Opportunities and Challenges in Sustainability
https://www.acadlore.com/journals/OCS

Assessing and Landscape Mapping of the Regulatory Ecosystem Services of Lake Hawassa Basin in Ethiopia: Implications for Sustainable Natural Resource Management

Bedilu Amare Reta*, Teshome Soromessa

Center for Environmental Science, College of Natural and Computational Sciences, Addis Ababa University, 1165 Addis Ababa, Ethiopia

* Correspondence: Bedilu Amare Reta (beamreta2021@gmail.com)

Received: 08-05-2025 **Revised:** 09-13-2025 **Accepted:** 09-26-2025

Citation: Reta, B. A. & Soromessa, T. (2025). Assessing and landscape mapping of the regulatory ecosystem services of lake Hawassa basin in Ethiopia: Implications for sustainable natural resource management. *Oppor Chall. Sustain.*, *4*(3), 220–239. https://doi.org/10.56578/ocs040305.

Abstract: Regulating services (RS) is one of the four ecosystem services (ES) derived from the diverse ecosystems in the Lake Hawassa Basin (LHB). These services are crucial for the local community, but ongoing anthropogenic activities are exerting negative pressure on these ecosystems, diminishing their capacity to provide RS. This study aimed to assess and map RS at the basin level and propose development options for decision-makers considering the study years of 2007, 2016 and 2024. The study utilized primary and secondary data collection and analysis, stakeholder consultations involving 60 participants, site visits, and tools such as land use land cover (LULC) classification using ArcGIS v10.1 and expert judgment matrix (EJM). The study prioritized 4 out of 11 RSs, created spatial pattern maps at the basin scale, and suggested development options to integrate into decision-making processes and sectoral policies. These recommendations aim to benefit current and future planning and management of development activities within the LHB. The study's methodology and results are vital for addressing biophysical and socioeconomic environmental problems, ensuring sustainable management of natural resources, and enhancing the well-being of the local community. The user-friendly methodology can be adopted globally, with future improvements suggested through additional methods like modeling and valuation of prioritized RS.

Keywords: Spatial pattern mapping; Regulating services; Lake Hawassa; Stakeholder consultations; Environmental problem; Ecosystem services

1. Introduction

Regulating services (RS) is one of the four ecosystem services (ES) derived from the function and structure of diverse ecosystems in Lake Hawassa Basin (LHB), the study area. RS is crucial for the local community, but ongoing human activities are exerting negative pressure on these ecosystems and diminishing their capacity to provide RS (Burkhard et al., 2012b; Carpenter et al., 2009; Costanza et al., 1997; Foley et al., 2005; Millennium Ecosystem Assessment, 2005; Perrings et al., 2011; The Economics of Ecosystems and Biodiversity, 2010). According to the Millennium Ecosystem Assessment Framework, the benefits of an ecosystem are primarily determined by the link between ES and human well-being (Millennium Ecosystem Assessment, 2005).

Human well-being comprises five main components: health, basic material needs for a good life, security, good social relations, and freedom of choice and action. Ecosystems support human well-being through existing RSs. Well-being also depends on the supply and quality of human services, technology, and institutions. The strength of the linkages between categories of ES and components of human well-being varies and includes indications of the extent to which socioeconomic factors can mediate the linkage (Millennium Ecosystem Assessment, 2005). As per this linkage, if a substitute for a degraded ecosystem service is available, there is a high potential for intervention. The strength of these linkages and the potential for intervention differ across ecosystems and regions. Besides the influence of RS on human well-being, other factors such as environmental, economic, social, technological, and cultural factors also play a vital role, and ecosystems are, in turn, affected by changes in human well-being (Millennium Ecosystem Assessment, 2005).

LHB are known for its rich and diverse aquatic and terrestrial natural resources, which have the potential to provide RS. These services play a major role in securing the livelihood of local people, with biophysical conditions, human-induced temporal, and spatial changes in LULC, and climate change determining the provision of ES in the study area (Burkhard et al., 2012b; Riitters et al., 2000). The concept of ES is vital for the maintenance and restoration of basin ecosystems like those that existed in the LHB and adds value to the current and future natural resource conservation management practices. Overall, implementing sustainable management practices is essential to improve the use and importance of natural resources and ES in the study area, supporting residents and the surrounding community (Maes et al., 2013).

Population growth and economic expansion are the primary drivers of LULC change worldwide, especially in developing countries that prioritize economic prosperity (Li et al., 2009; Mir et al., 2025; Tessema et al., 2024). Unsustainable management of natural resources has led to ecosystem conversion and degradation. There is a critical need to plan location-specific land use activities, including agricultural and fisheries activities that maintain ES (Egoh et al., 2007; Wade et al., 2010). Understanding the status of RSs and their dynamic patterns, including the relationship and interaction among ecosystem structures, functions, and landforms, is required for the effective management of RS. While previous studies have attempted to quantify and map ES' functional values, basin-scale assessment is still necessary to understand how RS functions and benefits in specific locations at the basin scale (Kindu et al., 2016).

Currently, human activities are putting pressure on the study area's ecosystem, disrupting and impacting the existing RSs within the LHB. Major threats include lack of coordination among sectors in controlling resource degradation, inadequate regulatory and enforcement mechanisms on unplanned resource abstraction and utilization, uncontrolled fishing practices, lake water abstraction for irrigation, improper land use management, deforestation, land degradation, lakeside farming which contribute increased erosion and sedimentation of the lake and other surrounding surface water sources, untreated effluent discharge of from industries, hospitals and other anthropogenic activities, low level of awareness, and knowledge of the importance and value of RS in the study area (Deng et al., 2016; Institute of Biodiversity Conservation, 2005).

Previously available studies were lacked to assess the regulating ES using social data, geospatial information, and expert perspectives. For instance, Abate et al. (2015) and Lencha et al. (2021) assessed the water quality of the Lake Hawassa (Yilma, 2019) on economic value of the wetlands (Belete et al., 2024) on provisioning ES of the lake landscape (Degife et al., 2019) on LULC and its drivers in the Lake Hawassa watershed. The study also identified major gaps related to incomplete ES studies, often focusing on a single ecosystem service or problem, limited in number, and lacking basin-scale assessment. These gaps prompted the study to extend its scope to include a basin-scale assessment of the prioritized four types of RSs. This shortfall of previous ES studies challenges the author to conduct an in-depth analysis of a comparative assessment of RS in the study area. The study aims to address these gaps and provide alternative options to decision-makers, NGOs, Experts, and development partners to use in their decision-making processes for existing and future watershed and basin management plans within LHB and similar areas nationwide. The study's output, coupled with efforts to integrate ecosystem service approaches into natural resource management plans, aims to safeguard the existing RS within the LHB. The ultimate goal is to suggest alternative development options to policymakers and development partners. Advancing this study can help to address gaps seen in ES assessment during planning for future Lake Hawassa Basin development activities, improving the use and management of RS in the study area, and can be input for future Lake Hawassa Basin planning and management.

2. Materials and Methods

This study was conducted in the same area as a previous study on provisioning services at Lake Hawassa Basin titled "Integrated Assessment and Mapping of Provisioning Services for Sustainable Management of Natural Resources: The Case of Lake Hawassa Basin, Ethiopia" by the same author. It used similar materials and methods (Reta & Soromessa, 2024).

2.1 Description of the Study Area

LHB is located 273 km from Addis Ababa, the capital city of Ethiopia, in the central northeast part of the Rift Valley Lake Basin (RVLB). The total Lake Hawassa catchment area is 436 km^2, centered around Lake Hawassa, which covers 7% of the study area and includes Hawassa Town. The closed shallow Lake Hawassa has no surface water outlet, with water exiting through subsurface outflow and evapotranspiration. The LHB is located between latitudes 6°48'45 to 7°49' 54 N and longitudes 38°16' 34" to 38°43'26 E. The LHB spans two regional states, Sidama and Oromia, covering 71% and 21%, respectively (Figure 1) (Reta & Soromessa, 2024; Ministry of Water and Energy, 2010b). The topography is flat to gently undulating, bounded by steep escarpments, with varied slopes: 56% flat to gentle (0–8%), 33% moderately sloping (8–30%), and 5% steep to very steep (> 30%). The altitude ranges from 1,680m at Lake Hawassa to 2,700 m on the eastern escarpment (Ministry of Water and Energy, 2010a; Reta & Soromessa, 2024). The local agroclimatic classification predominantly categorizes the area as a tepid, humid, sub-humid mountain, rift valley, and cold to humid agroecological zones. The mean annual rainfall at Hawassa is about 943.4 mm, with inter-annual variability but no significant trend. The mean monthly temperature varies from 18.6°C in November to 21°C in March. The mean annual temperature shows an increasing trend of about 0.05°C per year, attributed to climatic changes and increased deforestation (Ministry of Water and Energy 2007; Reta & Soromessa, 2024).

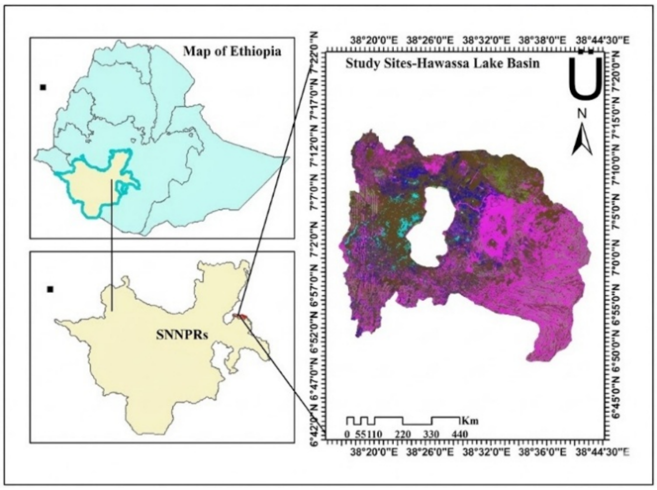


Figure 1. Lake Hawassa Basin location map

2.2 Conceptual Framework (Millennium Ecosystem Assessment)

The study adopts the Millennium Ecosystem Assessment conceptual framework (Millennium Ecosystem Assessment, 2005), which elucidates the dynamic interaction between ecosystems and their components, affecting human well-being due to direct and indirect shifts in human conditions that drive changes in ecosystem nature, structure, and function (Annex 1). Social, economic, and cultural factors associated with ecosystems modify human situations, and several natural forces influence the capacity of each ecosystem to provide RS in the study area (Millennium Ecosystem Assessment, 2005; Reta & Soromessa, 2024). The significant feature of the Millennium Ecosystem Service Assessment approach results from its interdisciplinary demand, underline the characterization of Lake Hawassa Basin goods and services and the respective basic ecological principles considered during the study. Moreover, the socioeconomic aspects that determine environmental evaluations and decision-making processes require in-depth analysis and understanding of the value and importance of RSs captured in this study for the successful implementation of this approach (Müller et al., 2009; Reta & Soromessa, 2024).

