Heliyon 10 (2024) e33921

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Wildlife habitat suitability analysis and mapping the former dhidhessa wildlife sanctuary using GIS-based analytical hierarchal process and weighted linear combination methods

Birhanu Tadesa Edosa[a,*], Mosissa Geleta Erena[b]

[a] Department of Earth Science, Wollega University, Nekemte, P. O. Box 395, Ethiopia
[b] Department of Biology, Wollega University, Nekemte, P. O. Box 395, Ethiopia

ARTICLE INFO

Keywords:
Analytical hierarchy process
Weight linear combination
Wildlife habitat suitability
Geographic information system
Dhidhessa wildlife sanctuary

ABSTRACT

Management of wildlife populations and the creation of conservation programs depend on the evaluation of wildlife habitats. Habitat suitability mapping is a technique typically used to map appropriate environmental factors and assess species existence in different areas. This study aims to map wildlife habitat suitability sites in Former Dhidhessa wildlife sanctuary, Ethiopia, using GIS-based Analytical Hierarchal Process and Weighted Linear Combination Methods. This study used both primary and secondary data sources. Datasets used to collect data include Digital Elevation Model (DEM), Landsat 9 (OLI/TIRS) and population data. Beside, large mammalian species occurrence data obtained from field survey was used. To map wildlife habitat suitability sites in Former Dhidhessa wildlife sanctuary, environmental factors such as proximity of road network, distance to surface water, land use land cover types, slope, population density and topography were used with the integration of species occurrence data recorded from the study area. These environmental factors scaled to common ranges, and assigned appropriate weights. The quantile classification method was utilized to classify suitability index into five zones (unsuitable, less suitable, moderately suitable, suitable, and highly suitable) to produce the map. Accordingly, the model revealed that 18.9 % of the study area is highly suitable, 19.5 % is suitable, 19.9 % is moderately suitable, 19.5 % is less suitable, and 22.2 % is unsuitable for wildlife. About 58.3 % of the study area is currently identified as suitable for wildlife whereas 41.7 % is unsuitable. This showed that the former Dhidhessa wildlife sanctuary is still having large suitable habitats that can support wide ranges of wildlife. Hence, based on the developed preliminary habitat suitability indices and maps, the federal and local governments shall reevaluate the status of former Dhidhessa wildlife sanctuary and develop future conservation and management plans to enhance the conservation of wildlife and their habitats in the area.

1. Introduction

Habitat suitability is the capacity of a habitat to sustain a viable population over an ecological time-scale. Knowledge of habitat suitability is crucial to plan on the sustainable conservation of wildlife and their habitats [1]. Assessing habitat suitability is a useful tool to understand the quality of wildlife habitat and its potential spatial distribution [2]. Determining habitat suitability for wildlife is

* Corresponding author.
E-mail address: biretedosa@yahoo.com (B.T. Edosa).

https://doi.org/10.1016/j.heliyon.2024.e33921
Received 8 March 2024; Received in revised form 30 April 2024; Accepted 30 June 2024
Available online 2 July 2024
2405-8440/

an important aspect of conservation planning and sustainable management of natural resources [3,4]. However, little attention has been given to the conservation of wildlife and their habitats. As a result, wildlife and their habitat conservation planning were failed and lead them to extirpation [5]. Hence, mapping wildlife habitat suitability in conservation planning and biodiversity management is crucial to address biodiversity loss and habitat degradation [6,7].

Habitat suitability (HS) describes a habitat's ability to support a particular wildlife species [8]. The more a habitat resembles its natural state, the more suitable it is for the species to live in it. HS is important to characterize how ideal a habitat is. Anthropogenic pressures are key factors that decline the habitat suitability of wildlife [9,10]. A simple way to describe HS is to determine how natural a habitat is. Efforts to limit anthropogenic impacts on species and habitats can be strengthened by using tools for biodiversity monitoring like habitat suitability model [11]. The habitat suitability index (HSI) model has been widely adopted to assess habitat suitability of various species in recent years [12,13]. Resources that a species needs to survive are often used as indicators. For instance, living and nonliving components such as water, land cover types, topography, vegetation cover, and human disturbance are powerful indicators between species and their environment that are important in categorizing habitat suitability of wildlife [14–16].

HS is estimated either by species-focused or habitat-focused. The different approaches are chosen based on research goals [17]. A habitat-focused approach is common for estimating the habitat suitability of wildlife [18]. It considers both the biotic or abiotic components of a habitat [19]. In habitat-focused approach, HS index is calculated by dividing the current habitat conditions by the optimum habitat conditions. The result of HS index ranges between 0 and 1. The wildlife habitat is completely unsuitable when HS is characterized with a value of 0, while a value of 1 represents the optimum conditions [20]. Since HS is a measure of species-habitat interactions, mapping HS is useful in conservation efforts. To create reliable habitat suitability maps, consistent estimation of HS has paramount significance [21]. Many wildlife habitats have been reduced in size, both outside and inside protected areas in tropical regions [22,23]. The disturbance and fragmentation of protected areas could affect its capacity to provide suitable habitat for wildlife [24,25]. Similarly, the disturbance and fragmentation of wildlife habitats in the former Dhidhessa wildlife sanctuary would be a threat for the future survival of wildlife in the area.

Dhidhessa wildlife sanctuary was formerly designed with the objective of conserving diverse wildlife, including endangered mammals such as African wild dog (*L. pictus*) and African elephant (*L. africana*). Recently, part of its former area was designated as a nominally controlled hunting area; the Haro Abba Dikko controlled hunting area, with a special focus on conservation of African buffalo. However, the other parts of the former Dhidhessa wildlife sanctuary are dominated by humans and used for large-scale sugarcane farms and subsistence agriculture. Subsequently, *L. pictus* and *L. africana* had extirpated from the former Dhidhessa wildlife sanctuary. Despite the loss of wildlife habitats in the area, large mammals such as African buffalo (*Syncerus caffer*), lions (*Panthera*

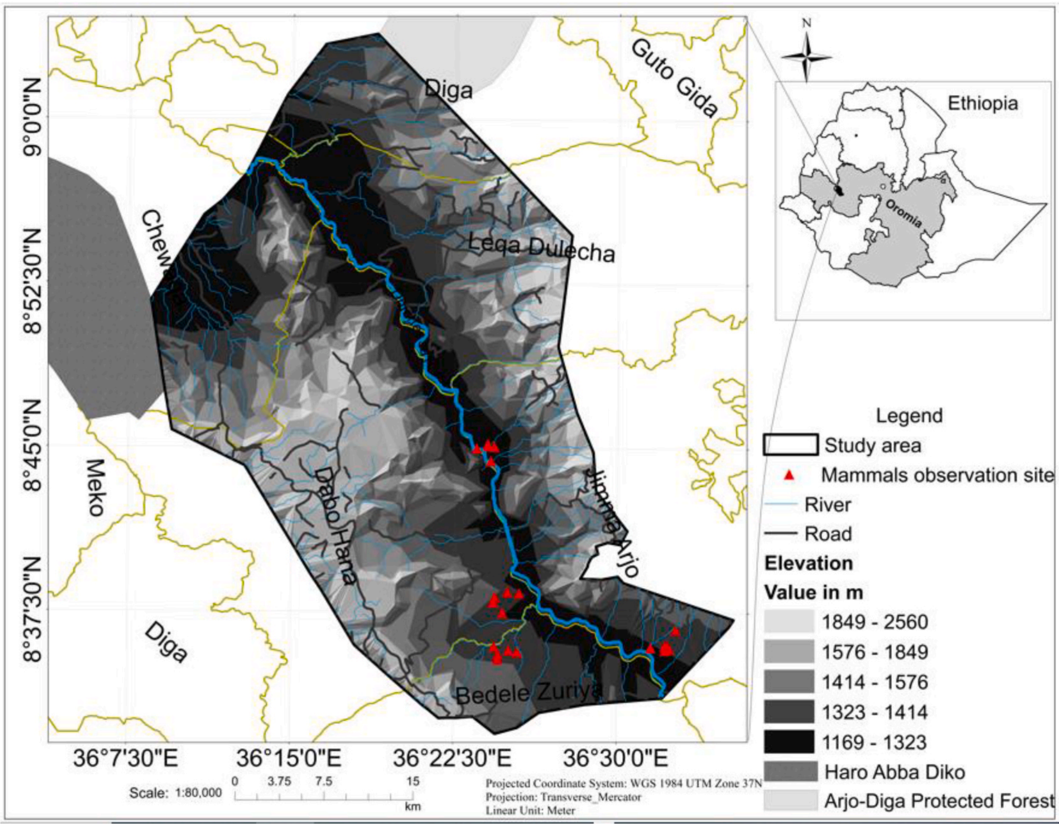

Fig. 1. Location map of the study area.

leo), leopards (*Panthera paradus*), hippopotamus (*Hippopotamus amphibius*), many more medium- and large-sized mammals and nonhuman primates are still found in the remnant forest patches of the former Dhidhessa wildlife sanctuary. To take future conservation initiatives and design connectivity across the potential wildlife habitats, mapping suitable wildlife habitats has an inimitable role to rehabilitate the disturbed protected area. Therefore, this study aims to evaluate and map wildlife's habitat suitability in the former Dhidhessa wildlife sanctuary in Ethiopia. The study also addressed the following questions in particular. 1. Which abiotic, biotic, and anthropogenic factors affect wildlife habitat suitability in the area? 2. Where are the best suitable habitats in the study area? 3. And is there a sufficient suitable habitat for wildlife in the former Dhidhessa wildlife sanctuary?

