam sites, with the model's suitability stream and overall suitability output maps proposed and evaluated as a result. Based on the topography and land use, the results showed that three proposed dam sites in the upper part of the watershed are likely preferable for irrigation, fishery, and clean drinking water supply. The three proposed dam sites in the watershed's lower reaches, however, are better suited to hydropower generation. In addition, remote sensing and GIS are useful in dam/reservoir site selection because they allow decision-makers to create, manipulate, and manage relevant thematic layers.

Keywords Chemoga watershed · Dams sites selection · Dam suitability · MCDA · Stream model

Introduction

Water scarcity has been significantly increasing with urban development and its associated growing population with its ever-increasing demand because water is the basis of life and livelihoods since it supports the health of ecosystems and is the fundamental element for sustainable development (Guppy & Anderson 2017). Freshwater availability is likely to be one of the major societal challenges of the twenty-first century, according to new global goals and commitments such as the United Nations Millennium Development Goals Water Mandate (Gleick 2014). Due to unplanned urbanization, limited water resources, and ineffective regulations for managing water supply and distribution, developing countries are more vulnerable to water scarcity than developed countries. To address the scarcity of water resources, it is necessary to regulate runoff by building a dam and reservoir (Yuan & Su 1988).

Dams are built to store and safely retain large amounts of water, which is then released for a variety of purposes including irrigation, hydropower, recreation, water supply, flood protection, inland navigation, and so on (Yasser et al. 2013). Irrigation, hydropower, recreation, water supply, and other projects all require the selection of a dam site (Li 2019). The proper selection of dam sites is beneficial to ensuring project safety, reducing construction time, and lowering construction costs. As a result, early in the

✉ Tesfa Gebrie Andualem
  tesfag23@gmail.com

1   Irrigation, Drainage and Flood Control Sector, Ethiopian Construction Design and Supervision Works Corporation, Addis Ababa, Ethiopia

2   Department of Hydraulic and Water Resources Engineering, Debre Tabor University, Debre Tabor, Ethiopia

3   Mawson Lakes Campus, UniSA STEM, University of South Australia, Adelaide, Australia

4   Hydrology and Water Resources Management, Africa Center of Excellence for Water Management, Addis Ababa University, Addis Ababa, Ethiopia

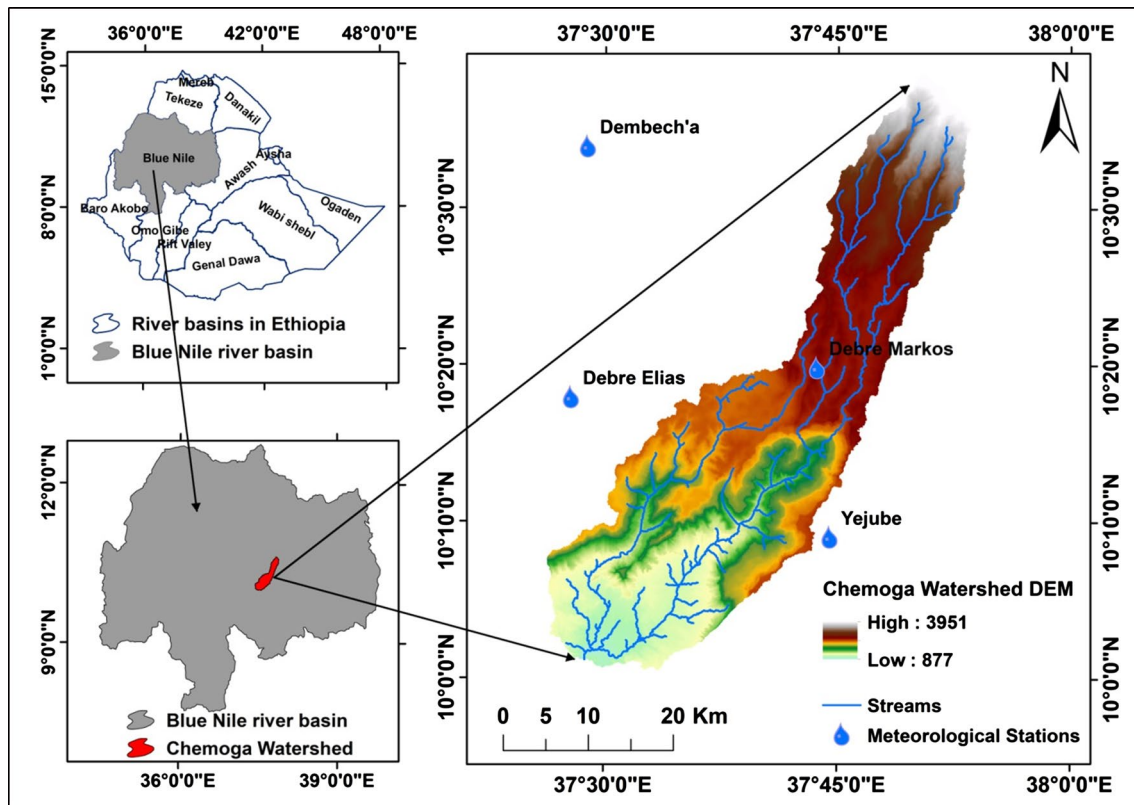5   Natural Resources Management Department, Debre Markos University, Debre Markos, Ethiopia

Fig. 1 Location of the study area

Table 1 Information of the data sources used in this study

Data type	Original format sources	Spatial resolution	Source of data
Rainfall data	Point	–	Ethiopian meteorological agency
DEM	Raster	12.5 m	https://search.asf.alaska.edu/
LULC data	Raster	10 m	https://livingatlas.arcgis.com/landcover/
Soil map	Vector	1:250,000	MoWR
Geological map	Vector	1:250,000	Geological survey of Ethiopia
Road network	Vector	–	http://geonode.wfp.org

construction process, selecting and evaluating various suitable dam sites are critical (Pan & Zhang 2021).

Ethiopia has many rivers, with a likely average of 1575 cubic meters of available water per capita per year among Sub-Saharan African countries. While there is plenty of water in the country, only 3% of water resources are accessible (Keredin & Prasada 2016). The dam suitability stream model (DSSM) and GIS-based MCDA techniques were used

Table 2 USDA-Soil conservation service (SCS) classification system, (1974); ERA (2013)

Hydrologic soil group (HSG)	Soil textures	Runoff potential	Infiltration rates
A	Sand, loamy sand or sandy loam	Low	High
B	Silt loam, or loam	Moderately low	Moderate
C	Sandy clay loam	Moderately high	Slow
D	Clay loam, silty clay loam, sandy clay, silty clay, or clay	High	Very slow

Table 3 Mean annual rainfall data for surrounding stations

Station	Location		Mean annual rainfall (mm) (1986–2018)
	Longitude	Latitude	
Debre Markos	37′ 43′ 44"	10′ 19′ 32"	1329.3
Dembech'a	37′ 28′ 47"	10′ 33′ 44"	1364.1
Debre Elias	37′ 27′ 54'	10′ 17′ 34"	1884.7
Yejube	37′ 44′ 37"	10′ 9′ 14"	1370.4

to generate the suitable dam/reservoir site map in this study. Chemoga watershed was one of the chosen watersheds, and it aids in the management and use of available water resources in order to alleviate water scarcity and increase agricultural productivity in the community through irrigation, clean drinking water, and other means. Many researchers use GIS-based MCDA to identify a suitable area to build a dam/reservoir in their areas of interest, such as topography, climate, hydrology, soils, agronomy, and socioeconomic factors (Luís & Cabra 2021; Nyirenda et al. 2021; Mohamed et al. 2021; Khudhair et al. 2020; Vikas & Tallavajhala 2020; Zhenfeng et al. 2020; Omid et al. 2019; Rami et al. 2019; Njiru & Siriba 2018; Faez &Abdul 2015; FAO 2003).

This study aimed to find suitable dam sites in the Chemoga watershed, in order to assist decision-makers in selecting the best location for a dam (s). This study assists water resource planners, designers, and decision-makers involved in dam building planning to reinforce their study or
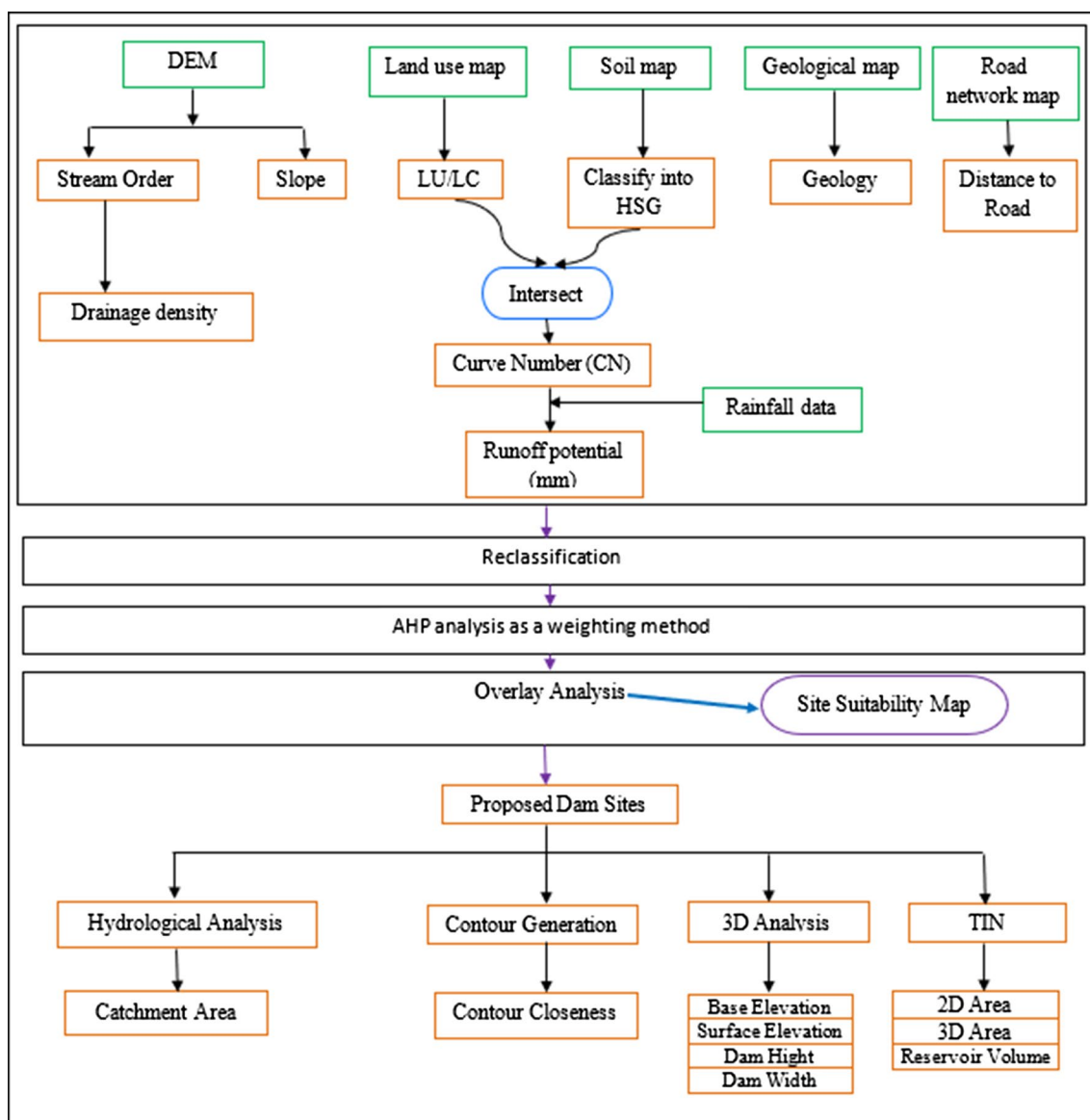

Fig. 2 Workflow of this study

emphasize their decision. Furthermore, it may prompt them to update their work in light of the proposed prospective dam locations in this study. Then, by using the methodology outlined below, suitable dam site maps were generated based on the selected influencing factors. Aside from that, this study proposed several dam sites with high suitability and computed their cross sections as well as some other parameters, such as dam height and width, reservoir volume, 2D surface area, 3D surface area, and catchment area.

Materials and methods

Description of the study area

The Chemoga watershed shown in Fig. 1 below covers an area of 1162.02 km² and found in the Amhara region, northwest Ethiopia, and geographically located between 10° 0′ 30″–10° 38′ 45″ N latitude and 37° 26′ 30″–37° 53′ 30″ E longitude. The river originates around Robe Gebeya town at an altitude of 3951 m above mean sea level with slope varies from almost flat to very steep and steadily decreases southwestwards to its confluence with the Blue Nile River at an altitude of 877 m a.m.s.l. The 33 years period (1986 to 2018) point rainfall data of four meteorological stations (Debre Markos, Dembech'a, Debre Elias, and Yejube) that are found within and around the watershed was collected from Ethiopian Metrology agency. As the data received were monthly rainfall, annual rainfall for each year at each station, and mean of 33 years for each station were calculated and then interpolated to inverse distance weight (IDW) in ArcGIS (Tables 1, 2, 3), the mean annual rainfall in the study region varied between 1329.3 mm in Debre Markos and 1884.7 mm in Debre Elias.