The Millennium Ecosystem Assessment Approach is based on the linkages between two pillars: ES and Human Well-being (Millennium Ecosystem Assessment, 2005) (Annex 2). The strength of these linkages between ecosystem service classes and components of human well-being indicates the extent to which the socioeconomic factors in the LHB intervene in the linkage. This linkage has significantly affected the existing RSs, defining the demand-supply chain within the study area (Annex 3) (Burkhard et al., 2014; Millennium Ecosystem Assessment, 2005; Reta & Soromessa, 2024).

2.3 Methods

Various methods and tools were employed in this study to identify, prioritize, and map the existing RS in the study area, as discussed in the following sections (Figure 2). Recognizing the relevance of this study for sustainable natural resource management, which is crucial for maintaining the existing RS, and the simplicity and user-friendliness of the study methodology; it is essential for interested parties conducting similar studies in the country and globally. This facilitates the straightforward application of these methods to support community livelihood, human well-being, and the sustainability of development projects at the Basin or watershed scale. However, the limited knowledge of this integrated ecosystem service assessment approach and the absence of similar studies in the area and country posed challenges for the author. Consequently, the author could not compare this study's results with any similar papers conducted using this method in the country. Therefore, this study stands out among previous studies in the country, significantly contributing to the swift identification of spatial patterns of RS at the basin scale and supporting sound decision-making processes during the planning and implementation of watershed and related development projects.

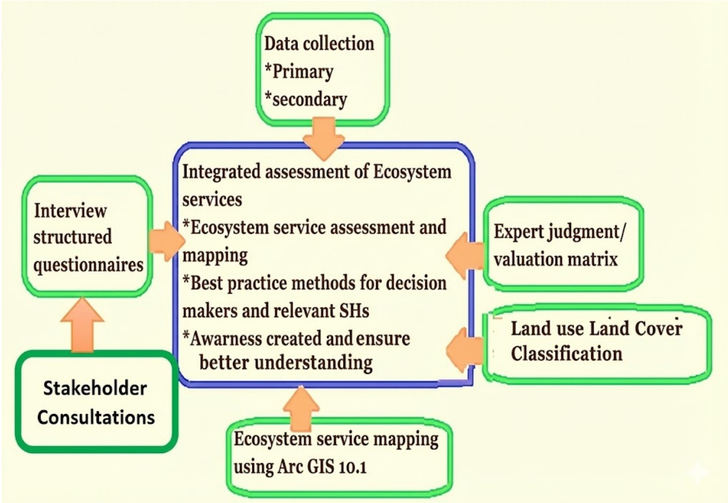


Figure 2. Typical methodological framework

2.3.1 Data collection

The study emphasized collecting relevant information to understand the situation and trends of RS in the LHB. The Millennium ES Assessment Approach was adopted due to its reduced demand for complex and costly data gathering, collating, and analyzing. Primary and secondary data, along with community and stakeholder opinions, were collected during consultation sessions to describe RS features and trends at national, regional, and local levels (Kosmus et al., 2012). Major data sources included LULC, household population, climate, hydrology, soil, slope, vegetation, etc. collected from the Ministry of Water and Energy and other relevant institutions. Consultations with government and non-government organizations, universities, fishery associations, and others at local, regional, and national levels were conducted. Stakeholder consultations, site visits, and reviews of various study papers and working documents were carried out to gather key study data.

2.3.2 Stakeholder consultations

Stakeholder consultation was crucial for collecting, organizing, and analyzing the required data. Snowball sampling was used to identify stakeholders, ensuring full participation and avoid missing key informants (Goodman, 1961). Sixty (60) stakeholders from diverse community groups, which were purposively selected were including farmers, fishermen, tourists, academicians, officials, and experts, were identified, consulted, and trained before engaging in the selection and prioritization of RS. The consultations were aimed at gathering information on stakeholders' perceptions and local knowledge regarding the importance and value of RS, informing and training them about the study methodologies, and seeking their consent to fully engage in the prioritization and selection process of the relevant four RS out of existing 11 RSs in the study area. Awareness and brief training on the Integrated Ecosystem Service Assessment Approach, including ecological, social, and economic factors, and the application of study checklists and the Expert Judgment Matrix (EJM) were provided to consulted stakeholders (LHB) (Fagerholm et al., 2012; Hein et al., 2006; Kandziora et al., 2013; Lamarque et al., 2011a).

2.3.3 Land use land cover classification

The LHB comprises several ecosystems with varied functions, structures, and processes. LULC maps, coupled with knowledge of each LULC unit's capacity to provide RSs, are used as tools for decision-makers to identify the potential of each ecosystem, possible conflicts, and their limits in environmental management (Burkhard et al., 2012a). Identifying and classifying LULC units played a crucial role in assessing and mapping the spatial patterns of the selected four relevant RSs. The identification exercise of each landscape unit was based on field survey findings and information from reviewed study documents and maps obtained from Ministry of Water and Energy, regional bureaus, universities, and other institutions. The study used 10 LULC units classified based on the RVLB master plan study conducted by (Ministry of Water and Energy, 2007) (Table 1).

The year 2007 was chosen as a baseline for this study and we adapted the data from the office of (Ministry of Water and Energy, 2007; Reta & Soromessa, 2024). The year 2016 and 2024 were deliberately selected to map the LULC following the standard land classification techniques. After the Landsat image was downloaded, the image was clipped by using the shape file of the Hawassa Lake Basin. Following that, each year LULC type was preprocessed and prepared using the ArcGIS software (Version 10.1). The images were classified following supervised classification using maximum likelihood classifier technique. The study tried to maintain the minimum level of image classification accuracy, which was 85% as recommended by many authors (Allam et al., 2019; Mohajane et al., 2018).

Table 1. Lake Hawassa Basin LULC classification

No.	LULC	Code
1	Intensively cultivated farm	ICF
2	Forest including lantations	FP
3	Grassland	GL
4	Lake	L
5	Marshland	ML
6	Shrubland	SL
7	Urban/Settlements	U/S
8	Woodland	WL

Source: Ministry of Water and Energy, 2007

2.3.4 Expert Judgment Matrix

EJM is a popular ES assessment technique for prioritizing and selecting essential RSs and mapping practices (Table 2). This matrix is technically simple and swiftly provides information regarding prioritized and selected RS for mapping exercises, facilitating the involvement of 60 consulted stakeholders. The study adopted a procedure to evaluate spatial differences among the prioritized RSs based on the analysis of existing landscape data and the respective capacity of each LULC unit to provide these services (Burkhard et al., 2014; Burkhard et al., 2012a; Burkhard et al., 2012b; Burkhard et al., 2009).

Table 2. Typical EJM/ Ecosystem Potential Matrix (ESPM)

No.	LULC	Water Purification	Flood Regulation	Erosion Regulation	Waste Regulation
1	Intensively cultivated farm				
2	Forest including plantation				
3	Grassland				
4	Lake				
5	Marshland				
6	Shrubland				
7	Settlement / Urban				
8	Woodland				

Source: Burkhard et. al., 2009; Mohajane et al., 2018

Table 3. Lists of prioritized RSs

RS	Rank
Erosion regulation	1
Flood (water flow) regulation	2
water purification	3
Waste Regulation	4
Global climate regulation	5
Air quality regulation	6
Local climate regulation	7
Nutrient regulation	8
Natural hazard regulation	9
Pest and disease control	10
Pollination	11

Source: Burkhard et. al. 2009; Burkhard et al. 2014

Table 4. EJM assessment scale (0–5)

Score	Description
0	No relevant capacity
1	Very low relevant capacity
2	Low relevant capacity
3	Medium-high relevant capacity
4	High relevant capacity
5	Very high relevant capacity

Source: Burkhard et. al. 2009

Following the conceptual framework adapted from (Burkhard et al., 2009; Mohajane et al., 2018) the study used the 2007 LULC data to assess, identify, and illustrate the capacity of each landscape unit to provide RSs and to determine the overall existing potential capacities of the LHB ecosystems. The selection and prioritization of four RS from the existing 11 RSs were conducted through consultations and brief training of 60 stakeholders on the approach before starting the selection and prioritization process. Stakeholders used consecutive numerical values of 1 to 11 to assign their preferences, with 1 being the most important and 11 being the least significant. The remaining 9 RSs were sorted and ordered ascendingly using numbers between the two extremes (Table 3).