2. Materials and methods

2.1. Description of the study area

The study is carried out in the former Dhidhessa wildlife sanctuary located in western Oromia Region of Ethiopia, between East Wollega and Buno Bedele Administrative Zones. Geographically, it is situated between 8° 37' 30″ N to 9° 00' 00″ N latitudes and 36° 07' 30″E to 36° 30' 00" E longitudes. It has an estimated total area of 15,2076.4ha (Fig. 1). It is located 540 km West of Addis Ababa, along Addis Ababa Nekemte-Bedele road. The altitude of the area ranges from 1169 to 2560 m. Its annual rainfall is 1400 mm. The rainy season extends from May to October. The vegetation of the study area is dominated by *Combretum*, *Commiphora*, and *Acacia* species mixed with dominantly grown savanna grass of *Hyparrhenia* species.

2.2. Methods

2.2.1. Types of datasets used and sources of acquisition

The study used both primary and secondary data sources (Table 1). The datasets used include Digital Elevation Model (DEM), obtained from Alaska Satellite Facility Distributed Active Archive Center (ASFDAAC) (https://search.asf.alaska.edu/#/), human population density (https://www.worldpop.org), Landsat 9 obtained from https://earthexplorer.usgs.gov/, and species location results obtained from a field survey. These data were used for wildlife habitat suitability mapping (WHSM).

2.2.2. Multi-criteria decision-making analysis

The study utilized GIS technology to organize, summarize, code, and analyze data related to the wildlife habitats. GIS data management tools and spatial analyst tools were utilized, with GIS-based multi-criteria decision-making (MCDM) being a crucial method for spatial analysis. In this method, weights were assigned to each selected criterion based on relative importance and then a weighted sum is calculated for each alternative. This method is high accuracy than other methods such as Shannon entropy and frequency ratio [26,27]. Hence, choosing an accurate and popular algorithm for wildlife habitat suitability assessment has a great impact on the present and the future. Accordingly, the alternative with the highest weighted sum is considered the most favorable. The detail general flow chart of the overall method is described in Fig. 2.

Analytical Hierarchy Process (AHP) is used to attain criteria weights in MCDM [28,29]. It involves the creation of a hierarchy of decision factors and the comparison between different pairs of habitat suitability factors to obtain a weight and a consistency ratio for each factor. The pairwise comparison was analyzed to produce weights that sum to 1, and the total weight should be added up to 100 % for the output map to be expressive and reliable. The pairwise comparison matrix was produced following [30] scale classification (Table 2).

A weight value was assigned to different habitat factors of the study area to compare its importance relative to other criteria in wildlife habitat suitability mapping. The weighted linear combination (WLC) method involves the linear combination of the spatial factors for producing wildlife habitat suitability maps [31]. In each class, rating value is assigned in GIS, and then the parameter layers

Table 1
Types and sources of spatial data used in mapping habitat suitability of wildlife.

Data types	Format	Resolution	Date of acquisition	Function	Data sources
Study area boundary	Vector/shapefile	–	2023	To generate the analysis extent of all variables.	Digitizing from Google Earth
Road network	Vector/shapefile	–	2023	To produce road proximity	Google Earth and ArcGIS online base map (http://www.openstreetmap.org)
Landsat 9 (OLI/ TIRS) Path:170 Row:54	Raster/image	30 m × 30 m	19, January 2023	Used to produce land use land cover (LULC)	USGS website (http://www.globeland30.org)
Population density	Raster/image	30 arc seconds	22, June 2020	To assess its impact on wildlife species	World population website (https://www.worldpop.org)
DEM	Raster/image	12.5 m × 12.5 m		To produce Slope, surface water and Topography	ASFDAAC website (http://www.gscloud.cn)
Species location	X, Y coordinates saved in Excel	–	2023	To identify wildlife location	Field survey by HGPS

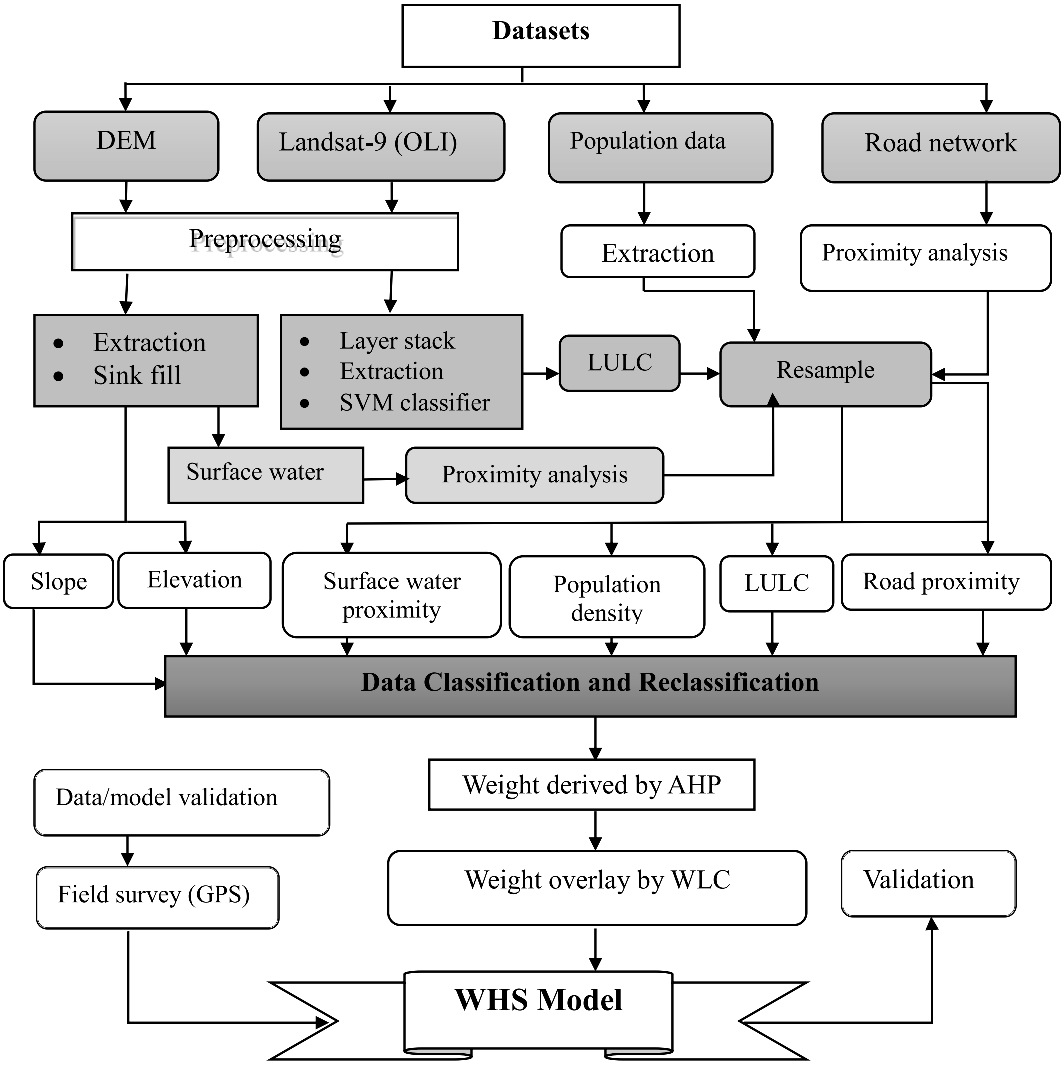

Fig. 2. Workflow of wildlife habitat suitability model of the study area.

Table 2
Classification scale used for pair-wise comparison of different habitat factors.