Data sources

For this study, data such as digital elevation model (DEM), hydrologic soil groups, rainfall, land use/cover, and geological data were collected. The digital elevation model (DEM) of 12.5 m resolution downloaded from https://search.asf.alaska.edu/ website is used for delineating the study watershed, generating slope and stream order maps. The land use/cover map was downloaded from https://livingatlas.arcgis.com/landcover/ with a 10 m resolution for the year 2020. The rainfall data for the surrounding four weather stations (Debre Markos, Dembecha, Debre Elias, and Yejube) for a period extending from 1986 to 2018 was collected from Ethiopian Meteorological Agency, whereas, the soil map and geological map of the study area were obtained from the Ethiopian Ministry of Water, Irrigation and Energy (MoWIE) and the Geological Survey of Ethiopia respectively.

Selection criteria and methodology

According to the Food and Agriculture Organization (FAO), six principal factors for selecting potential dam and reservoir zone were topography; climate; hydrology; soils; agronomy; and socioeconomics (FAO 2003). Therefore, six influencing thematic layers were used, such as stream order/drainage density, slope; Runoff potential; land use/cover, geology, and distance to the road. The method used in this study was GIS-based MCDA and dam suitability stream model (DSSM) is based on the stream order for identifying potential sites for

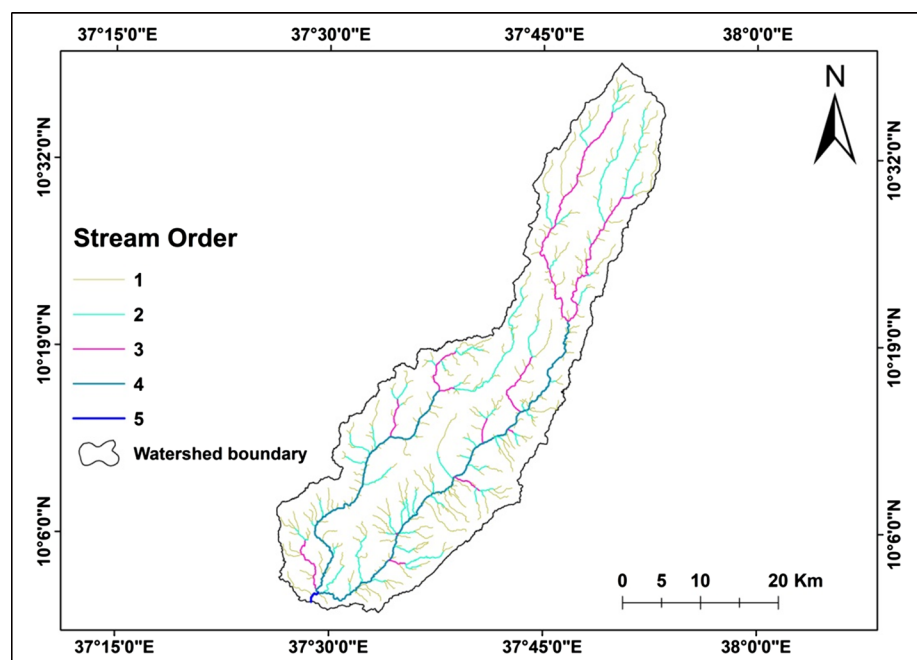**Fig. 3** Stream order map of the study area

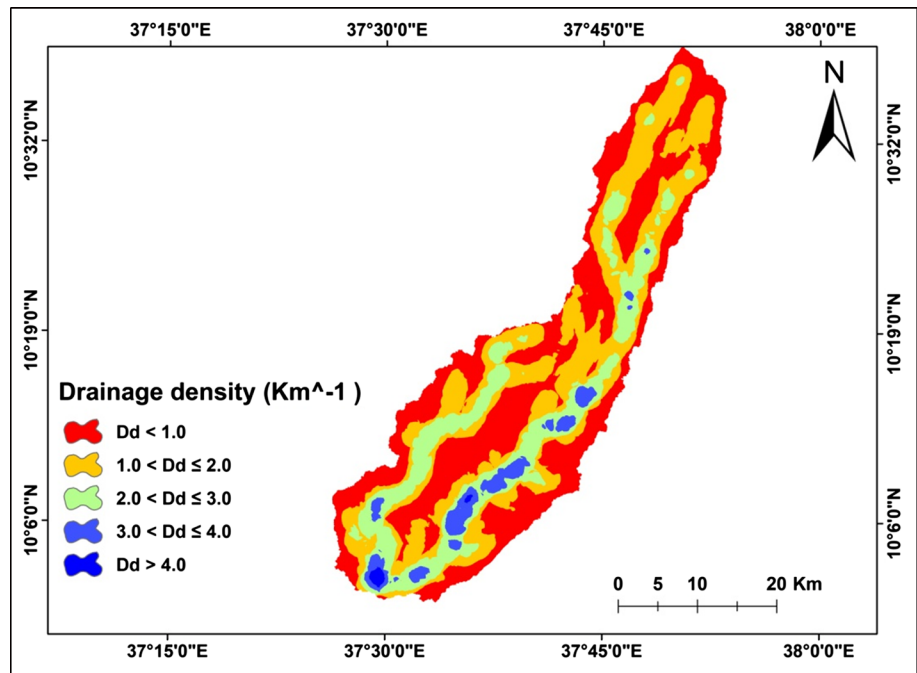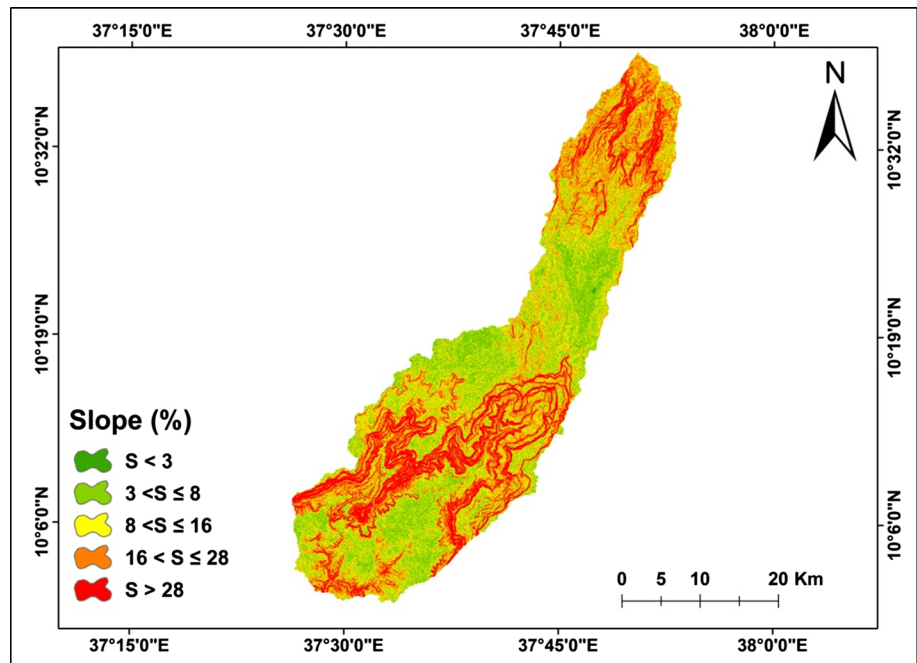**Fig. 4** Drainage density map of the study area

Fig. 5 Slope map of the study area

constructing a dam. The model follows five main steps as shown in (Fig. 2) below. First, selection and preparation of affecting factors in raster layer format; second, reclassification of the influencing factors; third, assigning weight for each influencing factor; fourth, overlay analysis in the ArcGIS platform; fifth, and finally, selecting and evaluating of dam site based on the dam evaluation parameters. The workflow steps of the study are discussed briefly below in Fig. 2.
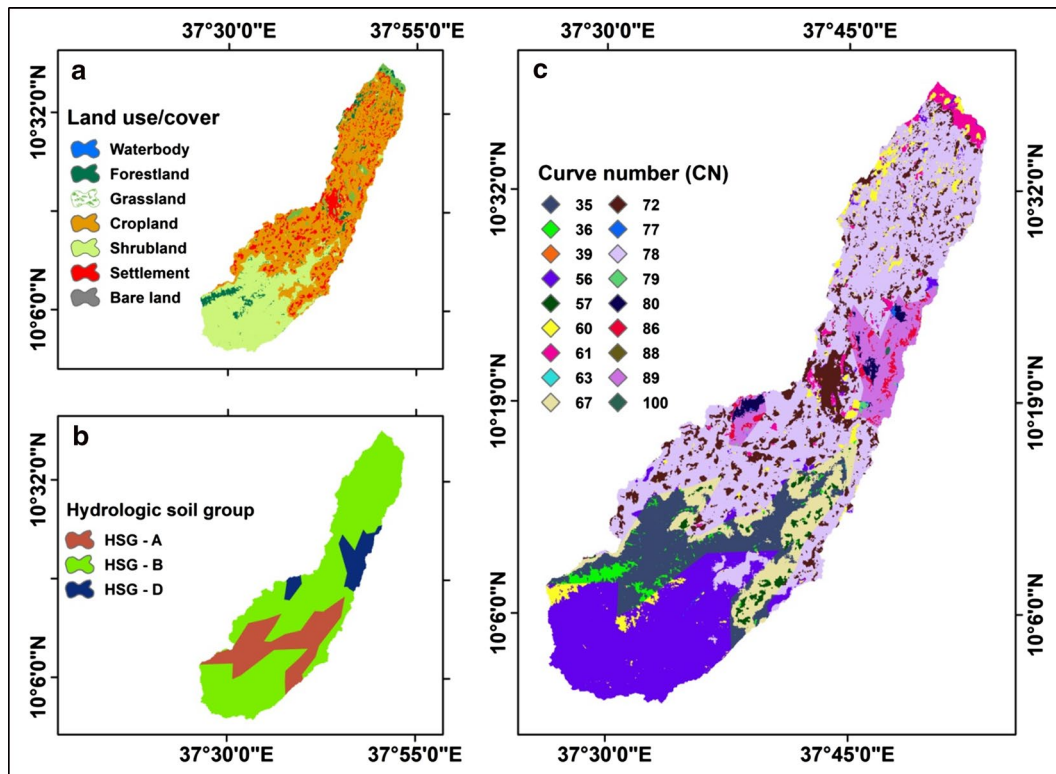
Fig. 6 **a** Land use/cover, **b** Hydrologic soil group, and **c** Curve number (CN) maps of the study area

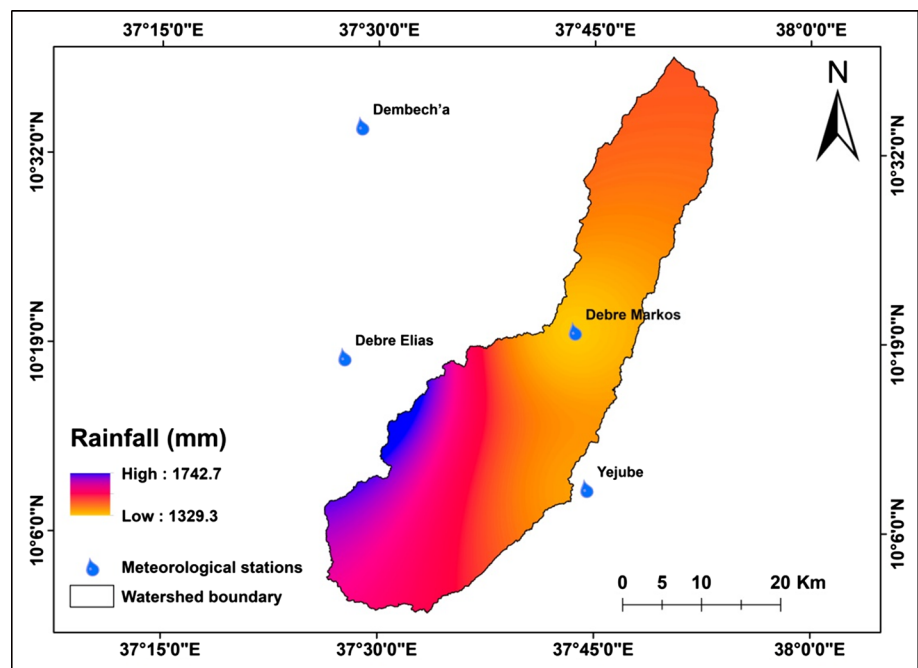**Fig. 7** Rainfall map of the study area