Table 5. Proposed indicators to represent RSs

No.	RS	Service Definition	Potential Indicators
1	Global climate regulation	Long-term storage of greenhouse gases in ecosystems.	Source-sink of methane, carbon dioxide and water vapour (t C/ha*a) Amount of stored trace gases in marine systems, vegetation and soils (t C/ha)
2	Local climate regulation	Changes in local climate components like wind, precipitation, temperature, radiation due to ecosystem properties.	Temperature (°C), albedo (%), precipitation (mm), wind (Bft), temperature amplitudes (°C), evapotranspiration (mm), shaded areas (ha, %) Leaf area index
3	Air quality regulation	Capturing/filtering of dust, chemicals and gases.	Air quality amplitudes (ppb) Air quality standards deviation (ppb) Level of pollutants in the air Critical loads (kg/ha*a) Difference between open land and throughfall (kg/ha*a)
4	Water flow regulation	Maintaining water cycle features (e.g. water storage and buffer, natural drainage, irrigation and drought prevention).	Groundwater recharge rate (mm/ha*a)
5	Water purification	The capacity of an ecosystem to purify water, e.g. from sediments, pesticides, disease-causing microbes and pathogens.	Water quality indicators: Sediment load (g/l) Total dissolved solids (mg/l) 14
6	Nutrient regulation	The capacity of an ecosystem to recycle nutrients, e.g. N, P.	Water quality indicators, e.g. N (mg/l), P (mg/l) Leakage of nutrients (kg/ha*a) Electrical conductivity (S/cm) Total dissolved solids (mg/l) Turnover rates of nutrients, e.g. N, P (y–1)
7	Erosion regulation	Soil retention and the capacity to prevent and mitigate soil erosion and landslides.	Vegetation cover (%) Loss of soil particles by water and wind (kg/ha*a) USLE factors for assessment of landslide frequency (n/ha*a)
8	Natural hazard protection	Protection and mitigation of floods, storms (hurricanes, typhoons…), fires and avalanches.	Number of prevented hazards (n/a) Natural barriers (dunes, mangroves, wetlands, coral reefs) (%, ha)
9[a]	Pollination	Bees, birds, bats, moths, flies, wind, non-flying animals contribute to the dispersal of seeds and the reproduction of lots of plants.	Species numbers and amount of pollinators (n/ha)
10[a]	Pest and disease control	The capacity of an ecosystem to control pests and diseases due to genetic variations of plants and animals making them less disease-prone and by actions of predators and parasites.	Populations of biological disease and pest control agents (n/ha)
11[a]	Regulation of waste	The capacity of an ecosystem to filter and decompose organic material in water and soils.	Amount and number of decomposers (n/ha) Decomposition rate (kg/ha*a)

[a]These ES are listed here because they can be of high importance in some ecosystems though the potential of double counting must be noted (Kandziora et al., 2012)

The output of stakeholders' prioritization and selection exercise was used to evaluate the spatial patterns of the selected 4 RSs along with the corresponding capacity of each LULC unit through analysis of existing landscape data (Burkhard et al., 2012a; Burkhard et al., 2009). Stakeholders also placed values for each RS in the blank EJM across the corresponding LULC unit, with the y-axis designated for 10 LULC types and the x-axis for 4 prioritized RSs, as depicted in Table 2. The capacity of each LULC to provide the respective RS was assessed and presented on a 0–5 scale (Table 4).

2.3.5 Mapping using ArcGIS 10.1

Mapping is essential to identify and demonstrate the potential capacity of each LULC unit and the spatial differences of the selected and prioritized four RS at the basin scale (Burkhard et al., 2012a). It helps to identify prevailing problems, especially in synergy and trade-offs among ES and between ES and biodiversity. Mapping plays a key role in communication to create awareness and initiate discussions on the importance and value of RSs among stakeholders, decision-makers, and development partners. The study presents the specific locations of top relevant RSs benefiting the community residing within and around the study area using spatial pattern RS mapping at the LHB scale. LULC data was used to map the selected and prioritized four RSs, following the mean value of each RS recorded in the EJM. All required data for mapping, including shapefiles, were obtained from Ministry of Water and Energy. LULC maps were produced by extracting information from these shapefiles.

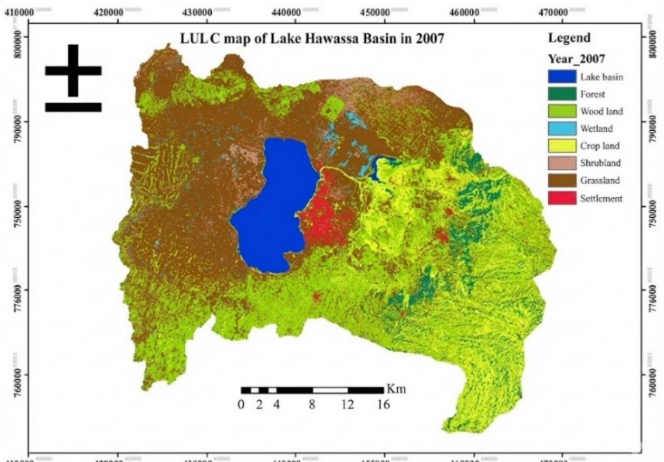
Relevant indicators for each selected RS were taken as input for analysis and mapping exercise (Kandziora et al., 2012) (Table 5). The selected 4 RS and the associated indicators were considered to collect information and used for further assessment to determine the spatial patterns of each RS within LHB (Kandziora et al., 2013). The spatial patterns of each RS generated from the LULC class were demonstrated on a basin scale map with varied colors attached to the 0–5 scale value assigned by stakeholders. Different colors were used to indicate the status of each LULC unit's capacity to provide the respective RSs, denoting zero (0), no relevant capacity and deep green representing (5), very high relevant capacity (Table 4). LULC and RS spatial pattern maps were plotted using ArcGIS v10.1 to illustrate detailed information on the status and potential of LHB's ecosystems to provide RS. These maps facilitate the identification and assessment of the spatial variation of existing annual potential RS in the study area. The detailed study findings are discussed in the result section below.

3. Results

This section discusses the integrated assessment and spatial pattern mapping of four prioritized RS at the basin scale: Erosion Regulation, Flood Regulation, Water purification, and Waste Regulation. These services were prioritized by 60 stakeholders, including local community members, fishermen, tourists, officials, experts from government organizations, and university academicians. The prioritization process was based on stakeholders' knowledge obtained through consultation and brief training, as well as their individual prior exposure and acquaintances with each RS. The selected RS were then mapped to depict their spatial variations at the basin scale.

3.1 Mapping of LULC

LULC plays a key role in mapping the spatial patterns of the four selected RS. The study uses 10 LULC classes, which are demonstrated in a pie chart (Annex 4) and LULC map (Figure 3). The LULC map and pie chart show that intensively cultivated smallholder farms accounted for 60.2% of the study area, with perennial crops, like Enset, Sugar Cane, and coffee mainly in the eastern hills and cereals like Sorghum, Maize, and Barely in the western and southern parts. The remaining 39.8% of the LHB is covered by other LULC units, such as Grassland (9.5%), Shrubland (7.8%), Lake (6.5%), Marshland (5.1%), Urban/Settlements (3.1%), intensively cultivated mechanized farms (2.5%), Woodland (2.3%), Dense Forest (2%) and Plantation Forest (0.9%), which mainly located around the Wendo Genet and Wendo Koshe hills found in the eastern part of the LHB (Table 6 and Figure 3).



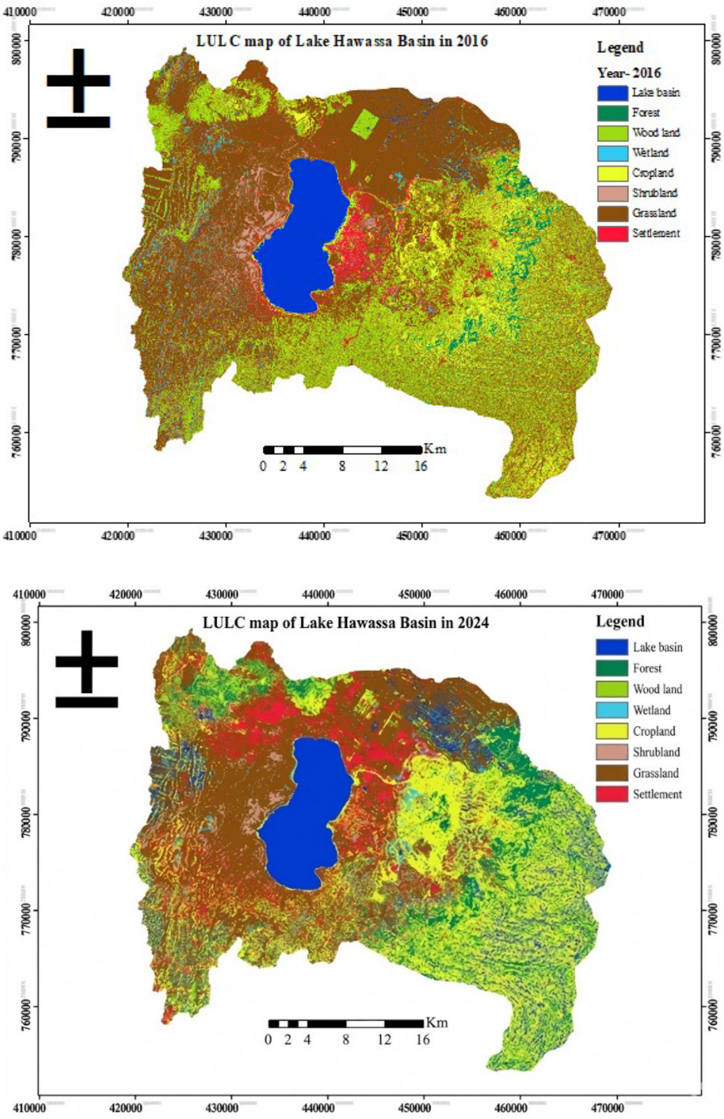


Figure 3. LULC map of Lake Hawassa Basin for the year 2007, 2016 and 2024, respectively

Recently, based on the LULC map of the study area, there was a shift in LULC from natural habitats to human modified ecosystem. The crop land (including both the smallholder and the mechanized farming) showed increment from nearly from 63.7 to 71.4%. This share of the total land size is significant. On the other hand, natural ecosystems like forest, grassland and shrub lands were declining (Table 6).

Table 6. Lake Hawassa Basin LULC (2007, 2016 and 2024)

No.	LULC	Area (km^2) (2007)	% (2007)	Area (km^2) (2016)	% (2016)	Area (km^2) (2024)	% (2024)
1	Intensively cultivated farm	897.6	62.7	948.5	66.2	962.2	67.2
2	Forest including plantation	42	2.9	40.2	2.81	38.2	2.7
3	Grassland	136.6	9.5	101.1	7.06	92.6	6.5
4	Woodland	33.3	2.3	30.2	2.11	28.2	2.0
5	Shrubland	111.5	7.8	92.9	6.49	80.7	5.6
6	Urban/Settlement	44.9	3.1	53.7	3.75	65.2	4.6
7	Marshland	72.9	5.1	71.4	4.98	70.7	4.9
8	Lake	93.5	6.5	94.3	6.58	94.5	6.6
Total		1432.3	100	1432.3	100	1432.3	100

Source: Ministry of Water and Energy (2007), baseline data

These varied LULC data indicate that the study area encompasses diverse ecosystems with different capacities to provide RSs, benefiting the local community. Grassland, Marshland, Forest, and Lake ecosystems, covering about 22% of the area play key roles in providing water purification, and waste, erosion, and flood regulation services. This service benefits the community members in environmental protection by preventing the area from flood and erosion hazards, managing wastes, and purifying water resources (Annex 4). This information is crucial for decision-makers and development partners to identify areas for erosion and flood regulation projects. The mean values of the four prioritized RS across the 10 LULCs, affected by anthropogenic activities, are shown in and radar diagram (Figure 4) and the EJM (Table 7).