Value or intensity of importance	Description
1	Equally important
3	Moderately important
5	Strongly or essentially important
7	Very strongly important
9	Extremely important
2, 4, 6, 8	Intermediate value
1/3	Less important
1/5	Moderately less important
1/7	Strongly less important
1/9	Very strongly less important

are weighted according to the importance or preference of each parameter relative to the others. To produce the final result, all prepared spatial factors are defined in a common coordinate system (WGS 1984 UTM Zone 37) and resampled into 12.5 m spatial resolution. Then, all continuous data were reclassified into five classes using the quantile classification method, and both continuous and discrete subclasses were rated. AHP was employed to derive the weights for WLC. Finally, all the derived weights and reclassified raster parameters were linearly combined in order to construct the final wildlife habitat suitability model.

2.2.3. Environmental factors analysis used for wildlife habitat suitability model

WHSM was produced by a collection of thematic layers that represent the normal events of medium- and large-sized mammalian species. Even though wildlife habitat suitability is determined by different environmental factors [32], this study selectively used for proximity of road network, distance to surface water, land use, land cover types, slope, population density, and topography have serious impacts on the habitat suitability of large mammals. The habitat suitability of large mammals is exceptionally considered because if their habitat is maintained, it indirectly supports other wildlife species in the area. To evaluate the impacts of selected environmental factors that affect wildlife habitat suitability in the present study area, different values are assigned for each factors and suitability classes (Table 3).

Development of AHP decision-making needs setting factor elements (variables) and analysis. It was used to capture aspects of the decision and compute the eigenvector of weights for different criteria used by creating a pair-wise comparison matrix. The choice of criteria that have a common spatial reference is an important and profound step in WLC of multi-criteria decision analysis. Hence, the criteria and assigning importance factors characterized in this study were chosen and weighted based on practical data analysis results, field observation, and different scholars working on habitat suitability. For example [33], give high weight to surface water proximity than road network proximity, likewise [34], gives high weight to road network proximity than slope. Although [35] give the weight of habitat suitability factors for surface water proximity, elevation, LULC, and slope serially, and [36] give the weight for elevation, slope, and land use land cover sequentially. However [37], used elevation and slope as equally importance. Based on the above considerations, the factors selected for wildlife habitat suitability assessment have their weight values done in Table 4 and the weight values of our factors (see Table 5) multiplied by 100 percent were depicted in Table 3 below. Generally, there is no questionnaire developed to find the coefficient importance of habitat factors, instead we used expert judgement based on the circumstances of the study site, and also on the ideas we have received from various scholars.

The maps of the factors selected as critical for wildlife habitat suitability are prepared after analysis in the ArcGIS environment. The maps in this manuscript are prepared by the spatial analyst tools available on ArcGIS software. Tools/methods used to make these maps are as follows: surfaces tool for slope map, segmentation and classification tool for LULC map, distance tool for surface water proximity and road network proximity map, reclass tool for suitability factors map, overlay tool for WHSM, and so on extraction tool was used to prepare elevation map and population density map. Geostatistics tool is almost unused.

2.2.4. Overlay wildlife habitat suitability factors

For the analysis of overlay wildlife habitat suitability, ArcGIS employs the following procedure. In the suitability analysis, each raster layer is given a weight. By allotting a weight to each raster during the overlay process, the impact of various criteria in the

Table 3
Weight and rank of criteria used for wildlife habitat suitability modeling.

Factors affecting wildlife habitat suitability	Factors subclasses	Unit	Suitability subclasses	Rate	Weight (%)	Reference
Road network	0–386.26	m	Unsuitable	1	3.08	[33–35,38–41]
	386.26–855.29		Less suitable	2		
	855.29–1572.64		Moderate suitable	3		
	1572.64–2565.88		Suitable	4		
	>2565.88		Highly suitable	5		
Surface water	0–194.25	m	Highly suitable	5	43.78	[2,31,33–35,38,39,41]
	194.25–427.36		Suitable	4		
	427.36–796.45		Moderate suitable	3		
	796.45–1379.21		Less suitable	2		
	>1379.21		Unsuitable	1		
Land cover	Water	LC	Restricted	Restricted	28.1	[2,31,33–37,39–44]
	Savanna wooded		Highly suitable	5		
	Natural forest		Suitable	4		
	Grassland		Moderate suitable	3		
	Settlement area		Less suitable	2		
	Bare land		Unsuitable	1		
Slope	0–6.33	%	Highly suitable	5	4.63	[2,31,34–37,40–42]
	6.33–11.61		Suitable	4		
	11.61–17.94		Moderate suitable	3		
	17.94–29.55		Less suitable	2		
	>29.55		Unsuitable	1		
Population density	23–49	N° of People/ km^2	Highly suitable	5	7.61	[31,34,44]
	49–71		Suitable	4		
	71–98		Moderate suitable	3		
	98–163		Less suitable	2		
	>163		Unsuitable	1		
Elevation	1169–1327	m	Highly suitable	5	12.8	[2,31,35–38,40,41,43].
	1327–1405		Suitable	4		
	1405–1570		Moderate suitable	3		
	1570–1842		Less suitable	2		
	>1842		Unsuitable	1		

Table 4
Pair-wise comparison of different factors for wildlife habitat suitability analysis.

Factors	Elevation	Land cover	Population density	Road network	Slope	Surface water
Elevation	1	1/3	3	5	3	1/5
Land cover	3	1	5	1/3	9	1/3
Population density	1/3	1/5	1	5	3	1/5
Road network	1/5	1/7	1/3	1	1/3	1/7
Slope	1/3	1/9	1/3	3	1	1/7
Surface water	5	3	5	7	7	1

Table 5
Principal eigenvector of the pair-wise comparison.

Factors	Weight
Elevation	0.1280
Land cover	0.2810
Population Density	0.0761
Road network	0.0308
Slope	0.0463
Surface water	0.4378

suitability model was monitored. For wildlife habitat suitability zonation, factors are classified by their significance, weight, and/or rate of effect on habitat suitability. The values of each zone are summed up to form the ultimate profit raster that speaks to the possible wildlife habitat range. Higher sum values represent a greater possibility for wildlife habitat. After each parameter is assigned with the appropriate scale value (1–5), AHP was used to compute its weight value. The computed weight values were multiplied by 100 % to provide the weight of the factors ranging from one to the 100 %. The weight linear combinations method was adopted from the equation defined by Ref. [47] to determine WHSM where;

$$WHSM = (Elevation)_{s*}(Elevation)_w + (Land\ cover)_{s*}(Land\ cover)_w + (Population\ density)_{s*}(Population\ density)_w + (Slope)_{s*}(Slope)_w + (Road\ network)_{s*}(Road\ network)_w + (Surface\ water)_{s*}(surface\ water)_w$$

w = the weighting of the coefficient (1–100 %) and s is the scale value (1–5) of the estimated zone. Finally, an optimal wildlife habitat suitability site was chosen based on the highest suitability values and mapped through a weighted linear combination (weight additive) and quantile classification method in a GIS environment.

2.2.5. Sensitivity analysis (SA)

SA is the examination of the association among constraints to develop the model. Its objective is to fix the parameters whose discrepancy leads to substantial variations in model results [28,45]. Sensitivity analysis techniques are not a mutual practice in GIS-based multicriteria decision-making methods [28]. For example, single parameter and map removal-based sensitivity analysis are widely used in the spatial MCDM [46,47]. In the present study, map removal-based sensitivity analysis was used to test the sensitivity of the various wildlife habitat parameters. SA measures the uncertainty or discrepancy in the output results obtained from realistic models. It tells how much each contributory factor contributes and the weights and ranks and rates given for their effect on the output map [47]. Consequently, map removal-based SA was conducted to test the sensitivity of the various spatial factors used for WHSM. As expressed by Ref. [46], the mathematical formula for map removal SA is as follows:

$$SA = \left| \frac{\frac{WHSM}{Y} - \frac{WHSM'}{Y'}}{WHSM} \right| * 100\% \quad (1)$$

where WHSM is the output of the wildlife habitat suitability model index of all the thematic factors, WHSM' is the thematic factor removed, Y is the number of the full thematic factors used to compute WHSM, and Y′ is the number of thematic factors used to compute WHSM'.

2.2.6. Model validation

To test the predictive power of decision making (DM), we measured the performance of the models in predicting species potential presence. In particular, this study has evaluated the agreement between each DM and a set of points of presence of species that were independently collected from the field. The presence of wildlife (medium and large-sized mammals) was determined by direct and indirect observation of each species during the wet and dry seasons. Indirect evidences such as foot prints, burrowing, vocals and droppings were used to determine the existence of different medium and large-sized mammals in the study area [48]. Moreover, the study used point data on species presence of the study area by gathering the available published and unpublished datasets, consisting mainly of observations and captures. Moreover, Handheld GPS (HGPS) was used to determining the presence of a wildlife location in the field. Species potential presence data collected from the field were obtained for the orders Artiodactyla, Carnivora, Primate, Rodentia, Tubulidentata, Lagomorpha, and Hyracoidea.