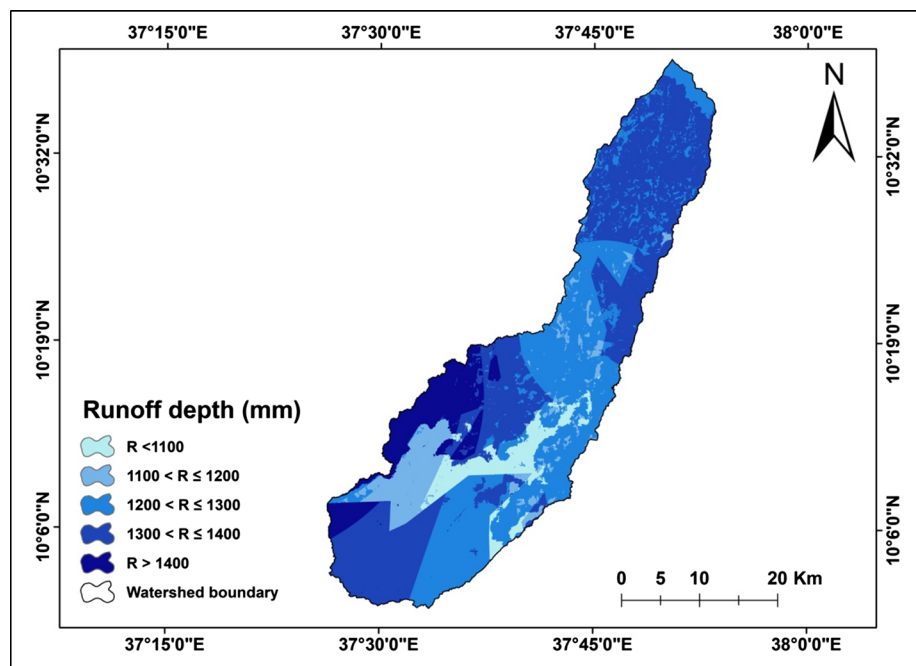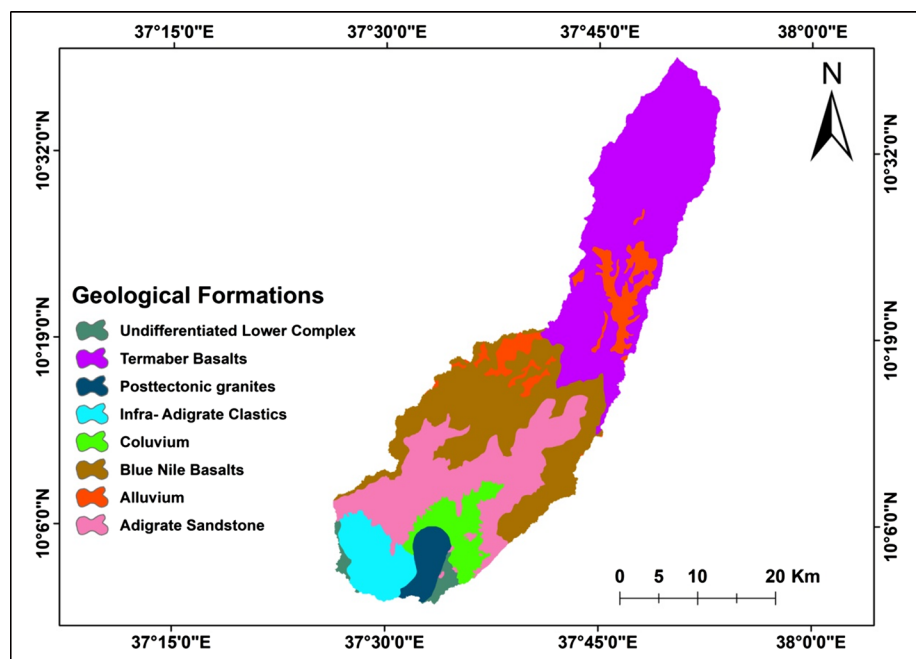**Fig. 8** Runoff depth map of the study area

Fig. 9 Geological formation map of the study area

Data analysis

Preparation and reclassification of factors

A watershed modeling approach was applied to delineate the Chemoga River watershed in the ArcGIS 10.3 platform by using the 12.5 m resolution DEM. The drainage density map of the study area was obtained from DEM data using hydrology tools under the ArcGIS spatial analyst tools. Then generate the drainage density map for this study area using line density tool in spatial analyst tools. Likewise, the slope map was prepared from DEM in the ArcGIS platform spatial analyst tools using slope sub tool under surface tools, and the slope's percentage was classified into five classes. In this study, the SCS-CN method, a commonly used method for estimating direct runoff from a watershed, was used to generate the runoff

depth map of the watershed (USDA 1972). The land use/ cover map for the study area is classified into six classes, including water bodies, grassland, Shrubland, Cropland, Forestland, and settlements. The distance to access roads was created by the Euclidean distance tool in ArcGIS. Each criterion's classification in a different class is based on expert opinions in the reclassification tool in ArcGIS (Engineers, Geologists, Hydrologists, and GIS experts) and literature (Zhenfeng et al. 2020; Ali et al. 2018; Njiru & Siriba 2018).

Stream order and drainage density

Different methods for quantitative stream order are suggested by many researchers. The most used ones are Strahler method (Strahler 1957) and Shreve method (Shreve 1966).

In both of these two methods, stream order is idealized as a tree with a strong root and slenderer branches.

According to the "top-down" system devised by Strahler, rivers of the first order are the outermost tributaries. If two rivers with different stream order merge, the resulting stream is given the higher of the two numbers (Strahler 1957). The Shreve method also gives the outermost tributaries the number "1". Unlike the Strahler method, at a confluence, the two numbers are added together (Shreve 1966). In this study, the Strahler method of quantifying stream order is used (Fig. 3). Then as the suitable dam site selection viewpoint, stream first order is highly suitable for constructing a dam and vice versa.

Drainage density is defined as the total length of the channel in a drainage basin divided by the watershed area (Horton 1932) and represented by the following equation:

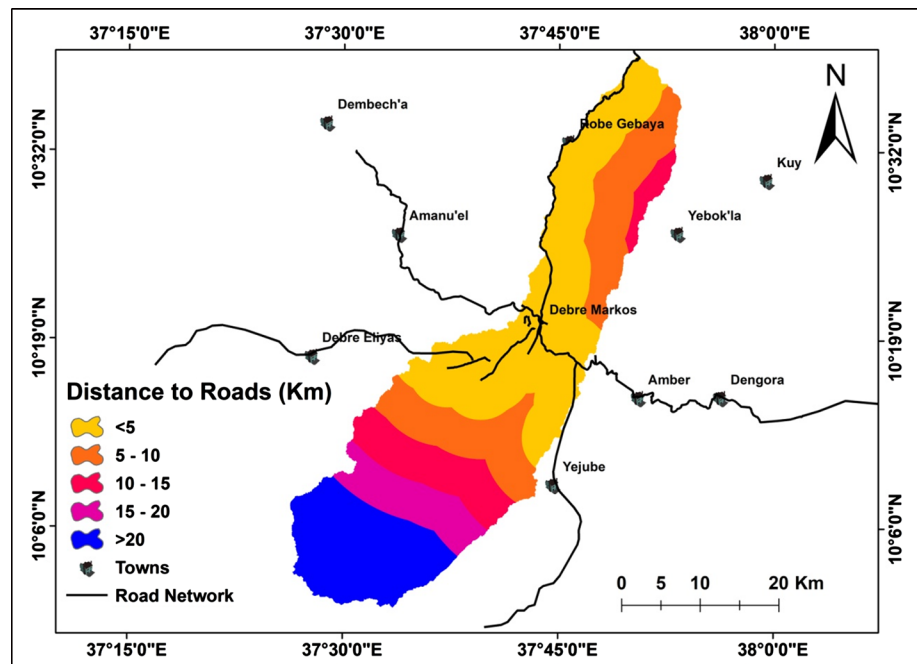**Fig. 10** Distance from road network map of the study area

Table 4 Saaty's scale of relative importance (Saaty, 1980; Saaty and Vargas 1991)

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderately importance	Experience and judgment slightly favor one activity over another
5	Strongly more important/much more important	Experience and judgment strongly favor one activity over another
7	Very strongly/far more important	Demonstrated importance an activity is strongly favored and its dominance demonstrated in practice
9	Extremely more important	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed
Reciprocals	Values for inverse comparison	

Table 5 Pairwise comparison of seven criterion matrix (Saaty, 1980; Saaty and Vargas 1991)

Factor	Stream order	Slope	Runoff potential (mm)	Land use	Geology	Distance to road
Stream Order	1					
Slope	1/2	1				
Runoff potential (mm)	1/3	1/2	1			
Land use	1/5	1/4	1/3	1		
Geology	1/7	1/6	1/5	1/3	1	
Distance to road	1/9	1/8	1/5	1/5	1/3	1

Table 6 Pairwise comparison of seven criterion decimal matrix (Saaty, 1980; Saaty and Vargas 1991)

Factor	Stream order	Slope	Runoff potential (mm)	Land use	Geology	Distance to road
Stream order	1.00	2.00	3.00	5.00	7.00	9.00
Slope	0.50	1.00	2.00	4.00	6.00	8.00
Runoff potential (mm)	0.33	0.50	1.00	3.00	5.00	7.00
Land use	0.20	0.25	0.33	1.00	3.00	5.00
Geology	0.14	0.17	0.20	0.33	1.00	3.00
Distance to road	0.11	0.13	0.14	0.20	0.33	1.00
Sum	2.29	4.04	6.68	13.53	22.33	33.00

Table 7 Normalized pairwise matrix calculated

Factor	Stream order	Slope	Runoff potential (mm)	Land use	Geology	Distance to road
Stream order	0.44	0.49	0.45	0.37	0.31	0.27
Slope	0.22	0.25	0.30	0.30	0.27	0.24
Runoff potential (mm)	0.15	0.12	0.15	0.22	0.22	0.21
Land use	0.09	0.06	0.05	0.07	0.13	0.15
Geology	0.06	0.04	0.03	0.02	0.04	0.09
Distance to road	0.05	0.03	0.02	0.01	0.01	0.03

Table 8 Determined relative criterion weights

Factor	Stream order	Slope	Runoff potential (mm)	Land use	Geology	Distance to road	Criteria weight
Stream order	0.44	0.49	0.45	0.37	0.31	0.27	0.39
Slope	0.22	0.25	0.30	0.30	0.27	0.24	0.26
Runoff potential (mm)	0.15	0.12	0.15	0.22	0.22	0.21	0.18
Land use	0.09	0.06	0.05	0.07	0.13	0.15	0.09
Geology	0.06	0.04	0.03	0.02	0.04	0.09	0.05
Distance to road	0.05	0.03	0.02	0.01	0.01	0.03	0.03

$$D_d = \frac{\sum_{i=1}^{n} L}{A_{basin}}$$

(1)

where D_d is the drainage density, n is the number of streams, L is the stream length (km), and A is the drainage basin (km).

The drainage density map is generated from digital elevation model (DEM). The range of drainage density map in the

Table 9 The Eigenvector weights of each flood factor obtained after the pairwise comparison

Factor	Normalized weight	Influence (%)
Stream order	0.39	39.0
Slope	0.26	26.2
Runoff potential (mm)	0.18	17.9
Land use	0.09	9.3
Geology	0.05	4.9
Distance to road	0.03	2.7
Sum	1.00	100

Chemoga watershed varies from 0 to 4.95 km^{-1} as shown in Fig. 4. The developed drainage density map was grouped into five intervals according to their importance for dam site suitability. These intervals are as follows: extremely suitable ($D_d > 4$) and it covers 0.3% area of the study area; very suitable ($3 < D_d \leq 4$) and it covers 4.5% area of the study area; Adapted ($2 < D_d \leq 3$) and it covers 18.0% area of the study area; Less suitable ($1 < D_d \leq 2$) and it covers 34.3% area of the study area; Unsuitable ($D_d < 1$) and it covers 42.9% area of the study area.

Slope (S)

The slope of an area is the main factor to select a suitable dam site, and it significantly affects the runoff, recharge, and movement of surface water as well as the amount of sedimentation (Adham et al. 2016; Kadam et al. 2012). A slope

map was generated using the slope tool under the surface group in the ArcGIS platform using 12.5 m resolution DEM.

As shown in Fig. 5 below, the range of slope in the Chemoga watershed varies from 0 to 513.4%. It is classified into five intervals: almost flat ($S < 3$) and it covers 4.0% area of the study area; gentle ($3 < S \leq 8$) and it covers 24.8% area of the study area; moderate ($8 < S \leq 16$) and it covers 29.9% area of the study area; steep ($16 < S \leq 28$) and it covers 22.5% area of the study area; very steep ($S > 28$) and it covers 18.8% area of the study area (Mohamed et al. 2021).

Rainfall-runoff modeling (SCS-CN)

The SCS-CN method has been established in 1954 by USDA SCS (Rallison 1980), defined in the Soil Conservation Service (SCS) by the National Engineering Handbook (NEH-4) Section of Hydrology to estimate surface runoff (Ponce & Hawkins 1996).