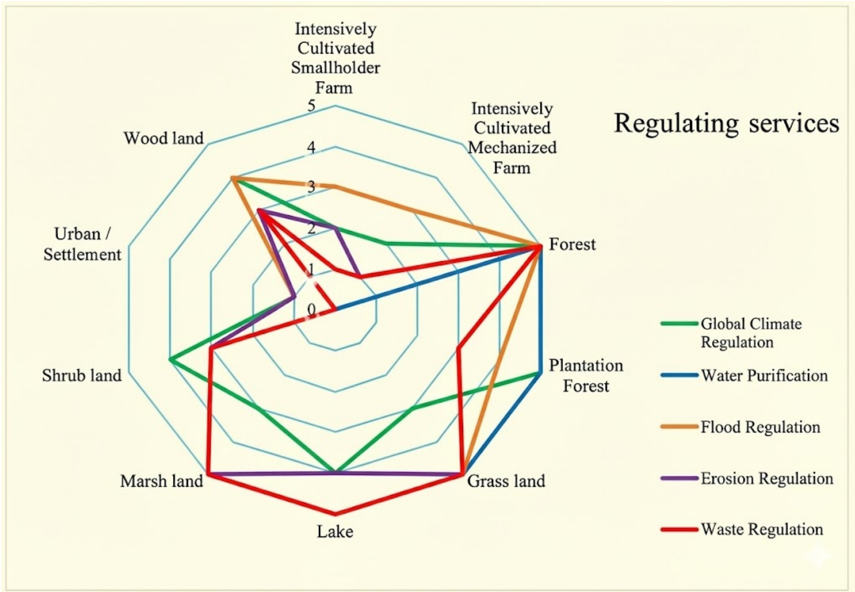


Figure 4. Radar diagrams for the mean value of annual potentials RS in Lake Hawassa Basin following the assessment scale from 0–5

Table 7. RS Mean value of LHB Ecosystem Service Potential matrix

No.	LULC	Water Purification	Flood Regulation	Erosion Regulation	Waste Regulation
1	Intensively cultivated farm	0	3	2	1
2	Forest including plantation	5	5	5	5
3	Grassland	5	5	5	5
4	Lake	4	4	4	5
5	Marshland	5	5	5	5
6	Shrubland	3	3	3	3
7	Settlement / Urban	1	1	1	0
8	Woodland	3	4	3	3
Mean value		3	4	3	3

3.2 RS Spatial Distribution Mapping

Several spatial pattern maps were plotted for the four selected RS, further elaborated in this section.

Water Purification: The spatial patterns of water purification services (Figure 5) show that grassland, marshland, and forest ecosystems have a mean value of very high relevant capacity (MV-5) to provide water purification RS. This benefits the local community through the self-treatment of surface water sources used for various purposes existing near their locality, without or with the limited intervention of development projects. Shrubland and woodland ecosystems have medium relevant capacity (MV-3) to provide water purification services to the local community, while intensive cultivation of mechanized and smallholder farm ecosystems have no relevant capacity (MV-0). The reason for the existence of low water purification capacity of cultivated land was due to the modification of the land. This caused change in soil physicochemical properties like soil compaction, loss of organic carbon soil and excess use of chemical fertilizers reduce the soil biota. As a result, it changes the hydrological cycle and increased the runoff and nutrient exports.

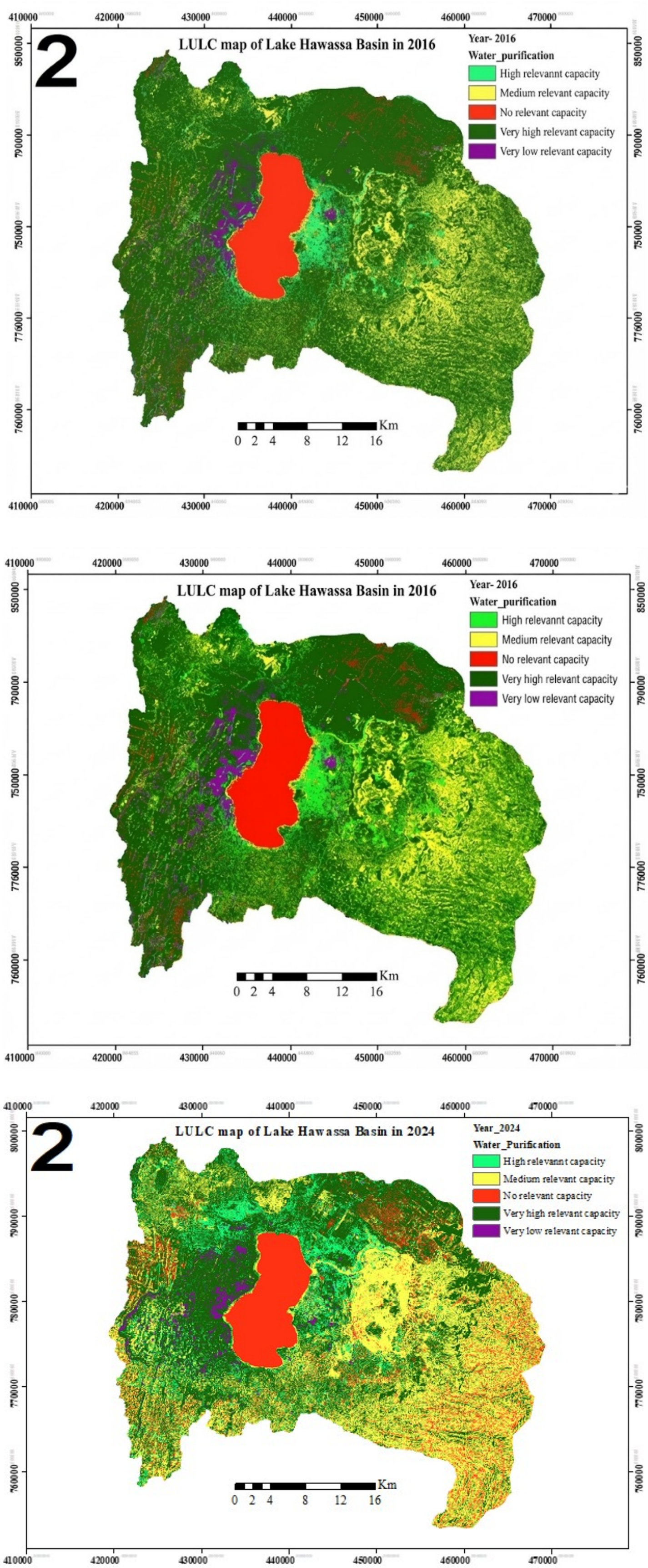


Figure 5. Spatial distribution of annual potential of Regulating ES_water purification in 2007,2016 and 2024, respectively