3. Results

3.1. *GIS-based MCDM for WHSM*

A pair-wise comparison of different factors for wildlife habitat suitability analysis revealed that land cover has a moderately higher weight value than elevation in determining the habitat suitability of wildlife. Similarly, proximity to surface water has a moderate weight over land cover and confirmed a very important and significant weight in determining wildlife habitat suitability than elevation, population density, road network, and slope in the study area (Table 4).

Theoretically, computed weight values of different factors that affect wildlife habitat suitability indicated that proximity to surface water (0.4378) had more impacts on determining wildlife habitat suitability, followed by land cover (0.281) and elevation (0.128). The weight values of slope gradient (0.0463) and road network proximity (0.0308) were less likely to impact wildlife habitat suitability in the area (Table 5).

3.1.1. *Proximity of road suitability*

Road distance network suitability was calculated by Euclidean distance using Arc GIS software spatial analyst (Fig. 3). Accordingly, wildlife species located closer to road networks are highly susceptible, whereas those found at a distance are free from disturbances. Based on the proximity of the road suitability analysis, about 20.98 %, 19.65 %, and 17.54 % of the mapped and classified areas were rated as moderately suitable, suitable, and highly suitable for wildlife, respectively. However, about 17.85 % and 23.96 % of the study area were unsuitable and less suitable, respectively.

3.1.2. *Surface water suitability*

Wildlife species prefer to live closer to water sources. Accordingly, a habitat closer to surface water is categorized as more suitable for wildlife species than distantly located water sources (Fig. 3). According to the established proximity classes, the highly suitable

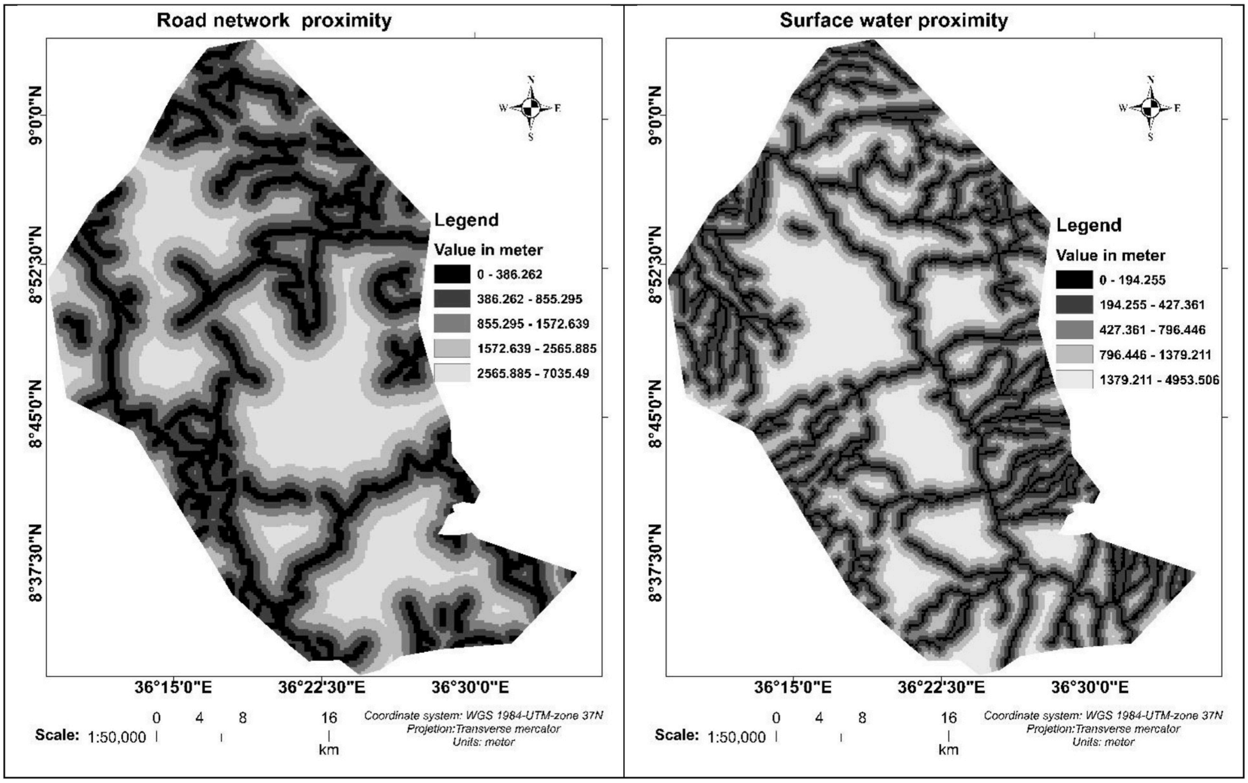

Fig. 3. Suitability analysis of road and surface water proximity classes.

class covers 9.94 %, followed by 23.18 % of moderately suitable and suitable (30.04 %) landmasses. The remaining 18.06 % and 18.77 % of the study area represent unsuitable and less suitable habitats for wildlife, respectively.

3.1.3. Land cover suitability

A land cover map of the study area was produced by a support vector machine (Fig. 3). It displays the land exploited by humans and naturally covered by vegetation (savanna wooded, natural forest, grassland), bare land, settlement area, and water body. Based on the land-cover suitability analysis, the largest part of the study area (30.81 %) is moderately suitable for wildlife, followed by highly suitable (19.94 %), suitable (19.92 %), less suitable (4.63 %) and unsuitable (24.38 %) habitats. The remaining 0.31 % of the study area was covered by water body, and considered as restricted since habitat suitability analysis does not include aquatic environment.

A land cover map of the study area was produced by a vector machine (Fig. 4). The land cover map showed an area exploited by humans and naturally covered by different vegetation types, bare land, settlement areas, and water bodies. Land-cover suitability analysis indicated that the largest part of the study area (30.81 %) was categorized as moderately suitable for wildlife, followed by highly suitable (19.94 %), suitable (19.92 %), less suitable (4.63 %), and unsuitable (24.38 %) for wildlife habitats. The remaining 0.31 % of the study area was covered by water and considered restricted since habitat suitability analysis does not include aquatic environments.

3.1.4. Slope suitability

The slope gradient of the study area largely falls between 6.332 and 11.609 %, which represents 22.81 % of the total area, and suitable for wildlife (Fig. 4). The second most dominant slope of the study area falls between 11.609 and 17.941 % covering 20.50 % of the total area. The least amount of slope (16.77 %) in the area accounted <6.332 %, which is highly suitable for wildlife. While the remaining slope >29.550 and 17.941–29.550 % were unsuitable (19.42 %) and less suitable (20.35 %) for wildlife.

3.1.5. Population density suitability

Human settlements and disturbances are the main causes for wildlife habitat losses. Wildlife species found in proximity to human settlements are highly vulnerable as it elicits conflicts. Hence, habitats far from human settlements are highly preferred and suitable for wildlife (Fig. 5). Accordingly, 19.57 % of the total area is highly suitable, whereas 18.33 % is unsuitable for wildlife species. The remaining 22.73 %, 20.51 %, and 18.86 % of the area were suitable, moderately suitable, and less suitable for wildlife, respectively.