The Soil Conservation Service Curve Number approach is frequently used empirical methods to estimate the direct runoff from a watershed (USDA 1972) in the study area. The infiltration losses are combined with surface storage by the relation of:

$$Q = \frac{P - I_a^2}{(P - I_a) + S} \tag{2}$$

where Q = accumulated direct runoff (mm), P = accumulated rainfall (potential maximum runoff) (mm), I_a = initial abstraction including surface storage, interception, and

Table 10 Random inconsistency indices

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.46	1.49

Table 11 Determined consistency ratios (CR)

Factor	Stream order	Slope	Runoff potential	Land use	Geology	Distance to road	Weighted sum value	Criteria weight	Consistency measure
Stream order	0.44	0.49	0.45	0.37	0.31	0.27	2.34	0.39	6.42
Slope	0.22	0.25	0.30	0.30	0.27	0.24	1.57	0.26	6.48
Runoff potential	0.15	0.12	0.15	0.22	0.22	0.21	1.08	0.18	6.42
Land use	0.09	0.06	0.05	0.07	0.13	0.15	0.56	0.09	6.20
Geology	0.06	0.04	0.03	0.02	0.04	0.09	0.29	0.05	6.04
Distance to road	0.05	0.03	0.02	0.01	0.01	0.03	0.16	0.03	6.09
Total	1.00	1.00	1.00	1.00	1.00	1.00		CI	0.06
								RI	1.24
								CR	0.04
								CR < 0.1	
								Consistency is acceptable	

Table 12 Weights of the thematic layers and runoff map with their assigned weights

S. No	Factor	Features	Local weight	Average weights
1	Stream order	1st order	3.5	39.0
		2nd order	6.9	
		3rd order	13.6	
		4th order	28.6	
		5th order	47.4	
	Drainage density (km/km^2)	$D_d < 1$	3.5	
		$1 < D_d \leq 2$	6.8	
		$2 < D_d \leq 3$	13.4	
		$3 < D_d \leq 4$	26.0	
		$D_d > 4$	50.3	
2	Slope (%)	$S < 3$	50.3	26.2
		$3 < S \leq 8$	26.0	
		$8 < S \leq 16$	13.4	
		$16 < S \leq 28$	6.8	
		$S > 28$	3.5	
3	Runoff potential (mm)	$R > 1400$	41.8	17.9
		$1400 \geq R > 1300$	26.4	
		$1300 \geq R > 1200$	16.5	
		$1200 \geq R > 1100$	10.4	
		$R < 1100$	4.9	
4	Land use/landcover	Barren land	35.1	9.3
		Grassland	23.9	
		Shrubland	16.2	
		Cropland	11.0	
		water bodies	7.6	
		Forestland	4.0	
		Settlement	2.3	
5	Geology	Termaber basalts	31.6	4.9
		Blue Nile basalts	26.4	
		Post-tectonic granites	14.6	
		Undifferentiated lower complex	10.1	
		Adigrate sandstone	7.0	
		Infra-adigrate clastics	4.7	
		Colluvium	3.2	
		Alluvium	2.3	
6	Distant to roads (Km)	< 5	41.6	2.7
		$5 < S \leq 10$	26.2	
		$10 < S \leq 15$	16.1	
		$15 < S \leq 20$	9.9	
		> 20	6.2	

infiltration prior to runoff (mm), and S = potential maximum retention (mm).

The relationship between I_a and S was developed from experimental catchment area data. It removes the necessity for estimating I_a for common usage. The empirical relationship used in the SCS runoff equation is as follows:

$$I_a = 0.2S \tag{3}$$

Substituting 0.2S for I_a in Eq. 5, the SCS rainfall-runoff equation becomes:

$$Q = \frac{(P - 0.2S)^2}{(P - 0.8S)} \tag{4}$$

S is related to the soil and cover conditions of the catchment area through the CN. CN has a range of 0–100, and S is related to CN by:

Table 13 Evaluation and essential parameters of the proposed dam sites

Parameters/proposed dams		Dam-1	Dam-2	Dam-3	Dam-4	Dam-5	Dam-6
Location	Longitude	363,221.05	349,405.30	348,241.29	333,927.34	343,980.52	337,751.36
	Latitude	1,154,248.30	1,136,062.56	1,121,416.40	1,117,505.25	1,114,987.87	1,108,565.20
	Stream order	3rd order	3rd order	4th order	4th order	4th order	4th order
Dam evaluation parameters	Base elevation (m)	2432	2186	1243	1156	1147	992
	Surface elevation (m)	2440	2200	1280	1220	1160	1040
	Dam height (m)	8	14	37	64	13	48
	Dam width (m)	245	186	875	344	173	187
	2D Surface area(m^2)	519,910	610,038	2,318,042	1,304,522	319,000	2,228,951
	3D Surface area (m^2)	522,441	612,292	2,328,583	1,359,061	321,124	2,266,706
	Max volume (m^3)	2,051,451	2,153,478	28,598,758	31,476,566	1,677,221	29,213,232
Catchment area (ha)		12,885	4384	63,620	28,562	71,788	80,394
Land Use coverage at full reservoir condition (ha)	Barren land	0.0	0.0	0.0	0.0	1.9	0.0
	Grassland	5.0	13.7	0.0	0.0	0.0	0.0
	Shrubland	0.0	0.0	40.8	99.3	98.1	99.0
	Cropland	95.0	82.6	56.5	0.0	0.0	0.0
	water bodies	0.0	0.0	0.0	0.0	0.0	0.1
	Forestland	0.0	0.4	2.7	0.7	0.0	0.9
	Settlement	0.0	3.3	0.0	0.0	0.0	0.0
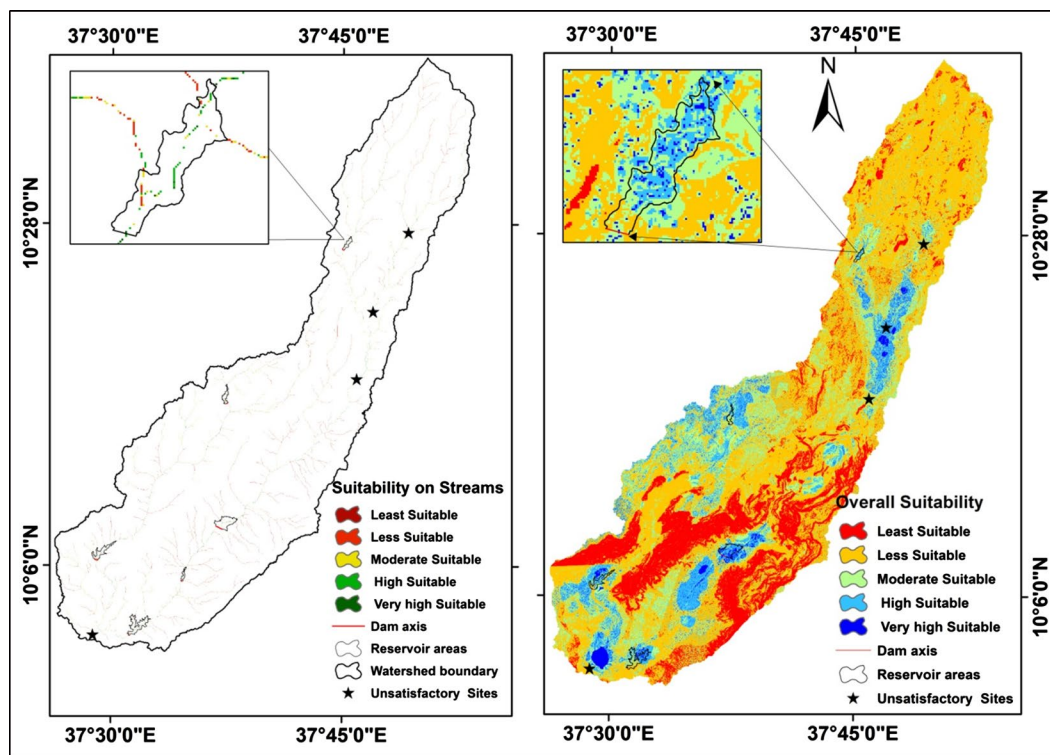
Fig. 11 Proposed dam sites (left) dam sites with suitability on stream (right) dam sites with overall suitability

$$S = \left(\frac{25400}{CN}\right) - 254 \tag{5}$$

Hydrological soil groups (HSG)

The USDA-Soil Conservation Service has developed four types of hydrologic soil groups based on infiltration rates namely A, B, C, and D in the soil classification system. The detailed description of the four hydrologic soil groups based on infiltration rate, texture, and runoff potential is discussed as follows in (Table 2).

The Hydrological Soil Groups (HSG) map of the study area was obtained from the Ethiopian Ministry of water resources (MoWR) and processed by ArcGIS to convert the vector data to raster. Three hydrological soil groups (Fig. 6b) have been found in the present study of Chemoga watershed HSG—A and it covers 20.3% area of the study area; HSG—B and it covers 72.5% area of the study area and HSG—D and it covers 7.3% area of the study area.

Curve number (CN)

The CN (a dimensionless number ranging from 0 to 100) is determined based on the hydrologic soil group and land cover of the specific watershed. In the present research work of Chemoga watershed, the CN values have been estimated based on LULC classes of hydrologic soil groups A, B, C, and D, and the CN ranges vary between 35 and 100 (Fig. 6c).

Rainfall analysis

For a rainfall-runoff factor, point rainfall data for 33 years (1986–2018) were collected from four stations (Debre Markos, Dembech'a, Debre Elias, and Yejube) within and around the watershed were received from the Ethiopian Metrology agency. As the data received were monthly rainfall, annual rainfall for each year at each station, and mean of 33 years for each station were calculated and then interpolated to inverse distance weight (IDW) in ArcGIS.
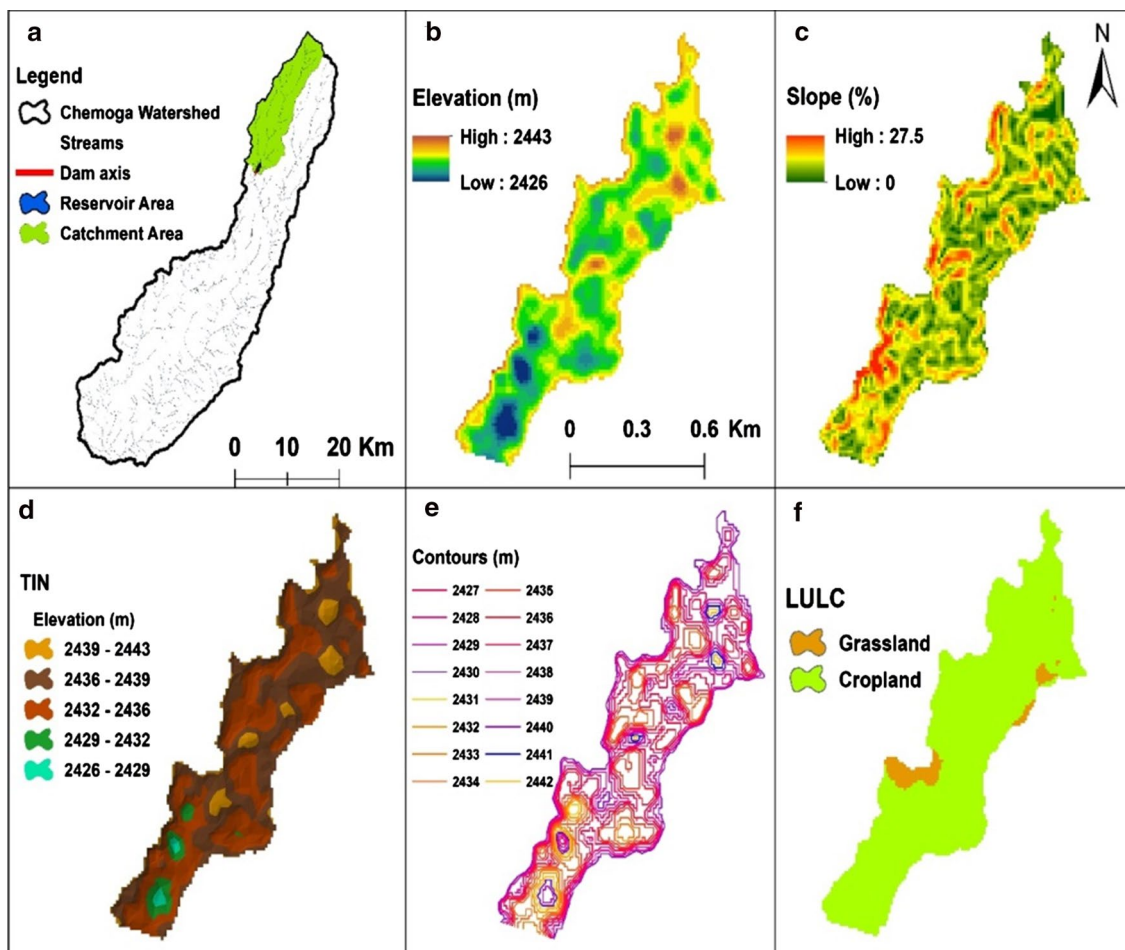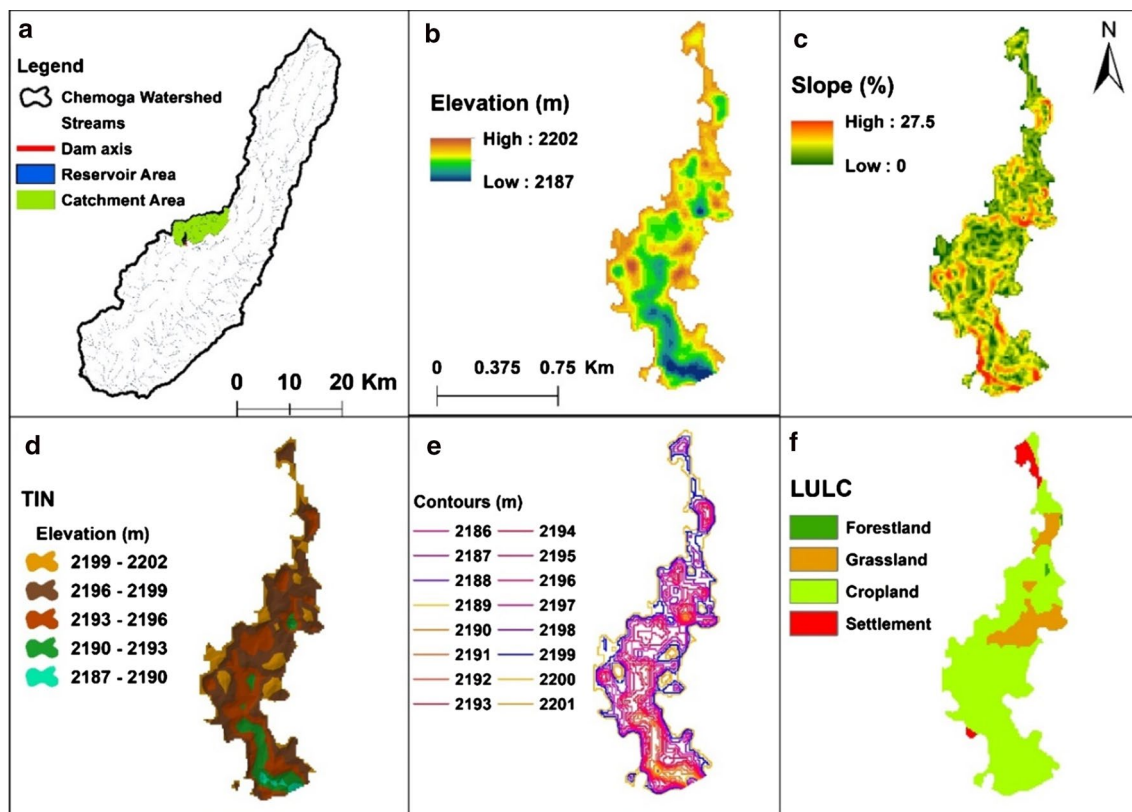