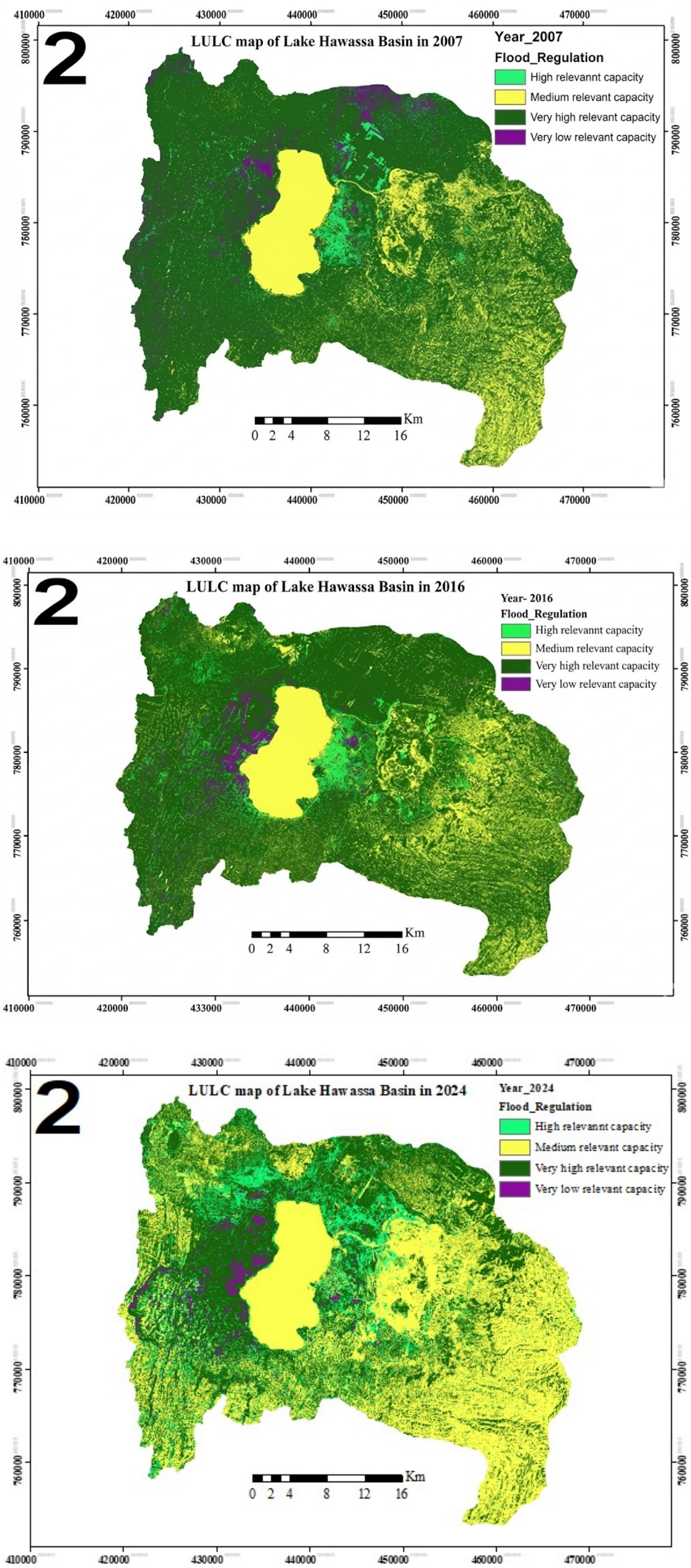
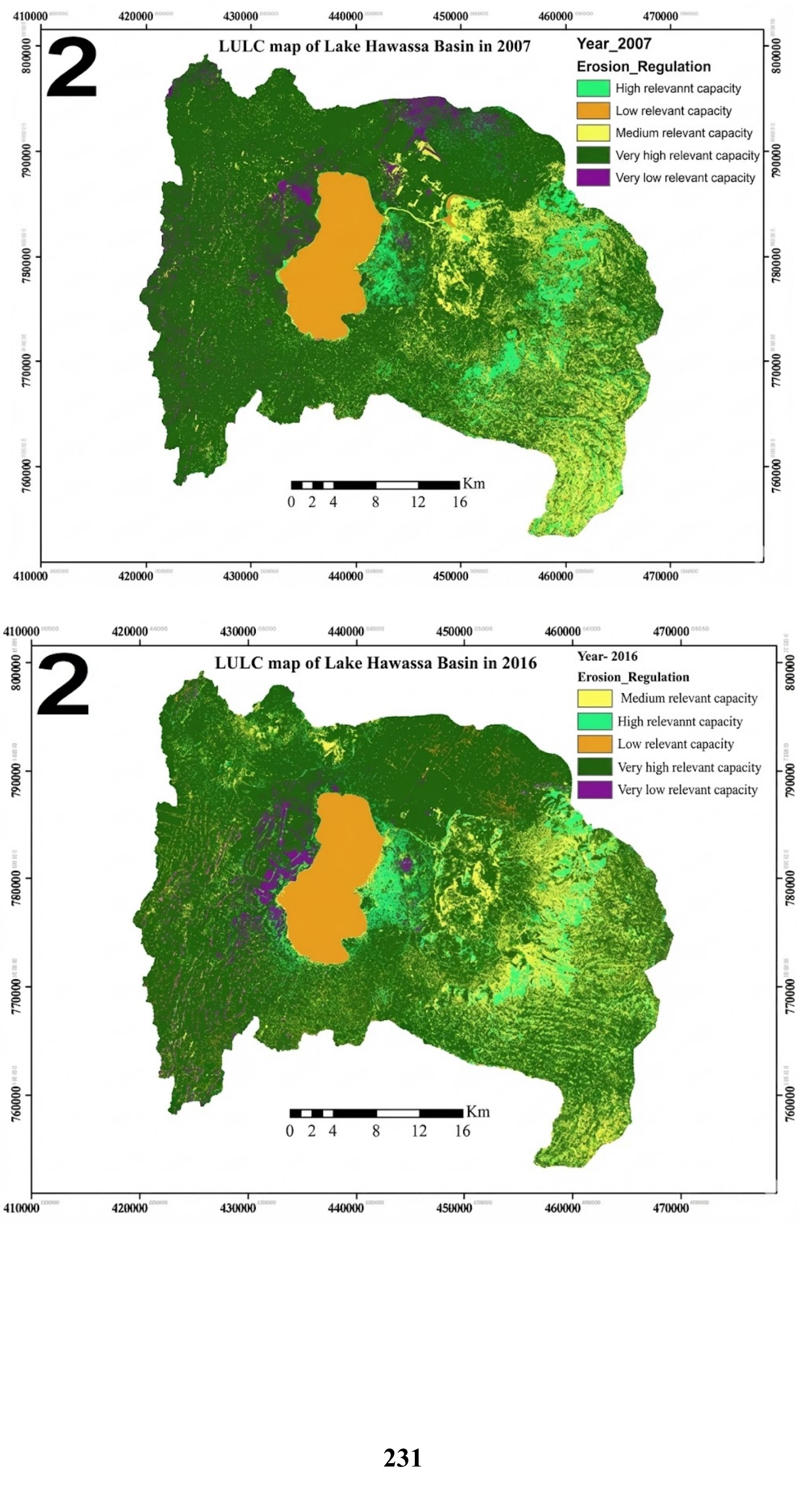


Figure 6. Spatial distribution of annual potential of Regulating ESS _Flood Regulation in 2007, 2016 and 2024

Flood Regulation: The spatial pattern of flood regulation services (Figure 6) indicates major variations between forest and urban ecosystems, ranging from very high to very low capacity. Grassland, forest, and marshland ecosystems have a very high capacity for flood regulation. This information is vital for planning flood and stormwater regulation projects. The reason for higher flooding incidence in urban areas was due to the existence of impervious surface, which blocks the rainwater from infiltrating into the underground. In addition, the settlement areas are devoid of vegetation, occupied by large people, and exposed to flood water, which reduced the flood regulatory service of urban lands.

Erosion Regulation: The spatial pattern of erosion regulation services (Figure 7) shows that urban and intensively cultivated areas have very low to low capacity (MV-1) for erosion regulation, covering about 65.8% of the study area. Lake, marshland, and forest ecosystems have a very high capacity (MV-5) for erosion regulation. The land size of 65.8% of the lake basin had low to very low erosion regulation services. These were mainly of the settlement and cultivation areas, which are known for lack of vegetation cover. Vegetation helps to absorb the rainwater, reduce energy from rainfall, and enhance its infiltration rate. In addition, cultivated lands are known for tillage practices, which exposed the soil to erosion.



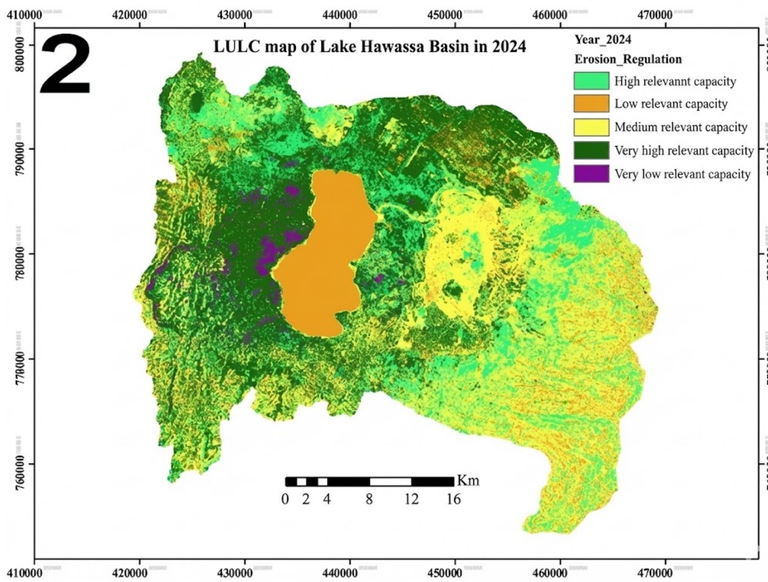
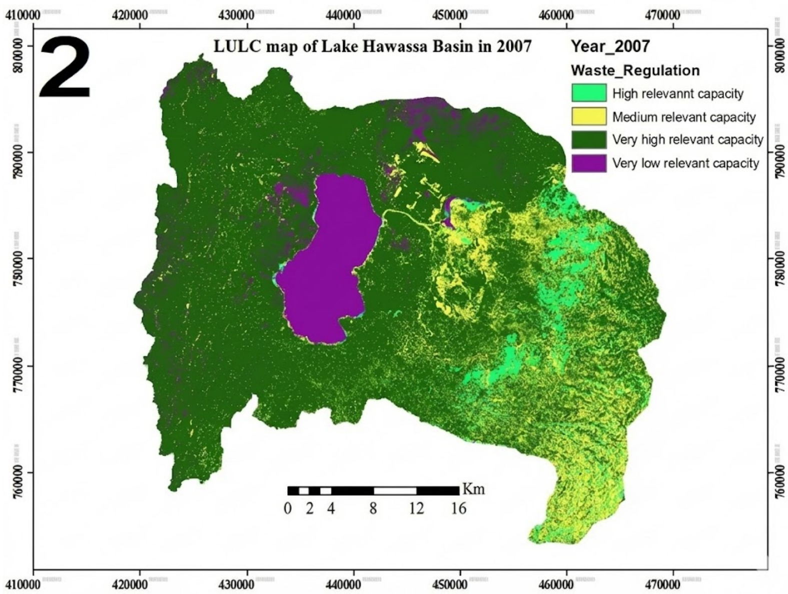


Figure 7. Spatial distribution of Regulating ESS _Erosion Regulation in 2007, 2016 and 2024, respectively

Waste Regulation: The spatial pattern of waste regulation services (Figure 8) shows varied capacities across ecosystems. Urban areas have no relevant capacity (MV-0), while intensive cultivation areas have very low capacity (MV-1). Lake, marshland, grassland, and forest ecosystems have a very high capacity (MV-5) for waste regulation. The likely cause for the low waste regulation capacity in urban and cultivated lands is linked with the existence of high human population per square kilometer area, economic activities and land modification, even which increase waste generation. These results inform decision-makers about the specific locations where waste management and other environmental management practices are needed, aiding in the planning and implementation of sustainable development projects in the LHB.



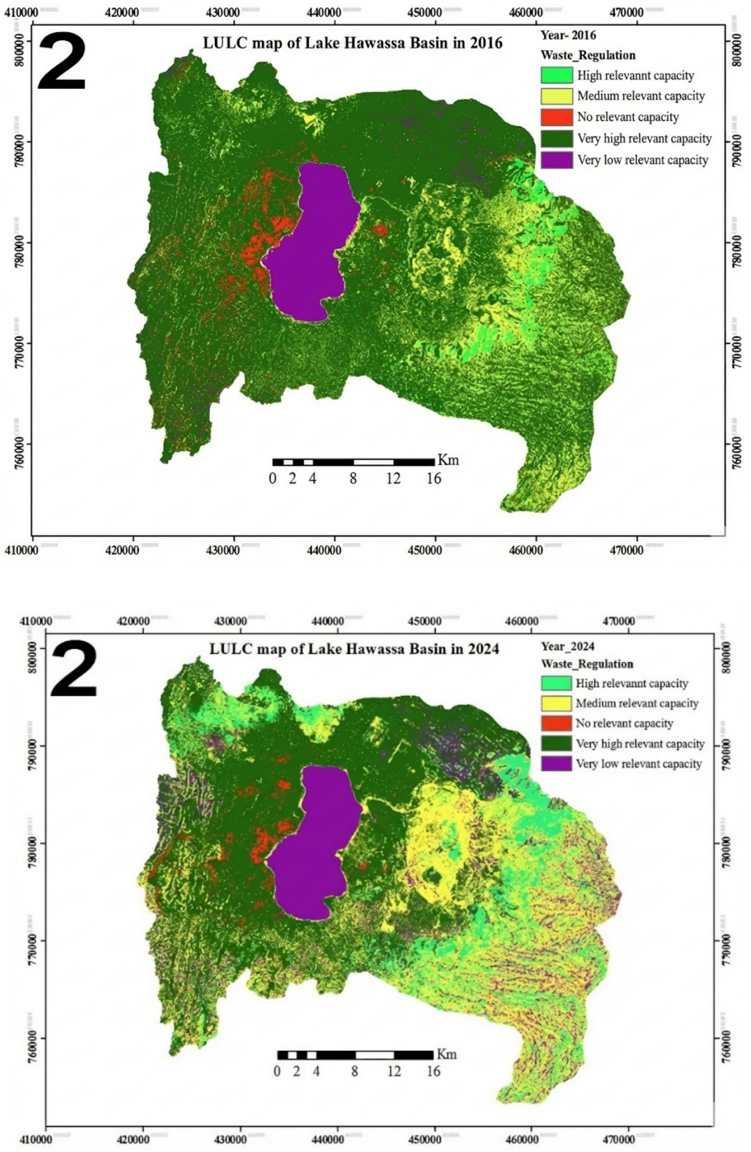


Figure 8. Spatial distribution of Regulating ESS _Waste Regulation in 2007, 2016 and 2024, respectively