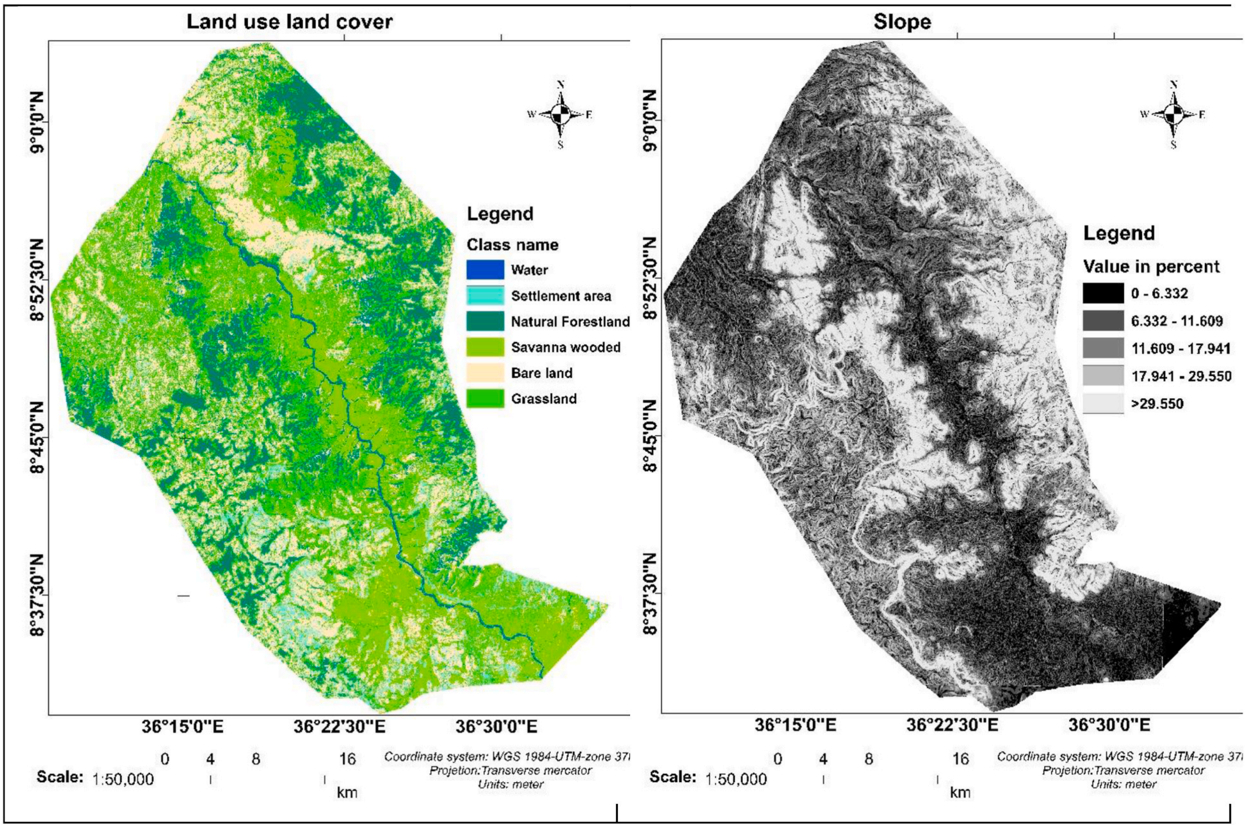

Fig. 4. Suitability analysis for land use land cover and slope classes.

3.1.6. Elevation suitability

This study revealed that, mountainous and steep terrain is not suitable for large mammals. High elevation is found on the surrounding edges of Dhidhessa valley escarpments where built ups and residential houses are high. However, the low land areas adjacent to the Dhidhessa River seem to be more suitable than the surrounding elevated escarpments on the southwest and eastern parts of the study area (Fig. 5).

A combined analysis of potential wildlife habitat suitability map, in the present study indicated that 18.9 % and 19.5 % of the study area were categorized as the highly suitable and suitable respectively, whereas 22.2 % was unsuitable for wildlife. The moderately suitable class covers 19.9 % of the study area. On the other hand, only 19.5 % of the study area was found to be less suitable for wildlife in the study area (Fig. 6; Table 6).

3.2. Sensitivity analysis

In multiple map removal, sensitivity analysis constraints instigating the least variation based on the standard deviation statistical value computed in the GIS environment and the final output was removed first, followed by the second, and so on. The sensitivity index shows that, land cover is an extremely significant factor of WHSM followed by surface water (Table 7).

3.3. Model validation

A total of 23-point locations of large mammals' occurrence within the study area were used for validating the wildlife habitat suitability model. The collected large mammal observation site was exactly overlaid with the suitable and highly suitable habitat categories. $R^2 = 1$ indicates the highest match of the model to the observed data whereas $R^2 = 0$ indicates the lowest. The validation results of this study indicated that the R^2 value of the measured and predicted results of the validation data set was found to be 0.7907 approximately 0.8 (Fig. 7).

About 52.17 % of habitat suitability categories fall into the fifth rate (368.24–500), and 30.43 % into the fourth rate (319.61–368.24) which is a highly suitable and suitable region for wildlife habitat, respectively. About 13.05 % (3rd rate) and 4.35 % (2nd rate) of the observation sites were fall into the moderately suitable (275.69–319.61) and less suitable (231.76–275.69) categories, respectively (Fig. 8).

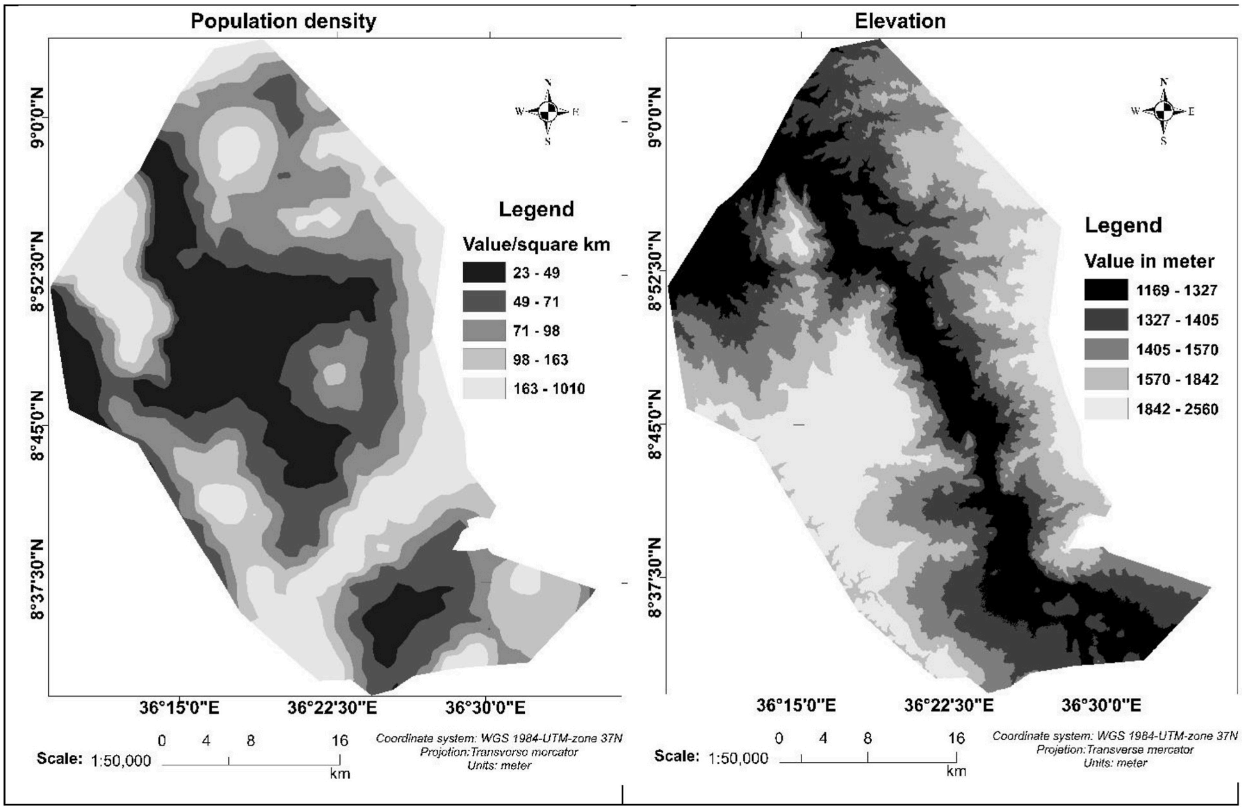

Fig. 5. Human settlement and elevation suitability classes analysis.

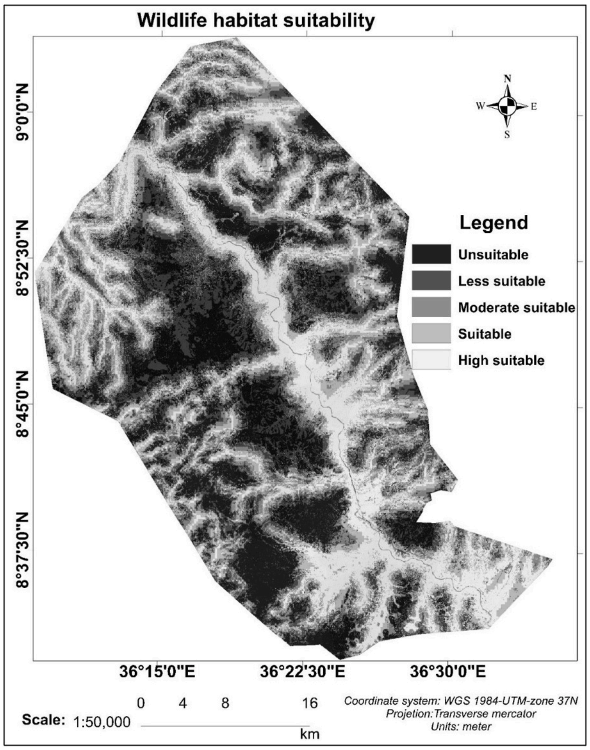

Fig. 6. An evaluated potential wildlife habitat suitability zones in the study area.