Fig. 12 Evaluation parameters for proposed Dam site 1: **a** Catchment area **b** DEM **c** slope **d** triangulated irregular network (TIN), **e** contours, **f** LULC

Fig. 13 3D view and cross section of proposed dam site-1
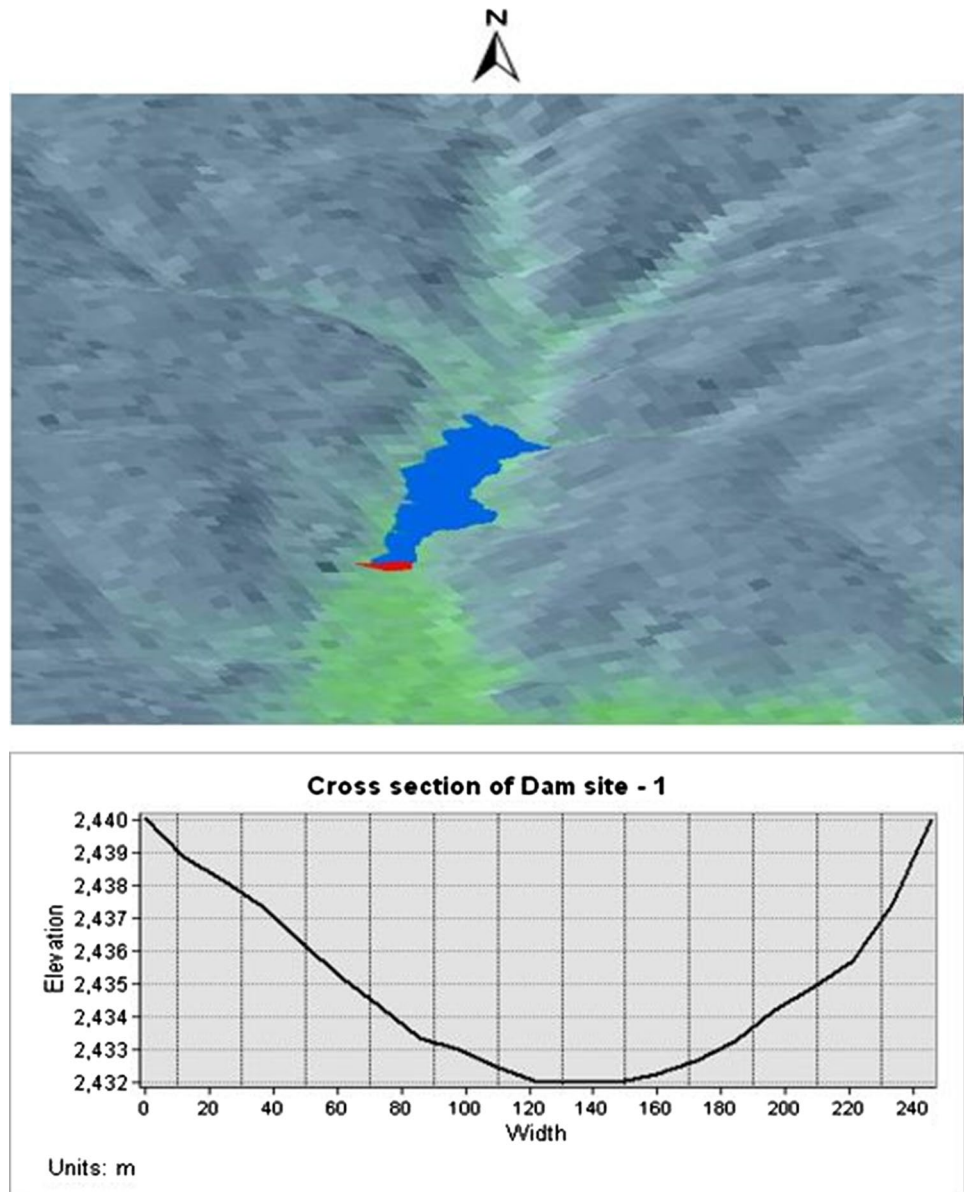
Estimation of rainfall-runoff

The average annual surface runoff depth was determined by using the SCS-CN method. It has revealed from the last thirty-three years of rainfall data of four stations within and around the watershed. The mean annual rainfall varies between 1329.3 (Debre Markos station) and 1783.8 mm (Debre Elias station). By using Eqs. 6 of the SCS-CN method, it is estimated that the runoff rate varies between 927 and 1,400 mm (Fig. 7). The runoff depth map of the study area was classified into five classes: these were $R > 1400$ mm, which covers 9.4% of the study area, 1400 mm $\geq R > 1300$ mm, which covers 42.2% of the study area, 1300 mm $\geq R > 1200$ mm that covers 34.2% of the study area,
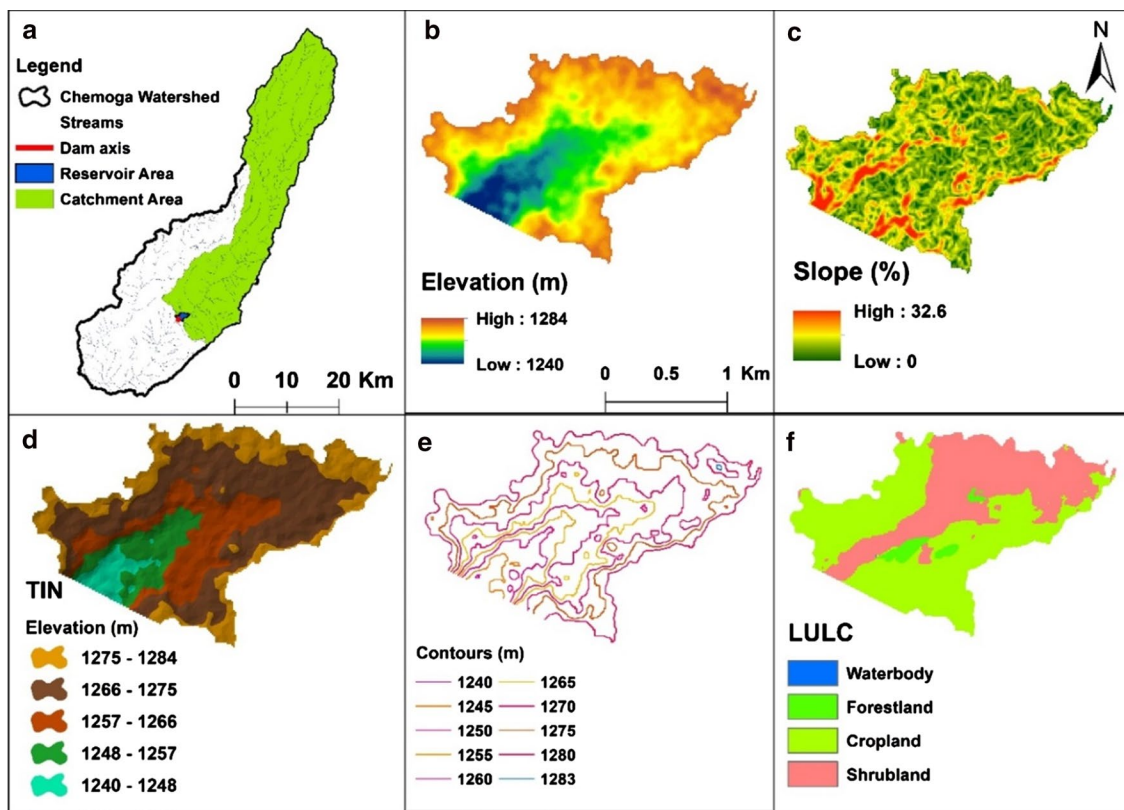
Fig. 14 Evaluation parameters for proposed Dam site 2: **a** Catchment area, **b** DEM, **c** slope, **d** triangulated irregular network (TIN), **e** contours, **f** LULC

1200 mm ≥ R > 1100 mm covering 8.3% of the study area, and R < 1100 covering 5.9% of the study area (Fig. 8).

Land use/land cover

Land use is an essential feature in surface runoff generation (Jha et al. 2014). Land use/cover of an area has an extreme impact on runoff velocity, infiltration process, evapotranspiration, and these processes have been played a vital role in the delineation of a suitable zone for the dam site. The land use land cover map of the Chemoga watershed shown in (Fig. 6a) expresses that there are seven major types of land use/cover namely, Barren land (0.04%); Grassland (2.65%); Shrubland (31.94%); Cropland (50.01%); water body (0.05%); Forestland (4.55%) and Settlement (10.76%) with their area coverage. Consequently, the most promising

land use/ land cover type for dam and reservoir sites were barren lands, grassland, and shrubland covers 41,004.6 ha (34.6%) of the total study area.

Geology

The geological character and rock type within a specific region affect the permeability of the dam which includes the capability of holding water for the dam (Marinos et al. 1997). Foundations are better on igneous rocks and hard metamorphic rocks like granite, gneiss, quartzite, etc. The geological features of the Chemoga watershed were collected from the Geological Survey of Ethiopia.