4. Discussion

The study area encompasses about 10 ecosystems with varied potential to provide RS. The capacity of each ecosystem to provide these services is determined by the presence of natural resources, including biodiversity, and their structure and function, which contribute to human well-being (Millennium Ecosystem Assessment, 2005; Burkhard et al., 2012b). One of the study's outputs of this study is information on the capacity of different ecosystems in the LHB to provide RS, which is crucial for sustainable planning and implementation of development activities. The findings highlight the spatial variability of each RS, resulting from the structure and function of existing ecosystems and their respective supply capacities.

This information could be essential inputs for planning and implementing natural resource conservation and management practices, as well as watershed management projects, ultimately benefiting the community (García-Nieto et al., 2013; Martínez-Harms & Balvanera, 2012; Reta & Soromessa, 2024). The study results drawn from the integrated ES assessment approach (Millennium Ecosystem Assessment, 2005) serve as a knowledge base for stakeholders, policymakers, and other interested parties in the nation or globally, illustrating the link between landscape type and RS distribution at the basin scale.

The study's findings on the spatial patterns of RS and the capacity of each LULC simplify the planning process for policymakers and development partners. This facilitates valid development-oriented decisions that fit the environmental and social settings of the study area. For example, ecosystems with low capacity for erosion and flood regulation may require interventions such as stormwater and drainage management, soil and water conservation, etc. to prevent and minimize flood-related disasters. Adequate consideration of these findings can help integrate them into project design, ensuring sustainable development with minimal costs and time savings.

The study considered four relevant RS out of eleven existing in the study area, prioritized by stakeholders from various social groups (Reta & Soromessa, 2024; Tengö et al., 2014). Their prioritization was based on the perceived value and importance of RS, relevant to human needs. The output of this prioritization exercise was used to fill the EJM, which served as a tool for mapping the spatial patterns of selected RS at the basin scale. Previous studies have highlighted the importance of including diverse stakeholder groups, particularly the local community, in ecosystem service assessment and prioritization exercises, as their exposure and knowledge to the landscape units vary (Lamarque et al., 2011b; Martín-López et al., 2012; Reta & Soromessa, 2024).

Engaging local stakeholders in the decision-making process contributes to collective knowledge during development planning and familiarizes them with an integrated ecosystem assessment approach (Reta & Soromessa, 2024; Tengö et al., 2014; Swetnam et al., 2011). This encourages knowledge sharing and shared actions, enhancing sustainable management practices and understanding the multifunctional nature of ecosystems, ensuring adequate delivery of RS (García-Llorente et al., 2012; Pilgrim et al., 2008; Pilgrim et al., 2007; Reta & Soromessa, 2024). Adopting this study's approach can help address environmental and socioeconomic problems, such as land degradation, deforestation, pollution, and erosion, ensuring environmentally friendly, socially acceptable, and economically feasible development activities.

One of the major causes for the decline in the RS was the expansion of crop cultivation in the basin. The findings of this study suggest the need for practicing sustainable land management practices such as reforestation, using physical and biological soil-water conservation structures in cultivated land (Biratu et al., 2023; Mengist et al., 2023; Mitiku et al., 2006). This could help to enhance the RS from cultivated land. The study can therefore deliver qualitative information for stakeholders to design and implement strategies for the improvement of Rs especially such as erosion control, waste regulation, water purification, and flood control in the Hawassa Lake basin.

Overall, the implementation of adequate and proper land management approaches is essential to enhance the benefits of the basin in terms of its RS (Biratu et al., 2023). For instance, in China, regulating ES using protection scenario result sustainable socioeconomic development mainly by increasing the water resource (Yang, 2012). ES are essential for human existence and managing them in an efficient way is vital for ecosystem and socioeconomic development (Deng et al., 2016).

5. Conclusion

Overall, this study helps RS to avoid and minimize environmental and socioeconomic problems by safeguarding or abating land degradation, deforestation, pollution, resource exploitation, etc. and ensures all development activities planned or implemented in the study area are environmentally friendly, socially acceptable, economically feasible through sustainable management of natural resources. In conclusion, the study's assessment and mapping of RS provide valuable information for integrating into national sectoral policies, benefiting the planning and management of development activities within the Lake Hawassa Basin. The integrated assessment of RS is crucial for planning and implementing individual projects, collecting reliable data, and understanding the socio-cultural realities of communities and ecosystems.

In addition, the study results together demonstrate that ecosystem services mapping is a highlighting tool "for grasping the socio-cultural realities of communities, regions, landscapes and ecosystems" and make evident the need for including different stakeholder groups in ecosystem service assessment and mapping captures diverse knowledge sources, human-environment relations, and value systems. Given the simplicity and user-friendliness that could be adopted by any interested parties as well as the limited output, to qualify further and gain much-advanced output, as a next step it is recommended to conduct similar study shall consider and be supported with additional methodological input of modeling and valuation of prioritized RS to enhance the study's output. Considering this, appropriate consideration of this study methodology and results will play a key role in sustainable development project implementation, securing the livelihood of community members and human well-being in Lake Hawassa Bain.

The study had several limitations, including a lack of similar studies in the area to compare, a limited number of stakeholders, inadequate facilities or shapefiles specific to the study area, and limited awareness of the integrated ecosystem service assessment approach. The study prioritized the ecosystem services based on the expert judgement and partly biasness may occur due to inherent biases of the expert and difficulties in including large number of experts. However, the study applied available secondary data to keep the quality information which could reduce the high dependency on professional judgments. Carefully, each RS was explained to the experts to prioritize according to their benefits to human wellbeing that could help to reduce their biasness.

Author Contributions

Conceptualization, B.A.R. and T.S.; methodology, B.A.R. and T.S.; formal analysis, B.A.R. and T.S.; investigation, B.A.R. and T.S.; resources, B.A.R. and T.S.; data curation, B.A.R. and T.S.; writing—original draft

preparation, B.A.R. and T.S.; writing—review and editing, B.A.R. and T.S. All authors have read and agreed to the published version of the manuscript.

Funding

This work is funded by Addis Ababa University, Ethiopia, and Kiel University, Germany.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Acknowledgements

Special thanks to Addis Ababa University and Kiel University for providing the necessary working environment, materials used for the fieldwork, and funding support.

Conflicts of Interest

The authors declare no conflict of interests.

References

Abate, B., Woldesenbet, A., & Fitamo, D. (2015). Water quality assessment of Lake Hawassa for multiple designated water uses. *Water Util. J.*, *9*, 47–60. ewra.net/wuj/pdf/WUJ_2015_09_05.pdf

Allam, M., Bakr, N., & Elbably, W. (2019). Multi-temporal assessment of land use/land cover change in arid region based on Landsat satellite imagery: Case study in Fayoum Region, Egypt. *Remote Sens. Appl. Soc. Environ.*, *14*, 8–19. https://doi.org/10.1016/j.rsase.2019.02.002.

Belete, M. D., Richards, N., & Gehrels, A. (2024). Ecosystem services provision through nature-based solutions: A sustainable development pathway to environmental stewardship as evidenced in the Protecting Lake Hawassa Partnership in Ethiopia. *Socio Ecol. Pract. Res.*, *6*, 331–345. https://doi.org/10.1007/s42532-024-00193-x.

Biratu, A. A., Solomon, B. B., Gebrehiwot, S. G., Melesse, A. M., Asmamaw, D. K., Hordofa, T., & Kidale, D. (2023). Implications of land management practices on selected ES in the agricultural landscapes of Ethiopia: A review. *Int. J. River Basin Manag.*, *21*, 3–20. https://doi.org/10.1080/15715124.2020.1870991.

Burkhard, B., de Groot, R., Costanza, R., Seppelt, R., Jørgensen, S. E., & Potschin, M. (2012a). Solutions for sustaining natural capital and ecosystem services. *Ecol. Indic.*, *21*, 1–6. https://doi.org/10.1016/j.ecolind.2012.03.008.

Burkhard, B., Kandziora, M., Hou, Y., & Müller, F. (2014). Ecosystem service potentials, flows, and demands: Concepts for spatial localization, indication, and quantification. *Landsc. Online*, *34*, 1–32. https://doi.org/10.3097/LO.201434.

Burkhard, B., Kroll, F., Müller, F., & Windhorst, W. (2009). Landscapes' capacities to provide ecosystem services: A concept for land-cover based assessments. *Landsc. Online*, *15*, 1–22. https://doi.org/10.3097/LO.200915.

Burkhard, B., Kroll, F., Nedkov, S., & Müller, F. (2012b). Mapping ecosystem service supply, demand, and budgets. *Ecol. Indic.*, *21*, 17–29. https://doi.org/10.1016/j.ecolind.2011.06.019.

Carpenter, S. R., Mooney, H. A., Agard, J., Capistrano, D., DeFries, R. S., Díaz, S., Dietz, T., Duraiappah, A. K., Oteng-Yeboah, A., Pereira, H. M., et al. (2009). Science for managing ecosystem services: Beyond the Millennium Ecosystem Assessment. *Proc. Natl. Acad. Sci. U. S. A.*, *106*, 1305–1312.