Table 6
Wildlife habitat suitability modeling index.

Habitat suitability zone	Rate	Index value	Area (ha)	Area (%)
Unsuitable	1	100–231.764	33721.369	22.2
Less suitable	2	231.764–275.686	29616.297	19.5
Moderate suitable	3	275.686–319.607	30284.734	19.9
Suitable	4	319.607–368.235	29757.094	19.5
Highly suitable	5	368.235–500	28696.906	18.9
Total			152076.4	100

Table 7
Map removal-based sensitivity analysis of different habitat factors (W = Surface water; R= Road network; S= Slope gradient; P= Population density; E = Elevation; L = Land cover).

S.No.	Removed constraints	Statistical variation index (%)			
		Minimum	Maximum	Mean	Standard deviation
1	WRSPEL				
2	RSPEL	−0.64	12.58	5.11	2.82
3	SPEL	−4.53	11.99	3.02	3.36
4	PEL	−36.97	12.71	0.00	4.72
5	EL	−21.55	10.53	−4.09	5.86
6	L	−49.48	16.67	−11.74	11.72

4. Discussion

The present study identified different wildlife habitat suitability classes in human-dominated landscape of the former Dhidhessa wildlife sanctuary. It could be important to inform the government and conservation authorities to reform the conservation action plan for cost-effective and efficient wildlife conservation in the area. Though the areas were invaded by humans and by small and large-scale investment, the wildlife habitat suitability map indicated that highly suitable, suitable, and moderately suitable classes accounted for about 58.3 % of the study area. Less suitable and unsuitable habitats accounted for 19.5 % and 22.2 % of the total study

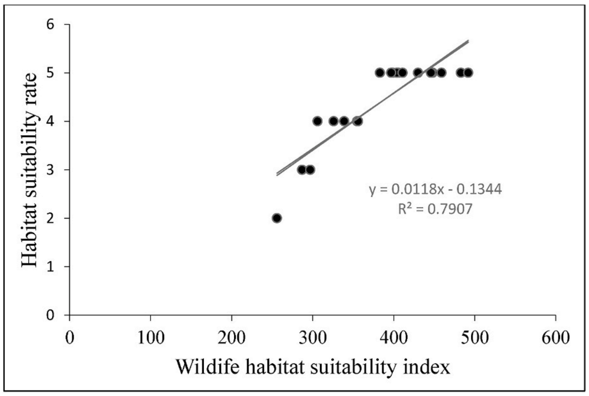

Fig. 7. Validation of wildlife habitat suitability model.

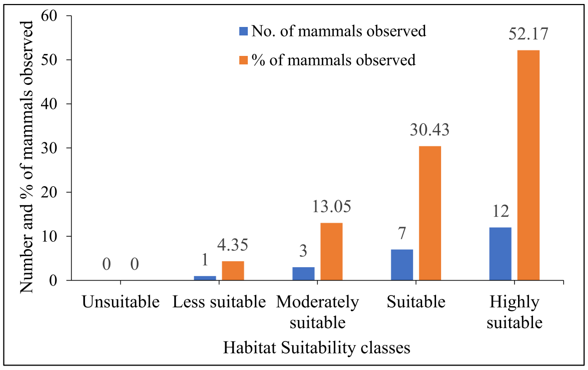

Fig. 8. Mammalian species observation in predicted potential wildlife habitat suitability classes of the study area.

area, respectively. The potential wildlife habitats identified in the former Dhidhessa wildlife sanctuary is suitable for wildlife due to the availability of a gentle slope with low elevation and huge savanna-wooded vegetation. This was confirmed by the diverse number of medium- and large-sized mammals recorded in the study area. Most large mammals were recorded in highly suitable and suitable wildlife habitat suitability classes. The wildlife habitat suitability map showed that high population density and a road network closer to wildlife areas were identified as unsuitable zones. Also, mountainous areas and very steep gradient zones were classified as unsuitable regions for wildlife habitats. In this study, highly suitable wildlife habitats are known to have low population density), a gentle slope, a low elevation value, a very far road network, are closer to vegetation covers, and are in good proximity to surface water. The reasons for the less suitable wildlife habitat are high population density, being far from surface water, near roads and settlements, steep slope areas, and hilly or high elevation areas.

The weight and rank of criteria used for wildlife habitat suitability modeling in this study indicated the greatest contribution of three predictor variables. Proximity to surface water accounted for 43.78 % of the weight value in determining wildlife habitat suitability modeling. This indicated that, regardless of other predictor variables, wildlife is unable to survive at longer distances from the sources of water. This is why the predicted suitable habitats of the GIS model revealed that most of the current suitable habitats and the occurrence of large mammals were observed in the lowland areas closer to rivers. As described by Refs. [33,35], surface water proximity gives higher weight to wildlife habitats than others in determining habitat suitability models. Land use land covers (e.g., savanna wooded, natural forest, grassland, settlement area, and bare land) were the second strongest predictor, accounting for 28.1 % weight values in wildlife habitat suitability modeling. It was classified into six potential habitat suitability classes, which were unsuitable, less suitable, suitable, moderate, suitable, and highly suitable. Based on the land-cover suitability analysis, the largest part of the study area (46855 ha, 30.81 %) is moderately suitable for wildlife, followed by highly suitable (30,329 ha, 19.94 %), suitable (30301 ha, 19.92 %), less suitable (7043 ha, 4.63 %), and unsuitable (37,075 ha, 24.38 %) for wildlife. Land use and land cover play a significant role in wildlife habitat suitability determination because they are mainly used as cover and as a source of forage. Elevation was the third predictor factor that determined wildlife habitat suitability modeling. As described by Ref. [49], elevated areas determine the moisture holding capacity of water and thereby have low fresh and palatable forages during the dry season. Moreover, most large mammals (especially grazers) do not prefer to graze on high elevations and steeper slopes because grazing on areas of slopes greater than 20 % requires more energy for up-and-down locomotion [50,51].

WHS modeling index result shows that 33,721 ha were unsuitable; 29,616 ha were less suitable; 30,285 ha were moderately suitable; 29757 ha were suitable; and 28696 were highly suitable. A field survey of large mammalian species occurrence indicated that most large herbivores were grazing in the moderately suitable, suitable, and highly suitable areas of the low elevated areas of the former Dhidhessa wildlife sanctuary. The lowland parts of the Dhidhessa wildlife sanctuary were predominantly covered by *Hyparrhenia* species that serve as forage and shelter. However, the elevated escarpments of the Dhidhessa wildlife sanctuary were mostly dominated by agriculture, built-up and a few forest patches. This made areas closer to the river and grassy habitats more suitable for large herbivores than the elevated areas disturbed by humans. As revealed by Refs. [50,52], riparian habitats attracted herbivores due to large amounts of nutritious, palatable forage, a moderate slope gradient, and reliable water. This study used only six environmental indicators, although several ecological systems interact to determine the habitat suitable for species. With the consideration of six environmental factors, this study showed the potential of Geographic Information Science (GIS) based AHP and WLC to provide useful information for wildlife habitat suitability mapping. AHP methods have been used by various researchers in general. For example, researchers [26,27] said that AHP method is high accurate and it is semi-qualitative method. Based on these ideas, the study used this method to describe the suitable wildlife habitat. The model result is validated by the adjusted R-square and the validation value is approximately 0.8. The species data used for this model validation were collected by handheld GPS at a few large mammal's locations. Hence, future studies shall consider many species occurrence data for precise habitat suitability determination of each wildlife species in the study area.