In this study, geological features have been identified into eight units, such as Termaber Basalts, Blue Nile Basalts, Adigrate Sandstone, Alluvium, Infra-Adigrate Classics,

Fig. 15 3D view and cross section of proposed dam site-2
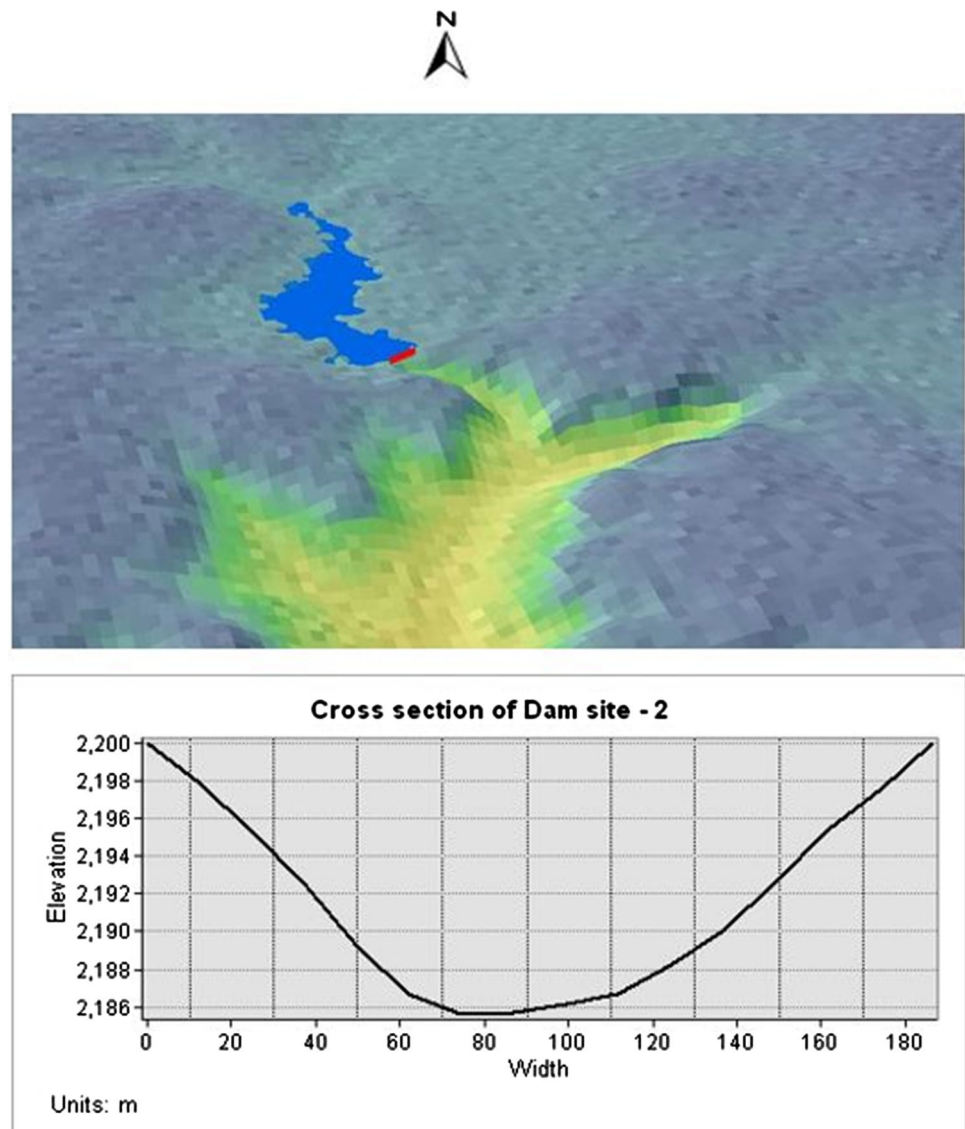
Colluvium, post-tectonic granites, Undifferentiated Lower Complex, and it was shown in Fig. 9. In the study area, we have been found that Termaber Basalts spreads maximum area and it was about 34.7% of the total area. Other features such as Blue Nile Basalts covers 23.4%; Adigrate Sandstone covers 20.2%; Alluvium covers 6.4%; Infra-Adigrate Classics covers 6.1%; Colluvium covers 5.0%; post-tectonic granites cover 3.0%, and Undifferentiated Lower Complex covers 1.3% of the total area.

Distance to the roads

The distance to the road network and rail is an essential factor for selecting a suitable dam site as it is one of the influencing socioeconomic criteria for site selection. It is assumed that sites located far from the road networks were unsuitable for dam construction because it costs a large amount of money to construct access roads and influence
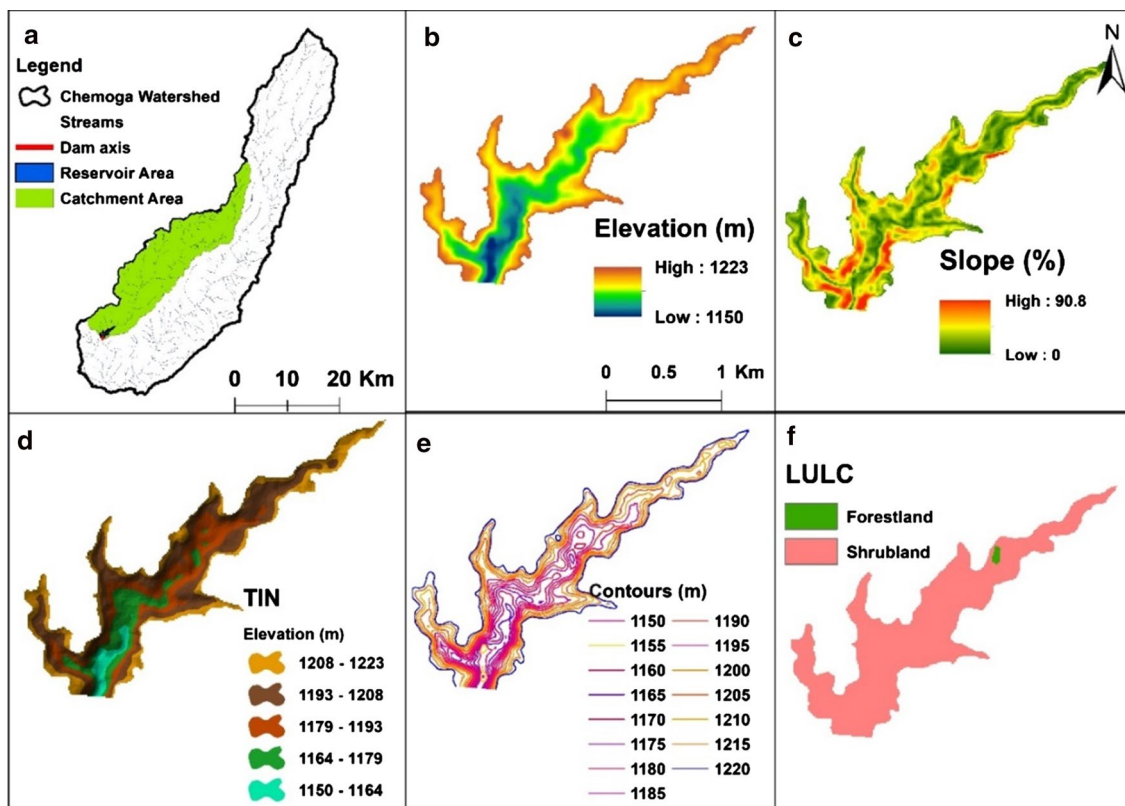
Fig. 16 Evaluation parameters for proposed Dam site 3: **a** Catchment area, **b** DEM, **c** slope, **d** triangulated irregular network (TIN), **e** contours, **f** LULC

the management process and vice versa (Njiru & Siriba 2018; Dorfeshan et al. 2014). A road network map for the study area was collected from http://geonode.wfp.org prepared for Humanitarian access by the United Nations Office for Humanitarian Affairs (OCHA). The distance from the road map of the study area has been classified into five classes: these were < 5 km and it covers 38.8% area of the study area, 5 to 10 km and it covers 22.7% area of the study area, 10 to 15 km and it covers 11.8% area of the study area, 15 to 20 km and it covers 8.2% area of the study area, > 20 km covers 18.5% area of the study area as shown in (Fig. 10).

Analytic hierarchy process (AHP) methodology

AHP is the most popular MCDM method for determining the weight of criteria or factors. In AHP, construct judgment matrices to allocate weights (Tables 4, 5, 6, 7, 8, 9, 10, 11) and the thematic layers of each level/criterion class, and measure their relative importance using Saaty's s 1–9 scale. Weights were assigned to each factor class to express the importance or preference of each factor class relative to the other factor classes in generating suitable dam sites. This was done using related review literature, field observation, and expert judgment to fill out a pairwise comparison matrix from which Eigenvectors and consistency ratios were generated for each of the criteria being considered. The factors for choosing a suitable dam site are rated on a scale of 1 to 9, with 1 indicating equal importance and 9 indicating one factor is more important than the other. One is less important than the other when the reciprocal of 1 to 9 (1/1 and 1/9) is used (Saaty 1980; Saaty & Vargas 1991). The basic steps to determine the

Fig. 17 3D view and cross section of proposed dam site-3
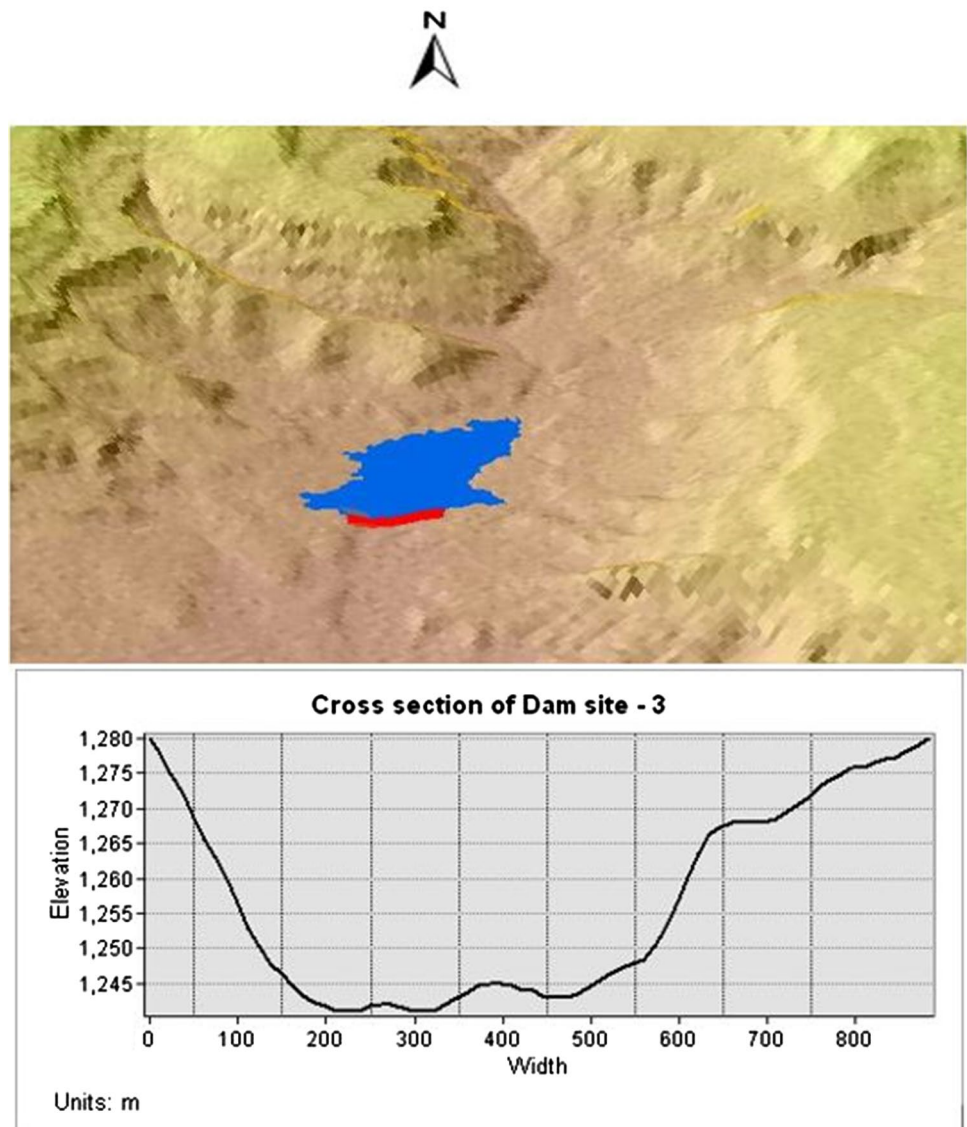
indicator's weight and consistency ratio (CR) were finalized on the assignment of weights to different criteria.

Step 1. Establishment of judgment matrices (*P*) by pairwise comparison.

$$P = \begin{pmatrix} P_{11} & P_{12} & \cdots & P_{1n} \\ P_{21} & P_{22} & \cdots & P_{2n} \\ \vdots & \cdots & \ddots & \vdots \\ P_{n1} & P_{n2} & \cdots & P_{mn} \end{pmatrix} \quad (6)$$

where *n* denotes the *n*th row and *m* denotes the *m*th column elements of the judgment matrix.

Step 2. Calculation of normalized weight.

This step is to normalize the matrix by totaling the numbers in each column. Each entry in the column is then divided by the column sum to yield its normalized score. The sum of each column is 1.