Costanza, R., d'Arge, R., De Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R. V., & Paruelo, J. (1997). The value of the world's ecosystem services and natural capital. *Nature*, *387*, 253–260. https://doi.org/10.1038/387253a0.

Degife, A., Worku, H., Gizaw, S., & Legesse, A. (2019). Land use land cover dynamics, its drivers and environmental implications in Lake Hawassa Watershed of Ethiopia. *Remote Sens. Appl. Soc. Environ.*, *14*, 178–190. https://doi.org/10.1016/j.rsase.2019.03.005.

Deng, X., Li, Z., & Gibson, J. (2016). A review on trade-off analysis of ES for sustainable land-use management. *J. Geogr. Sci.*, *26*, 953–968. https://doi.org/10.1007/s11442-016-1309-9.

Diriba, A., Begna, R., Zerfu, H., Alemayehu, A., Ayana, A. N., & Tsegaye, N. T. (2024). Analyzing the extent and drivers of land use/land cover change in Southwestern Ethiopia. *Discov Sustain.*, *5*(1), 505. https://doi.org/10.1007/s43621-024-00734-0.

Egoh, B., Rouget, M., Reyers, B., Knight, A. T., Cowling, R. M., van Jaarsveld, A. S., & Welz, A. (2007). Integrating ES into conservation assessments: A review. *Ecol. Econ.*, *63*, 714–721. https://doi.org/10.1016/j.ecolecon.2007.04.007.

Fagerholm, N., Käyhkö, N., Ndumbaro, F., & Khamis, M. (2012). Community stakeholders' knowledge in landscape assessments: Mapping indicators for landscape services. *Ecol. Indic.*, *18*, 421–433. https://doi.org/10.1016/j.ecolind.2011.12.004.

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., Chapin, F. S., Coe, M. T., Daily, G. C., Gibbs, H. K., et al. (2005). Global consequences of land use. *Science*, *309*, 570–574. https://doi.org/10.1126/science.1111772.

García-Llorente, M., Martín-López, B., Iniesta-Arandia, I., López-Santiago, C. A., Aguilera, P. A., & Montes, C. (2012). The role of multi-functionality in social preferences toward semi-arid rural landscapes: An ecosystem service approach. *Environ. Sci. Policy*, *19*, 136–146. https://doi.org/10.1016/j.envsci.2012.01.006.

García-Nieto, A. P., García-Llorente, M., Iniesta-Arandia, I., & Martín-López, M. (2013). Mapping forest ES: From providing units to beneficiaries. *Ecosyst. Serv.*, *4*, 126–138. https://doi.org/10.1016/j.ecoser.2013.03.003.

Goodman, L. A. (1961). Snowball sampling. *Ann. Math. Stat.*, *32*, 148–170. https://doi.org/10.1214/aoms/1177705148.

Hein, L., van Koopen, K., de Groot, R. S., & van Ierland, E. C. (2006). Spatial scales, stakeholders and the valuation of ES. *Ecol. Econ.*, *57*, 209–228. https://doi.org/10.1016/j.ecolecon.2005.04.005.

Institute of Biodiversity Conservation. (2005). *Site action plan for the conservation and sustainable use of Lake Awassa biodiversity (Rift Valley Lake project)*. ebi.gov.et/wp-content/uploads/2021/10/EBI-Organizational-Description-Brochure.pdf

Kandziora, M., Burkhard, B., & Müller, F. (2012). Interactions of ecosystem properties, ecosystem integrity, and ecosystem service indicators: A theoretical matrix exercise. *Ecol. Indic.*, *28*, 54–78. https://doi.org/10.1016/j.ecolind.2012.09.006.

Kandziora, M., Burkhard, B., & Müller, F. (2013). Mapping regulating services at the local scale using data of varying spatial and temporal resolution. *Ecosyst. Serv.*, *4*, 47–59. https://doi.org/10.1016/j.ecoser.2013.04.001.

Kindu, M., Schneider, T., Teketay, D., & Knoke, T. (2016). Changes of ecosystem service values in response to land use/land cover dynamics in Munessa–Shashemene landscape of the Ethiopian highlands. *Sci. Total Environ.*, *547*, 137–147. https://doi.org/10.1016/j.scitotenv.2015.12.127.

Kosmus, M., Renner, I., & Ullrich, S. (2012). *Integrating ES into development planning: A stepwise approach for practitioners based on the TEEB approach. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH.* https://www.cbd.int/cepa/cepafair/2018/presentations/cepa-fair-2018-giz-values-pub.pdf

Lamarque, P., Quétier, F., & Lavorel, S. (2011a). The diversity of the ecosystem services concept and its implications for their assessment and management. *C. R. Biol.*, *334*, 441–449. https://doi.org/10.1016/j.crvi.2010.11.007.

Lamarque, P., Tappeiner, U., Turner, C., Steinbacher, M., Bardgett, R. D., Szukics, U., Schermer, M., & Lavorel, S. (2011b). Stakeholder perceptions of grassland ecosystem services in relation to knowledge on soil fertility and biodiversity. *Reg. Environ. Change*, *11*, 791–804. https://doi.org/10.1007/s10113-011-0214-0.

Lencha, S. M., Tränckner, J., & Dananto, M. (2021). Assessing the water quality of lake Hawassa Ethiopia—Trophic state and suitability for anthropogenic uses—Applying common water quality indices. *Int. J. Environ. Res. Public Health*, *18*, 8904. https://doi.org/10.3390/ijerph18178904.

Li, J., Carlson, B. E., & Lacis, A. A. (2009). A study on the temporal and spatial variability of absorbing aerosols using Total Ozone Mapping Spectrometer and Ozone Monitoring Instrument Aerosol Index data. *J. Geophys. Res.*, *114*, D09213. https://doi.org/10.1029/2008JD011278.

Maes, J., Teller, A., & Erhard, M. (2013). *Mapping and assessment of ecosystems and their services: An analytical framework for ecosystem assessments under Action 5 of the EU Biodiversity Strategy to 2020*. https://publications.jrc.ec.europa.eu/repository/handle/JRC81328

Martínez-Harms, M. J., & Balvanera, P. (2012). Methods for mapping ecosystem service supply: A review. *Int. J. Biodivers. Sci. Ecosyst. Serv. Manag.*, *8*, 17–25. https://doi.org/10.1080/21513732.2012.663792.

Martín-López, B., Iniesta-Arandia, I., García-Llorente, M., Palomo, I., Casado-Arzuaga, I., García Del Amo, D., Gómez-Baggethun, E., Oteros-Rozas, E., Palacios-Agundez, I., Willaarts, B., et al. (2012). Uncovering ecosystem service bundles through social preferences. *PLoS ONE*, *7*(6), e38970. https://doi.org/10.1371/journal.pone.0038970.

Mengist, W., Soromessa, T., & Feyisa, G. L. (2023). Responses of soil and water-related ES to landscape dynamics in the eastern Afromontane biodiversity hotspot. *Heliyon*, *9*, e22639. https://doi.org/10.1016/j.heliyon.2023.e22639.

Millennium Ecosystem Assessment. (2005). *Ecosystems and human well-being: General synthesis.* Island Press. https://www.millenniumassessment.org/documents/document.356.aspx.pdf

Ministry of Water and Energy. (2007). Rift Valley Lakes Basin integrated resources development master plan study project. https://www.cmpethiopia.org/content/download/3032/12444/file/RiftValley_RBA.pdf

Ministry of Water and Energy. (2010a). *Rift Valley Lakes Basin integrated resources development master plan study project: Phase 3 final report: Lake Hawassa Sub-Basin integrated watershed management feasibility study: Annex K,* Environmental impact assessment.

Ministry of Water and Energy. (2010b). *Rift Valley Lakes Basin integrated resources development master plan study project: Phase 3 final report: Lake Hawassa Sub-Basin integrated watershed management feasibility study: Volume I, Main report.*

Mir, Y. H., Mir, S., Ganie, M. A., Bhat, J. A., Shah, A. M., Mushtaq, M., & Irshad, I. (2025). Overview of land use and land cover change and its impacts on natural resources. In *Ecologically Mediated Development: Promoting Biodiversity Conservation and Food Security* (pp. 101–130). Springer. https://doi.org/10.1007/978-981-96-2413-3_5.

Mitiku, H., Herweg, K., & Stillhardt, B. (2006). *Sustainable Land Management: A New Approach to Soil and Water Conservation in Ethiopia.* Mekelle University. https://dl.ojocv.gov.et/admin_/book/sustainable%20Land%20managment.pdf

Mohajane, M., Essahlaoui, A., Oudija, F., El Hafyani, M., El Hmaidi, A., El Ouali, A., Randazzo, G., & Teodoro, A. C. (2018). Land use/land cover (LULC) using Landsat data series (MSS, TM, ETM+ and OLI) in Azrou Forest, in the Central Middle Atlas of Morocco. *Environments*, *5*(12), 131. https://doi.org/10.3390/environments5120131.

Müller, F., Burkhard, B., & Kroll, F. (2010). Resilience, integrity and ecosystem dynamics: Bridging ecosystem theory and management. In *Landform–Structure, Evolution, Process Control* (pp. 221–242). Springer-Verlag. https://doi.org/10.1007/978-3-540-75761-0_14.

Perrings, C., Duraiappah, A., Larigauderie, A., & Mooney, H. (2011). The biodiversity and ecosystem services science-policy interface. *Science*, *331*, 1139–1140. https://doi.org/10.1126/science.1202400.

Pilgrim, S., Cullen, L., Smith, D. J., & Pretty, J. (2008). Ecological knowledge is lost in wealthier communities and countries. *Environ. Sci. Technol.*, *42*(4), 1004–1009. https://doi.org/10.1021/es070837v.

Pilgrim, S., Smith, D. J., & Pretty, J. (2007). A cross-regional assessment of the factors affecting eco-literacy: Implications for policy and practice. *Ecol. Appl.*, *17*, 1742–1751. https://doi.org/10.1890/06-1358.1.

Plieninger, T., Dijks, S., Oteros-Rozas, E., & Bieling, C. (2013). Assessing, mapping, and quantifying cultural ES at the community level. *Land Use Policy*, *33*, 118–129. https://doi.org/10.1016/j.landusepol.2012.12.013

Reta, B. A. & Soromessa, T. (2024). Integrated assessment and mapping of provisioning services for sustainable management of natural resources, the case of Lake Hawassa Basin, Ethiopia. *Heliyon*, *10*(3), e24847. https://doi.org/10.1016/j.heliyon.2024.e24847.