5. Conclusion

The former Dhidhessa wildlife sanctuary is currently invaded by the human population and used for small and large-scale agriculture activities. However, wildlife habitat suitability analysis done using GIS-based analytical hierarchal processes and weighted linear combination methods in the study area revealed that more than half of the study area is appropriate for the conservation of wildlife species in the area. The observations of large mammals such as African buffalo, lion, hippopotamus, and leopard confirmed the potential of the study area to host diverse large mammals if appropriate conservation measures are designed in the future. The existence of Haro Abba Diko Controlled hunting area in the west and Arjo-Diga protected forest on the northern part of the former Dhidhessa wildlife sanctuary may continue to serve as a source for the former Dhidhessa wildlife sanctuary. Unless appropriate conservation and mitigation measures are implemented, extirpation will be the fate of the existing large mammals such as *Syncerus caffer*, *Panthera leo*, *Panthera paradus* and *Hippopotamus amphibius* in the former Dhidhessa wildlife sanctuary. For the sustainable conservation of large mammals in the former Dhidhessa wildlife sanctuary, wildlife habitats shall be conserved and linked with the adjacent protected areas using landscape connectivity. Small and large-scale agricultural activities and other investments shall not be entertained within the potential wildlife habitats in the study area. Moreover, future conservation and management action should gear towards solving the problem of anthropogenic activities such as habitat fragmentation through the design of appropriate corridors within the study area to reconnect the fragmented suitable wildlife habitat patches. Generally, the federal and regional governments shall rethink on the current status of Dhidhessa wildlife sanctuary and plan on how to strengthen the conservation of wildlife and their habitat in the area.

Ethical approval for publication

Approval was obtained from the local ethics committee. On behalf that, we decided to submit it to this journal, and the work was approved for publication.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. The research was only funded by the Wallaga University.

Data availability statement

Data associated with this study will be made available on request, and deposited at http://10.13.8.73:8080/wurepository/

CRediT authorship contribution statement

Birhanu Tadesa Edosa: Writing – original draft, Validation, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Mosissa Geleta Erena:** Writing – review & editing, Visualization, Supervision, Resources, Funding acquisition, Data curation.

Declaration of competing interest

We declare that this manuscript is our original work, has not been published by anyone else, and that all sources of material used for the manuscript haven't been copied from others. Although the authors declare that, they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like to thank Wollega University for financial support.

References

[1] T. Liu, Z. Jiang, W. Wei Wang, G. Wang, X. Song, A. Xu, C. Li, Changes in habitat suitability and population size of the endangered Przewalski's gazelle, Glob. Ecol. Conserv. 43 (2023) e02465, https://doi.org/10.1016/j.gecco.2023.e02465.

[2] P. Wang, B. Feng, L. Zhang, X. Fan, Z. Tang, X. Dong, J. Zhang, C. Zhou, W. Bai, Assessment of habitat suitability and connectivity across the potential distribution landscape of the sambar (*Rusa unicolor*) in Southwest China, Front. Conserv. Sci. 3 (2023) 1–7, https://doi.org/10.3389/fcosc.2022.909072.

[3] E. Fernandez-Juricic, M.P. Venier, D. Renison, D.T. Blumstein, Sensitivity of wildlife to spatial patterns of recreationist behavior: a critical assessment of minimum approaching distances and buffer areas for grassland birds, Biol. Conserv. 125 (2005) 225–235, https://doi.org/10.1016/j.biocon.2005.03.020.

[4] J.G. Hiddink, S. Jennings, M.J. Kaiser, Assessing and predicting the relative ecological impacts of disturbance on habitats with different sensitivities, J. Appl. Ecol. 44 (2007) 405–413, https://doi.org/10.1111/j.1365-2664.2007.01274.x.

[5] J. Young, A Reference Guide for Future Strategic Planning and Project Funding: Ethiopian Protected Areas, a 'Snapshot', EWCA, Addis Ababa, 2012, p. 46. https://reddplusethiopia.wordpress.com.

[6] V.C. Radeloff, A.M. Pidgeon, P. Hostert, Habitat and population modeling of roe deer using an interactive geographic information system, Ecol. Model. 114 (1999) 287–304, https://doi.org/10.1016/S0304-3800(98)00164-1.

[7] K. Yamada, J. Elith, M. McCarthy, A. Zerger, Eliciting and integrating expert knowledge for wildlife habitat modelling, Ecol. Model. 165 (2003) 251–264, https://doi.org/10.1016/S0304-3800(03)00077-2.

[8] C. Kellner, J. Brawn, J. Karr, What is habitat suitability and how should it be measured? in: D.R. McCullough, R.H. Barrett (Eds.), Wildlife 2001: Populations Springer, Dordrecht, The Netherlands, 1992, pp. 476–488.

[9] M.M. Ibrahim, A. Duker, C. Conrad, M. Thiel, H. Shaba Ahmad, Analysis of settlement expansion and urban growth modelling using geoinformation for assessing potential impacts of urbanization on climate in abuja city, Nigeria, Rem. Sens. 8 (3) (2016) 220, https://doi.org/10.3390/rs8030220.

[10] H.K. Kija, J.O. Ogutu, L.J. Mangewa, J. Bukombe, F. Verones, B.J. Graae, J.R. Kideghesho, M.Y. Said, E.F. Nzunda, Spatio-Temporal changes in wildlife habitat quality in the greater serengeti ecosystem, Sustain. Times 12 (6) (2020) 2440, https://doi.org/10.3390/su12062440.

[11] M. Di Febbraro, L. Sallustio, M. Vizzarri, D. De Rosa, L. De Lisio, A. Loy, B.A. Eichelberger, M. Marchetti, Expert-based and correlative models to map habitat quality: which gives better support to conservation planning? Glob. Ecol. Conserv. 16 (2018) e00513 https://doi.org/10.1016/j.gecco.2018.e00513.

[12] Y. Cui, B. Dong, L. Chen, X. Gao, Study on habitat suitability of overwintering cranes based on landscape pattern change—a case study of typical lake wetlands in the middle and lower reaches of the Yangtze River, Environ. Sci. Pollut. Res. 26 (2019) 14962–14975, https://doi.org/10.1007/s11356-019-04697-y.

[13] S. Yao, X. Li, C. Liu, J. Zhang, Y. Li, T. Gan, B. Liu, W. Kuang, New assessment indicator of habitat suitability for migratory bird in wetland based on hydrodynamic model and vegetation growth threshold, Ecol. Indicat. 117 (2020) 106556, https://doi.org/10.1016/j.ecolind.2020.106556.

[14] B. Chen, P. Cui, H. Xu, X. Lu, J. Lei, Y. Wu, M. Shao, H. Ding, J. Wu, M. Cao, G. Liu, Assessing the suitability of habitat for wintering Siberian cranes (*Leucogeranus*) at different water levels in Poyang Lake area, China. Polish, J. Ecol. 64 (2016) 84–97, https://doi.org/10.3161/15052249PJE2016.64.1.008.

[15] D. Wen, Y. Hu, Z. Xiong, Y. Chang, Y. Li, Y. Wang, M. Liu, J. Zhu, Potential suitable habitat distribution and conservation strategy for the Siberian crane (*Grus leucogeranus*) at spring stopover sites in northeastern China, Pol. J. Environ. Stud. 29 (2020) 3375–3384. https://10.15244/pjoes/113453.

[16] V.T. Lakoba, D.Z. Atwater, V.E. Thomas, B.D. Strahm, J.N. Barney, A global invader's niche dynamics with intercontinental introduction, novel habitats, and climate change, Glob. Ecol. Conserv. 31 (2021) e01848, https://doi.org/10.1016/j.gecco.2021.e01848.

[17] L. Wu, C. Sun, F. Fan, Estimating the characteristic spatiotemporal variation in habitat quality using the invest model-A case study from guangdong–Hong Kong–Macao greater bay area, Rem. Sens. 13 (2021) 1008, https://doi.org/10.3390/rs13051008.

[18] C.R. Williamson, H. Campa III, A.B. Locher, S.R. Winterstein, D.E. Beyer Jr., Applications of integrating wildlife habitat suitability and habitat potential models, Wildl. Soc. Bull. 45 (2021) 70–84. https://10.1002/wsb.1152.

[19] S. Polasky, E. Nelson, D. Pennington, K.A. Johnson, The impact of land-use change on ecosystem services, biodiversity and returns to landowners: a case study in the state of Minnesota, Environ. Resour. Econ. 48 (2011) 219–242. https://doi:10.1007/s10640-010-9407-0.

[20] A. Berta Aneseyee, T. Noszczyk, T. Soromessa, E. Elias, The InVEST habitat quality model associated with land use/cover changes: a qualitative case study of the winike watershed in the omo-gibe basin, southwest Ethiopia, Rem. Sens. 12 (2020) 1103, https://doi.org/10.3390/rs12071103.

[21] A.K. Skidmore, N. Pettorelli, N.C. Coops, G.N. Geller, M. Hansen, R. Lucas, S. Mücher, B. O'Connor, M. Paganini, H.M. Pereira, M.E. Schaepman, W. Turner, T. Wang, M. Wegmann, Environmental science: agree on biodiversity metrics to track from space, Nature 523 (2015) 403–405, https://doi.org/10.1038/523403a.