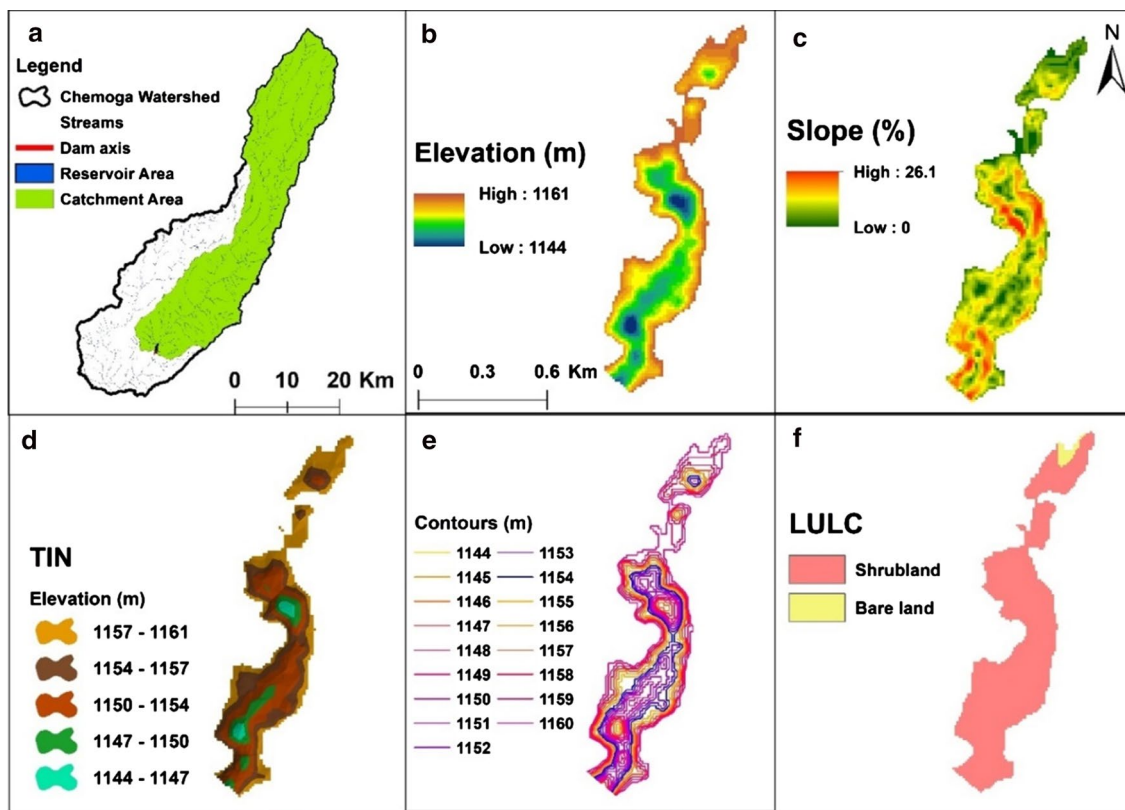$$W_n = \left(GM_n \Big/ \sum\nolimits_{n=1}^{ni} GM_n \right) \quad (7)$$

Fig. 18 Evaluation parameters for proposed Dam site 4: **a** Catchment area, **b** DEM, **c** slope, **d** triangulated irregular network (TIN), **e** contours, **f** LULC

where the geometric mean of the *i*th row of the judgment matrices is calculated as:

$$GM_n = \sqrt[ni]{P_{1n}P_{2n}LP_{mn_i}} \tag{8}$$

Step 3. Calculates a consistency ratio (CR) to verify the coherence of the judgments. Now, calculate the consistency ratio and check its value. The purpose of doing this is to make sure that the original preference ratings were consistent.

$$CR = \frac{CI}{RI} \tag{9}$$

Consistency index (CI) is denoted as follows:

$$CI = \frac{\lambda_{max} - n_i}{n_i - 1} \tag{10}$$

Max is the eigenvalue of the judgment matrix and it is calculated as:

$$\lambda_{max} = \sum_{n=1}^{n_i} \frac{(PW)_n}{n_i w_n} \tag{11}$$

where *W* is the weight vector (column). Random index (RI) can be obtained from standard tables (Saaty 1980). In practice, a CR of 0.1 or below is considered acceptable. Any higher value at any level indicates that the judgments warrant re-examination.

Weight values were assigned for each factor and their future classes based on their influence in selecting suitable dam sites, with the most important factor receiving the highest weight and vice versa (Tables 12, 13). Order/drainage density is the most important factor in this study stream, with a weight of 39%, followed by slope, runoff potential, land use, geology, and distance to the road, with weights of 26.2, 17.9, 9.3, 4.9, and 2.7%, respectively.

Fig. 19 3D view and cross section of proposed dam site-4
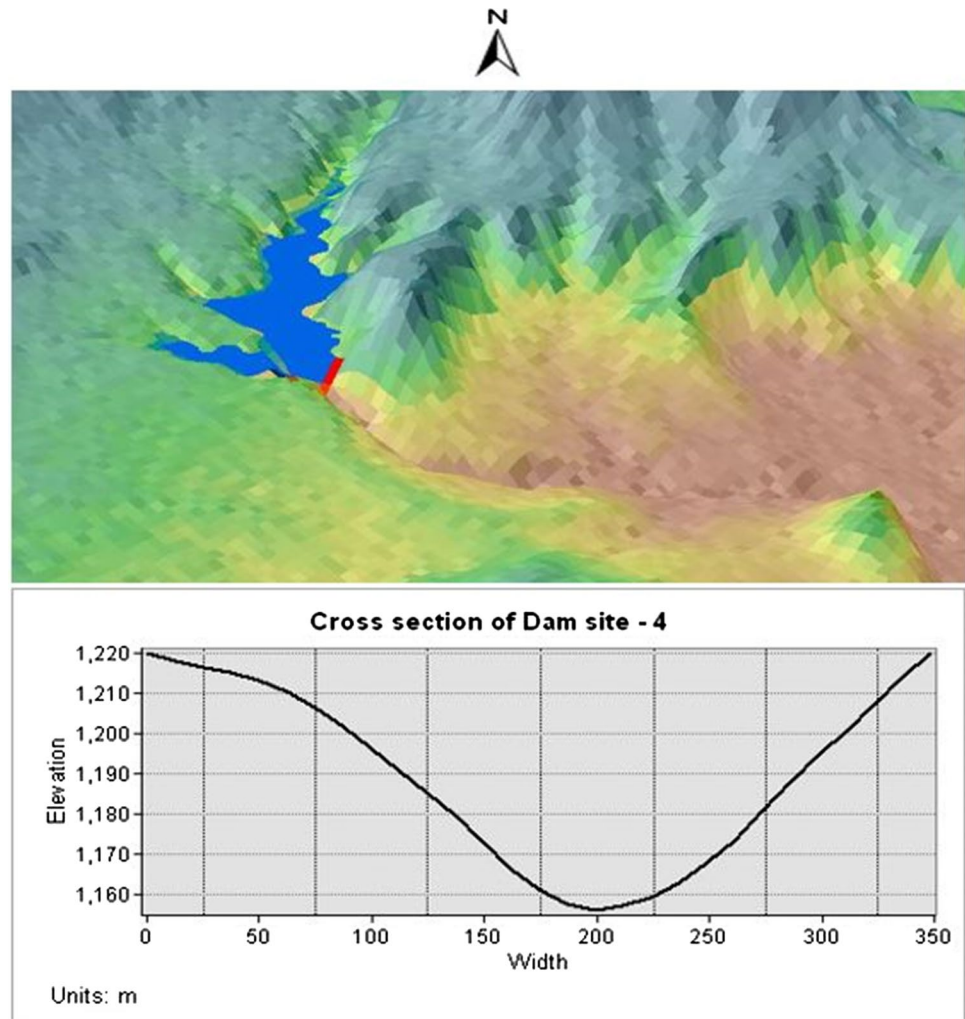
Weighted overlay analysis

The potentially suitable dam site map was created using a weighted index overlay analysis for the Chemoga watershed by adding the weight values of each thematic layer and taking into account six influencing factors. The data for each influencing factor were gathered from various sources and analyzed using the ArcGIS Arc Map 10.3.1 platform as a geo-rectified thematic layer. Then, to generate the suitability on the stream map, the first of two final output maps is obtained by overlaying the influencing factors, including the stream order. Second, we ignore the

stream order layer in favor of the drainage density layer in order to obtain the study area's overall suitability map.

Result and discussion

Dam site suitability map

Two different dam suitability maps are finally obtained as "suitability on stream" and "overall suitability" for constructing a dam (Fig. 11). Both maps are divided into five levels of suitability: very high, high, moderate, less, and least suitable sites. As previously stated, the suitability of the stream

Fig. 20 Evaluation parameters for proposed Dam site 5: **a** Catchment area, **b** DEM, **c** slope, **d** triangulated irregular network (TIN), **e** contours, **f** LULC

map was obtained by overlaying the factors as a reclassified raster layer and assigning the highest weight to it using the stream order factor. As a result, the analysis selected suitable pixels on the streams, but other layers, such as slope, runoff potential, LULC, geology, and distance to roads, were also considered.

Fig. 11 shows that the first and third sites (counting from top to bottom) are undesirable because their cross-sectional widths are quite lengthy and span vast reservoir regions, including agriculture and rural villages. As a result, the environmental and socioeconomic standards are not met. The second site (counting from top to bottom) is similarly located in a very favorable area, both in terms of stream compatibility and overall suitability; however, it is categorized as an unacceptable site due to the presence of an existing dam in that location. As a result, it was

classed as unsatisfactory because there was no need to build a new dam there. The fourth location, located near the watershed's exit, is regarded as unacceptable since it is so close to the Blue Nile River, and constructing a dam in that region may affect future dams and reservoirs across the Blue Nile. However, if no dam can be built on the Blue Nile's downstream section, it may be considered as a suitable dam location.

Evaluation of proposed dam sites

The proposed dam sites are evaluated using nine parameters: 3D surface area, 2D surface area, the maximum volume of the reservoir, dam base elevation, dam surface elevation, dam height, dam width, catchment area, and contour closeness (Figs. 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23). The

Fig. 21 3D view and cross section of proposed dam site-5
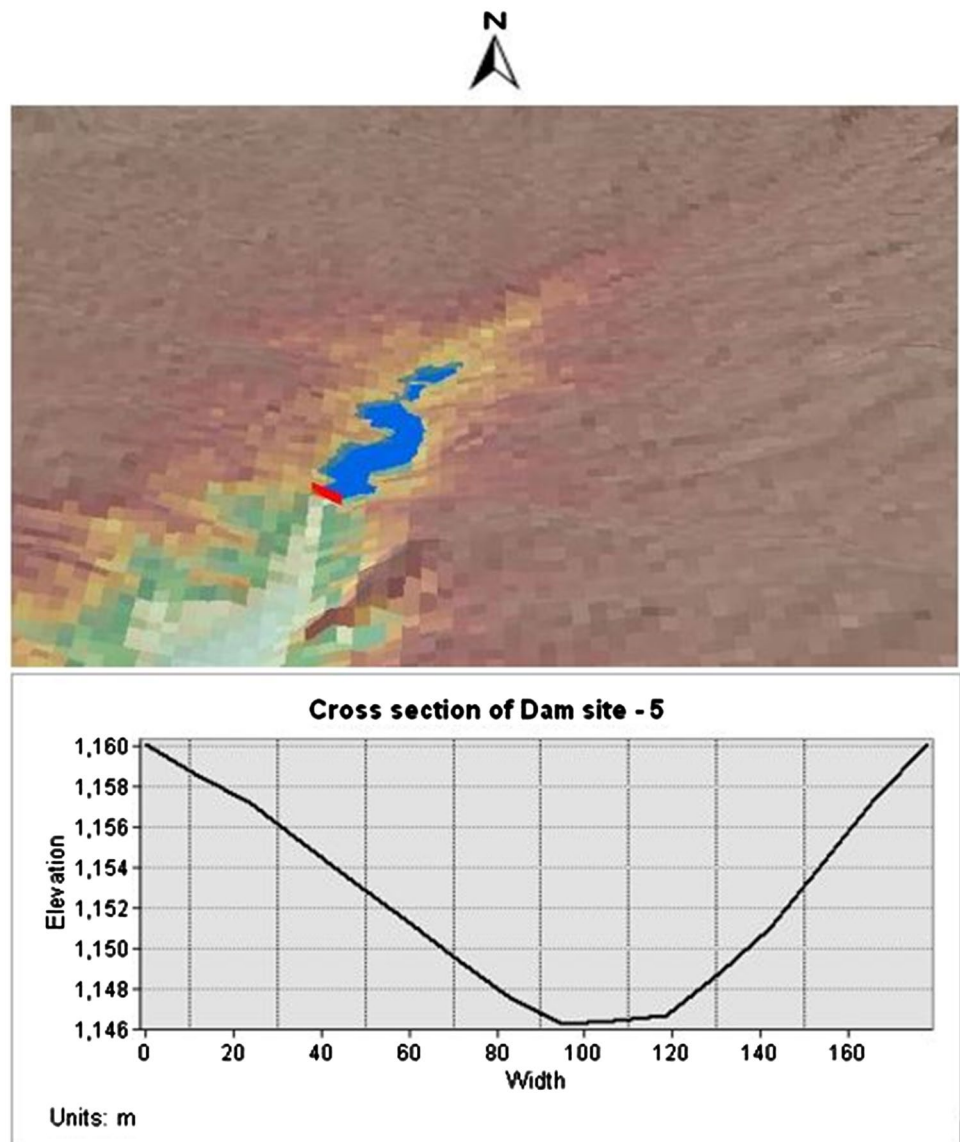
clipped reservoir coverage DEM is used to create contour maps with 1 m and 5 m contour intervals. Then, using the contours, a triangulated irregular network (TIN) was created to determine the reservoir's 2D, 3D surface area, and volume. The surface volume sub tool in the 3D analyst tool in the ArcMap platform is used to determine the reservoir's 2D, 3D surface area and volume, as well as the cross section (height and width) of the proposed dam, as shown in the figures below. Finally, hydrological tools in the Spatial Analysis Tools are used to generate the watershed using the dam location as an outlet point to measure the catchment area.