Riitters, K. H., Wickham, J. D., Vogelmann, J. E., & Jones, K. B. (2000). National land-cover pattern data. *Ecology*, *81*, 604. https://doi.org/10.1890/0012-9658(2000)081[0604:NLCPD]2.0.CO;2.

Ryan, R. L. (2011). The social landscape of planning: Integrating social and perceptual research with spatial planning information. *Landsc. Urban Plan.*, *100*, 361–363. https://doi.org/10.1016/j.landurbplan.2011.01.015.

Swetnam, R. D., Fisher, B., Mbilinyi, B. P., Munishi, P. K. T., Willcock, S., Ricketts, T., & Mwakalila, S. (2011). Mapping socio-economic scenarios of land cover change: A GIS method to enable ecosystem service modeling. *J. Environ. Manag.*, *92*, 563–574. https://doi.org/10.1016/j.jenvman.2010.09.007.

Tengö, M., Brondizio, E. S., Elmqvist, T., Malmer, P., & Spierenburg, M. (2014). Connecting diverse knowledge systems for enhanced ecosystem governance: The multiple evidence base approach. *Ambio*, *43*, 579–591. https://doi.org/10.1007/s13280-014-0501-3.

Tesfaye, M. S. (2019). Assessment of ES for sustainable management of Lake Hawassa and its biodiversity, Southern Ethiopia. *Int. J. Sci. Eng. Res.*, *10*, 230.

Tessema, M. W., Abebe, B. G., & Bantider, A. (2024). Physical and socioeconomic driving forces of land use and land cover changes: The case of Hawassa City, Ethiopia. *Front. Environ. Sci.*, *12*, 1203529. https://doi.org/10.3389/fenvs.2024.1203529.

The Economics of Ecosystems and Biodiversity. (2010). *Mainstreaming the economics of nature: A synthesis of the approach, conclusions, and recommendations of TEEB.* https://www.researchgate.net/publication/230743686_Mainstreaming_the_Economics_of_Nature_a_Synthesis_of_the_Approach_Conclusions_and_Recommendations_of_TEEB

Wade, A. S. I., Asase, A., Hadley, P., Mason, J., Ofori-Frimpong, K., Preece, D., Spring, N., & Norris, K. (2010). Management strategies for maximizing carbon storage and tree species diversity in cocoa-growing landscapes. *Agric. Ecosyst. Environ.*, *138*, 324–334. https://doi.org/10.1016/j.agee.2010.06.007.

Yang, B. (2012). Regulation strategies of regional land use management based on ES: A case study in Wanquan Town, Zhejiang Province of East China. *Chin. J. Appl. Ecol.*, *23*, 1677–1684. https://pubmed.ncbi.nlm.nih.gov/22937655/

Yilma, G. (2019). Wetlands ecosystem service in terms of economic values: A case of Lake Hawassa, southern Ethiopia. *Plants Environ.*, *1*, 89–96. https://plantsandenvironment.peri.org.in/article/13/13-611.pdf

Appendix

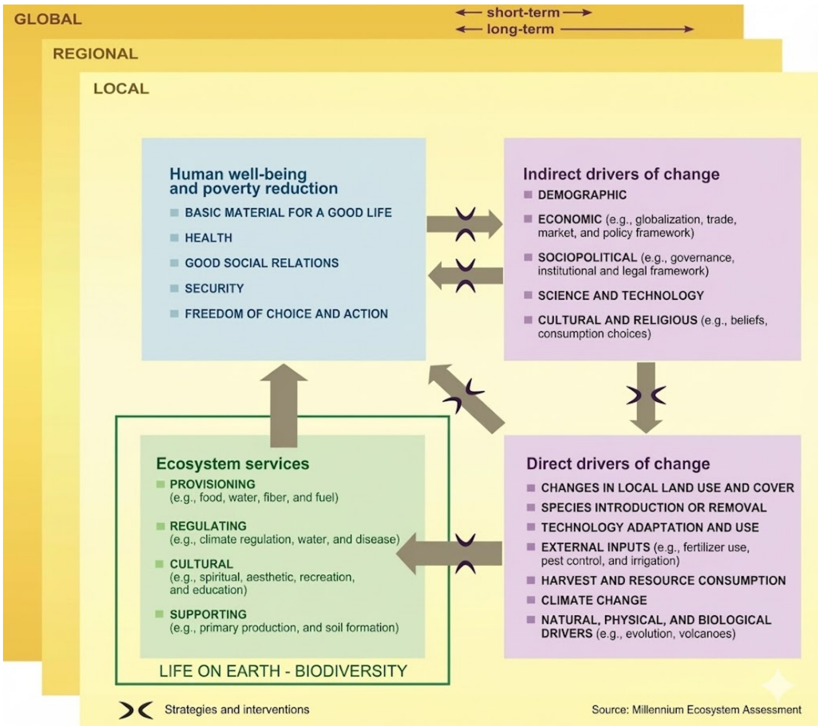


Figure A1. Conceptual framework of interactions between biodiversity, human well-being, and drivers of change

Sources: Millennium Ecosystem Assessment, 2005

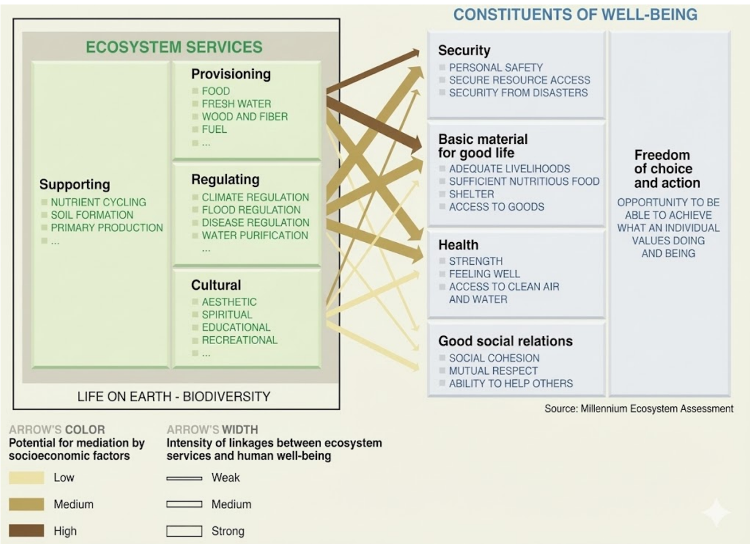


Figure A2. Linkages between ES and human well-being

Source: Millennium Ecosystem Assessment, 2005

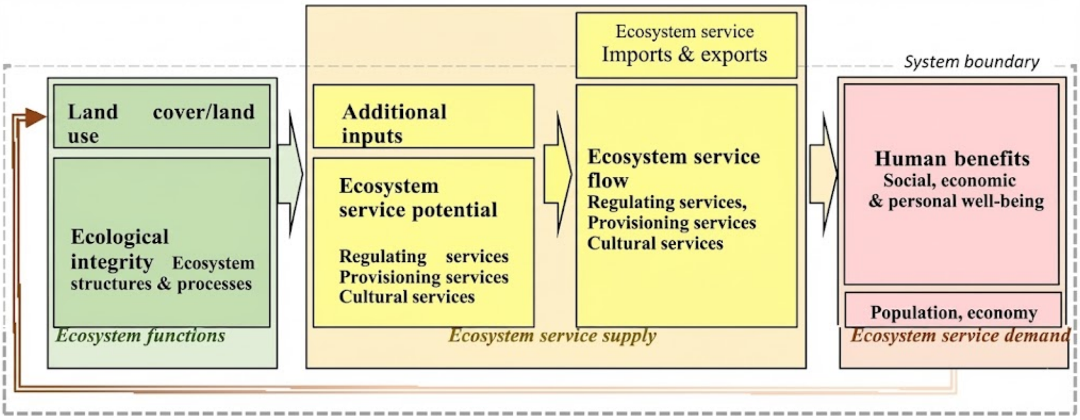


Figure A3. Conceptual model showing relations of ecosystem functions, services, and benefits
Sources: Burkhard et al., 2014

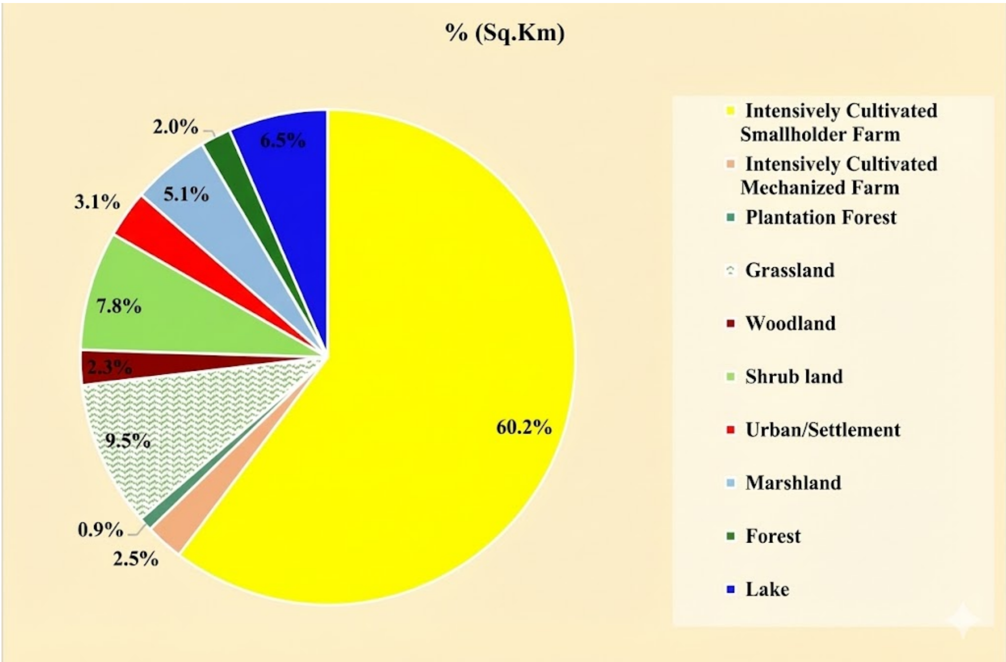


Figure A4. Pie chart for lake Hawassa basin LULC type and area coverage in percent (2007)
Source: Ministry of Water and Energy, 2007; Ministry of Water and Energy, 2010a; Ministry of Water and Energy, 2010b