[22] R. DeFries, A. Hansen, A.C. Newton, M.C. Hansen, Increasing isolation of protected areas in tropical forests over the past 20 years, Ecol. Appl. 15 (2005) 19–26.

[23] N.S. Sodhi, Introduction (Part I), in: N.S. Sodhi, G. Acciaioli, M. Erb, A.K.-J. Tan (Eds.), Biodiversity and Human Livelihoods in Protected Areas: Case Studies from the Malay Archipelago, Cambridge University Press, Cambridge, UK, 2008, pp. 9–19.

[24] G.A. De Leo, S. Levin, The multifaceted aspects of ecosystem integrity, Conserv. Ecol. 1 (1) (1997) 3. http://www.consecol.org/vol1/iss1/art3. December 2022.

[25] M. Didion, M.-J. Fortin, A. Fall, Forest age structure as indicator of boreal forest sustainability under alternative management and fire regimes: a landscape level sensitivity analysis, Ecol. Model. 200 (2007) 45–58, https://doi.org/10.1016/j.ecolmodel.2006.07.011.

[26] B.W. Elvis, M. Ars'ene, N.M. Th'eophile, K.M. Bruno, O.A. Olivier, Integration of shannon entropy (SE), frequency ratio (FR) and analytical hierarchy process (AHP) in GIS for suitable M'eiganga area, Adamawa Cameroon, J. Hydrol.: Reg. Stud. 39 (2022) 1–24, https://doi.org/10.1016/j.ejrh.2022.100997.

[27] J. Seyedmohammadi, M.N. Navidi, Applying fuzzy inference system and analytic network process based on GIS to determine land suitability potential for agricultural, Environ. Monit. Assess. (2022) 1–19, https://doi.org/10.1007/s10661-022-10327-x.

[28] Y. Chen, J. Yua, S. Khan, Spatial sensitivity analysis of multi-criteria weights in GIS-based land suitability evaluation, Environ. Model. Software 25 (2010) 1582–1591, https://doi.org/10.1016/j.envsoft.2010.06.001.

[29] J. Seyedmohammadi, F. Sarmadian, A.A. Jafarzadeh, R.W. McDowell, Development of a model using matter element, AHP and GIS techniques to assess the suitability of land for agriculture, Geoderma (2019) 80–95, https://doi.org/10.1016/j.geoderma.2019.05.046.

[30] T. Saaty, The Analytic Hierarchy Process, McGraw-Hill, New York, 1980.

[31] F.H. Buruso, Habitat suitability analysis for hippopotamus (*H. amphibious*) using GIS and remote sensing in Lake Tana and its enviros, Ethiopia, Environ. System Resea. 1–15 (2017), https://doi.org/10.1186/s40068-017-0083-8.

[32] C. Zhou, R. Wan, J. Cao, L. Xu, X. Wang, J. Zhu, Spatial variability of bigeye tuna habitat in the Pacific Ocean: hindcast from a refined ecological niche model, Fish. Oceanogr. 30 (2021) 23–37, https://doi.org/10.1111/fog.12500.

[33] F. Ahmad, L. Goparaju, A. Qayum, Wild life habitat suitability and conservation hotspot mapping: remote Sensing and GIS based decision support system, AIMS Geosciences (2018) 66–87.

[34] P. Kumar, S. Sinha, M. Dobriyal, A.K. Pandey, R. Tomar, M. Rani, Modeling potential suitable tiger habitat in sariska national park (India) using habitat suitability and integrated geospatial approach, Int. J. Environ. Sci. (2020) 52–62. https://doi:10.53390/ijes.v11i2.4.

[35] N.F. Khodri, T. Lihan, M.A. Mustapha, T.M. Taher, N.A.T. Arifin, N.I. Abdullah, S.M. Nor, Prediction of leopard habitat suitability in Taman Negara main forest complex, Malaysia, J. Environ. Biol. (2021) 806–811. https://doi:10.22438/jeb/42/3(SI)/JEB-11.

[36] E. Ozsahin, M. Ozdes, A.C. Smith, D. Yang, Remote sensing and GIS-based suitability mapping of termite habitat in the african savanna: a case study of the lowveld in kruger national park, Land (2022) 1–18, https://doi.org/10.3390/land11060803.

[37] M.K. Rosyidy, A. Wibowo, GIS-based spatial model for habitat suitability of babirusa (babyrousa celebensis), in: Gorontalo Province, Jurnal Geografi Lingkungan Tropik, 2020, pp. 35–45.

[38] M.I. Reza, S.A. Abdullaha, S.B. Norc, M.H. Ismaild, Integrating GIS and expert judgment in a multi-criteria analysis tomap and develop a habitat suitability index: a case study of largemammals on the Malayan Peninsula, Ecol. Indicat. (2013) 149–158. https://doi:10.1016/j.ecolind.2013.04.023.
[39] J.E. Sanare, E.S. Ganawa, A.A. Salih, Wildlife habitat suitability analysis at serengeti national park (SNP),Tanzania case study Loxodonta sp, J. Ecosyst. Ecography (2015) 1–8. https://doi:10.4172/2157-7625.1000164.
[40] S.A. Tadesse, B.P. Kotler, A GIS−based habitat suitability model for the mountain nyala tragelaphus buxtoni in the southeastern highlands of Ethiopia and its implication for conservation, Inter. J. Avian and Wildlife Biol. 2018–223 (2018). https://doi:10.15406/ijawb.2018.03.00089.
[41] H. Su, M. Bista, M. Li, Mapping habitat suitability for Asiatic black bear and red panda in Makalu Barun National Park of Nepal from Maxent and GARP models, Sci. Rep. (2021), https://doi.org/10.1038/s41598-021-93540-x.
[42] R. Store, J. Jokimäki, A GIS-based multi-scale approach to habitat suitability modeling, Ecol. Model. 169 (2003) 1–15, https://doi.org/10.1016/S0304-3800(03)00203-5.
[43] R.J. Aspinall, G. Burton, L. Landenburger, Mapping and Modeling Wildlife Species Distribution for Biodiversity Management, 2021, 11 1, pp. 1–11.
[44] Z.W.H. Zhu, Z. Yang, D. Li, Y. Wang, Assessing habitat suitability and habitat fragmentation for endangered Siberian cranes in Poyang Lake region, China, Ecol. Indicat. (2021) 1–14, https://doi.org/10.1016/j.ecolind.2021.107594.
[45] M. Mosbahi, S. Benabdallah, M.R. Boussema, Sensitivity analysis of a GIS-based model: a case study of a large semi-arid catchment, Earth Sci Inform (2015) 569–581. https://doi:10.1007/s12145-014-0176-0.
[46] R. Thapa, S. Gupta, S. Guin, R. Kaur, Sensitivity analysis and mapping the potential groundwater vulnerability zones in Birbhum district, India: a comparative approach between vulnerability models, Water Sci 32 (2018) 44–66, https://doi.org/10.1016/j.wsj.2018.02.003.
[47] D. Dhinsa, F. Tamiru, B. Tadesa, Groundwater potential zonation using VES and GIS techniques: a case study of Weserbi Guto catchment in Sululta, Oromia, Ethiopia, Heliyon 15 (2022) e10245, https://doi.org/10.1890/03-5258.
[48] M. Norton-Griffiths, Counting Animals Handbook, African Wildlife Foundation, Nairobi, 1978.
[49] D.W. Bailey, J.E. Gross, E.A. Laca, L.R. Rittenhouse, M.B. Coughenour, D.M. Swift, P.L. Sims, Mechanisms that result in large herbivore grazing distribution patterns, J. Range Manag. 49 (5) (1996) 386–400, https://doi.org/10.2307/4002919.
[50] R.L. Gillen, W.C. Krueger, R.F. Miller, Cattle use of riparian meadows in the Blue Mountains of northeastern Oregon, J. Range Manag. 38 (3) (1985) 205–209, https://doi.org/10.2307/3898967.
[51] X. Sun, Z. Jiang, F. Liu, D. Zhang, Monitoring spatio-temporal dynamics of habitat quality in Nansihu Lake basin, eastern China, from 1980 to 2015, Ecol. Indicat. 102 (2019) 716–723, https://doi.org/10.1016/j.ecolind.2019.03.041.
[52] E.M. Beaury, C.S. Jarnevich, I. Pearse, A.E. Evans, N. Teich, P. Engelstad, J. LaRoe, B.A. Bradley, Modeling habitat suitability across different levels of invasive plant abundance, Biol. Invasions (2023) 1–14, https://doi.org/10.1007/s10530-023-03118-z.