There are large suitable areas in the northeast (middle) and around the outlet of the study area, as shown above in the overall suitability map in Fig. 11 (right). However, because of the existing dam/reservoir in the middle of the watershed, which is mostly covered by rural settlements, there is no need to build a new dam mean that" there is an existing dam in that location and the model grouped as unsatisfactory. Areas with existing dams are considered unsatisfactory because the model categorises locations as good or unsatisfactory based on the likelihood of future dam construction. The suitable area near the watershed's outlet
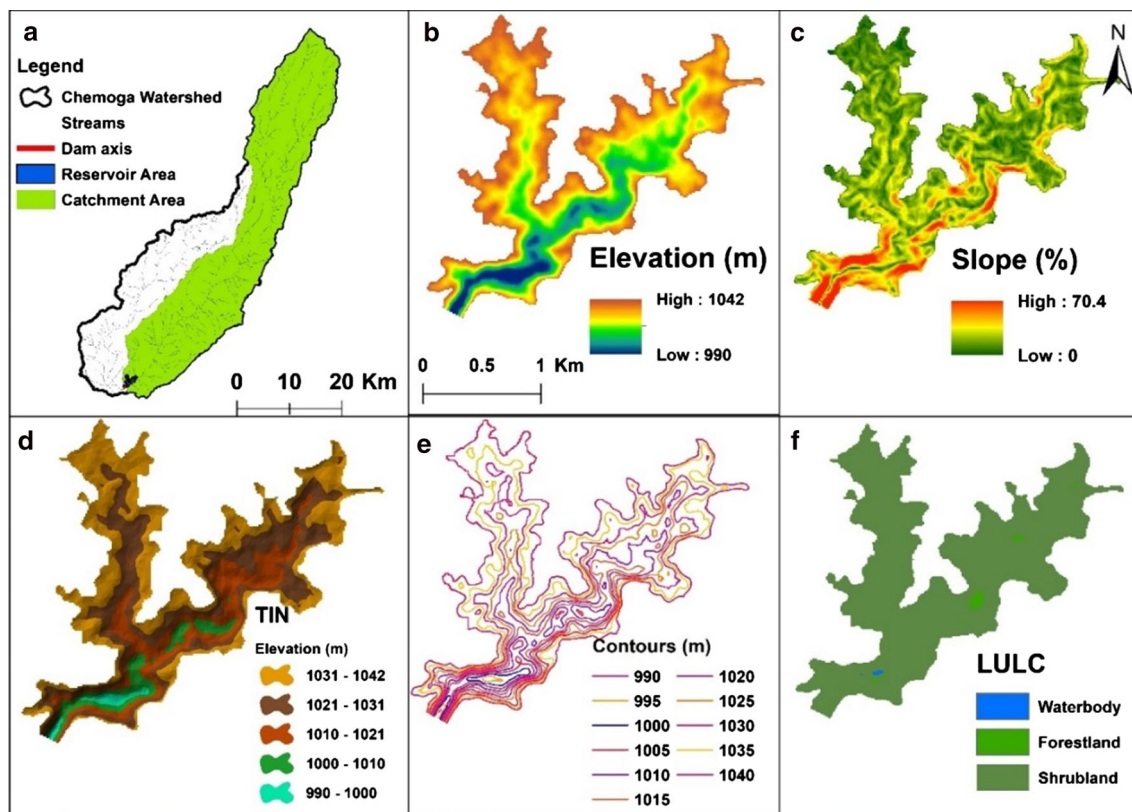
Fig. 22 Evaluation parameters for proposed Dam site 6: **a** Catchment area **b** DEM **c** slope **d** triangulated irregular network (TIN), **e** contours, **f** LULC

is also unsatisfactory because it is so close to the Blue Nile River, and building a dam at the Chemoga watershed's outlet may be influenced by future dams and reservoirs on the Blue Nile. Furthermore, there are suitable areas at low-order streams that are otherwise unsuitable. Then, in this study, six suitable dam sites in the Chemoga watershed were identified by evaluating both stream map and overall suitability, as well as checking the listed dam evaluation parameters, with four unsatisfactory sites that may be preferable for ponds and small rainwater harvesting locations.

Validation of the dam site suitability map

In various parts of the world, researchers are using various models to find suitable dam sites, but it is critical to adequately validate the output of the models with real-world ground conditions or recorded observations. When determining the suitability of a dam site, it may be preferable to validate the model output with existing dams in the watershed (Odiji et al. 2021). As a result, in this dam site suitability study, the results obtained from the used model are compared to the area with an existing dam and reservoir,

Fig. 23 3D view and cross section of proposed dam site-6
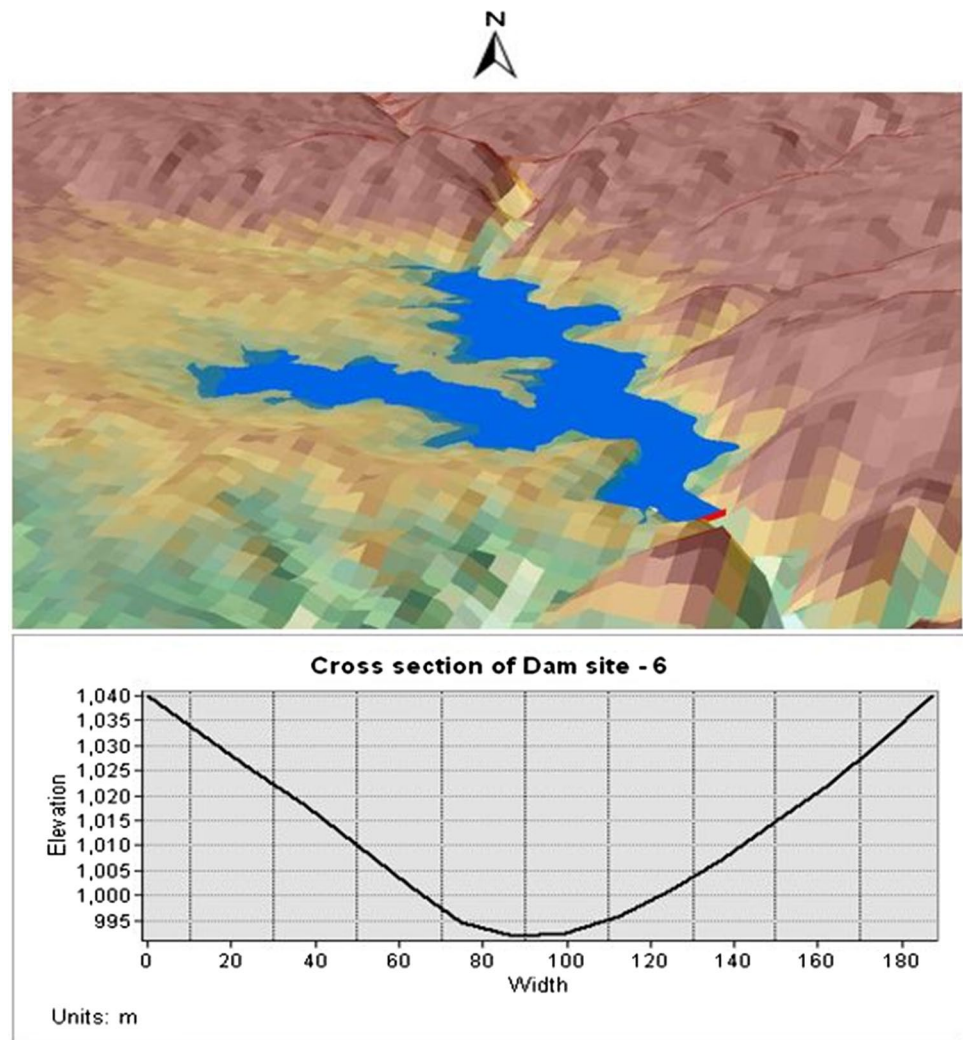
which is selected and built with a detailed design. As shown in Fig. 24, an existing dam in the watershed was built in the model's generated output's very high suitable dam site location. The model is then found to be appropriate for identifying dam site locations at the desk study level.

Conclusions

The Chemoga watershed was investigated using remote sensing and geographic information system (GIS) techniques, as well as the dam suitability stream model and multi-criteria decision analysis. The output suitability map was created using six influencing thematic layers, including stream order/drainage density, slope, Runoff potential, land use/cover, geology, and distance to the road. According to related review literature, field observation, and expert judgment, the most important features in identifying a suitable dam site were stream order/drainage density (39%), slope (26.2%), and runoff potential (17.9%). Stream order is important among the other features because it ensures that enough water is available to be stored in the dam. Finally, based on the two output suitability maps, six potential dam sites were proposed (Suitability on streams and Overall suitability).
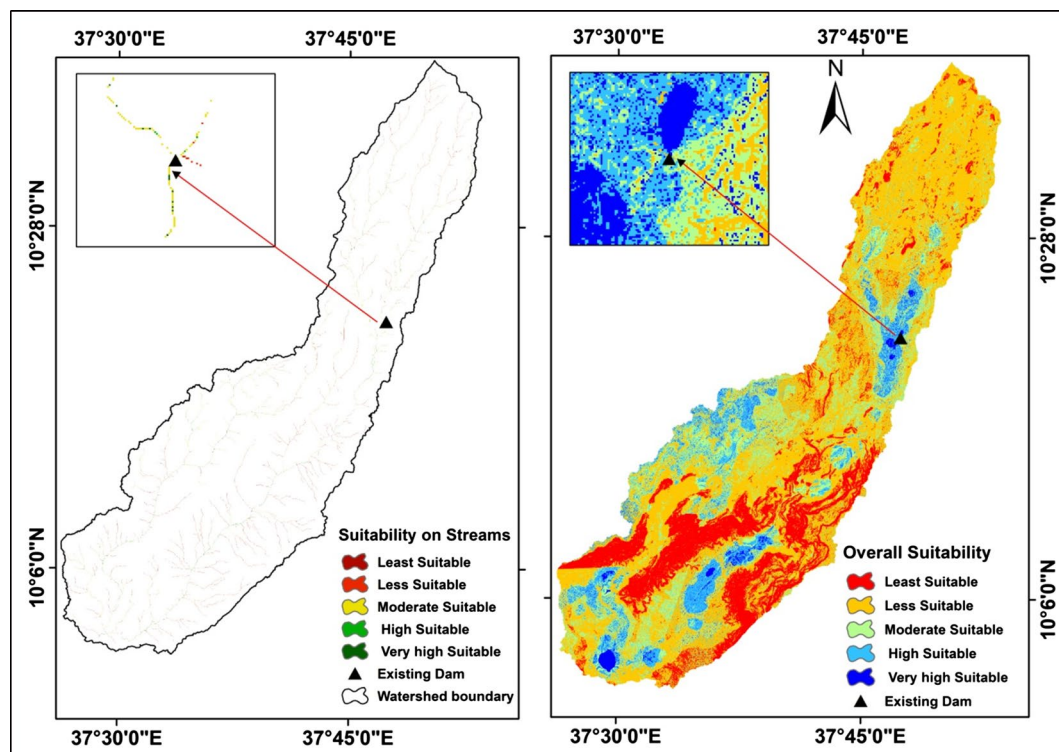
Fig. 24 Existing dam site location comparison with model output for validation

The dam height ranges from 8 to 64 metres depending on the cross section of the dam axis; the dam width ranges from 173 to 875 metres; the reservoir maximum storage capacity ranges from 1.68 to 31.48 million cubic metres depending on the distribution of topographic conditions in the surrounding area; and the reservoir 2D surface area ranges from 3.19 to 231.8 ha among the proposed six dams. Settlements and most of the land used for rain-fed agricultural purposes surround the proposed dam sites in the upper part of the study area, such as dam sites 1, 2, and 3. As a result, building a dam provides numerous benefits to the local community. Proposed dam sites 4, 5, and 6 in the lower part of the watershed, based on topographic location and availability of irrigable command area, are not preferred for irrigation but are most suitable for generating hydropower electric, fishery, and recreation.

Declarations

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