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Economic Assessment of Selected Regulatory Ecosystem Services (RES) in the Elgeyo and Nyambene Watersheds Ecosystems in Kenya

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Abstract

Evidence of increased valuation of ecosystem services (ES) globally is significant. However, most of these studies focus on marketed subsets of ES at national and international levels. Ecosystems differ in spatial scale, biophysical and ecological structure, and functionality. This requires conducting studies at the local level to understand how, for example, the watershed ecosystem contributes to humanity locally and nationally. This study focuses on selected regulatory ecosystem services (RES) in Kenya's catchment area ecosystems (Elgeyo and Nyambene). Field-based sampling and Landsat imagery with secondary information were used to generate biophysical and ecological data. The study used market price-based, cost-based, and unit transfer methods for RES valuation. The study estimates the total value of the six selected regulatory ecosystem services (RES) at KES 41.4 billion (US$386.7 million) and KES 14.73 billion (US$137.71 million) for Elgeyo and Nyambene, respectively. This equates to KES 1.64 million (US$15,331.19) and KES 2.72 million (US$25,375) per hectare per year. Extrapolating the study estimates to the national level, the country's regulatory ecosystem services would range from US$18.4 billion to US$30.45 billion annually. This equates to between 16.7% and 27.7% of Kenya's GDP in 2021, underscoring the importance of watersheds to the national economy.

Keywords

Ecosystem Services, Regulatory Ecosystem Services, Market Pricing, Cost-Based Technique, Per Capita, GDP

1. Introduction

Ecosystem services (ES) are benefits gained by societies from natural ecosystems

(Costanza et al., 1997; Daily, 1997; Millennium Ecosystem Assessment (MA), 2005), besides ecological functions, are critical to sociocultural, economic, and human well-being (de Groot et al., 2012; Deal et al., 2012). Global forest ecosystems support millions of populations, particularly neighbouring communities, by providing both tangible and intangible benefits and supporting societal livelihoods and economies (Boyd & Banzhaf, 2007; Deal et al., 2012). Tangible benefits include fresh water, food, medicine, and fuelwood, while intangible benefits include a pleasant landscape, improvements in global climate, wildlife habitat, and regulation of atmospheric gas chemistry (Daily, 1997; Deal et al., 2012; Millennium Ecosystem Assessment (MA), 2005; Raymond et al., 2009; Vo et al., 2012). Despite the immense contribution to humankind, the contribution of ecosystem services remains invisible in socioeconomic, policy, and development discourses (Millennium Ecosystem Assessment (MA), 2005; Smith et al., 2013), and many decisions made about such ecosystems without considering actual ES monetary value (Mwaura et al., 2016).

The forested ecosystem covers 4.4 million hectares (7.7%) of the total land area of Kenya (FAO, 2015). And approximately 2.4 million hectares are under the management of the state (MoE&F, 2018) and 1.2 million hectares are closed canopy (watersheds) (MoE&F, 2018). The literature reports that forest ecosystems contribute about 3.6% to the gross domestic product (GDP), with records of about 1.3% of its contribution reported in national accounts (FAO, 2015). Literature has captured a small subset of ecosystem services in national accounts, notably timber products, while largely ignoring forest-regulated ecosystem services (RES) and non-use services. This level of accounting does not capture most ecosystem services and therefore not reflected in decision-making processes (East Africa Commission (EAC), 2014; Nahuelhual et al., 2007; TEEB, 2010). These measures arise for a couple of reasons, including the poor ability to assess and quantify ecosystem benefit on-site (Costanza et al., 2017), the complexities associated with multiscale and multi-dimensionality (de Groot et al., 2010), assessment approaches, data scarcity, and distortion of ES market among others. The lack of data on most ES values has made it difficult for conservationists and environmentalists to argue their case, particularly for promoting sustainable conservation, improving resource allocation, counteracting harmful strategies, and project implementation in watersheds. Studies have linked the invisibility of monetary value to setbacks in sustainable conservation (de Groot et al., 2002), overexploitation, degradation, and eventual decline in inventory and flow of benefits (Millennium Ecosystem Assessment (MA), 2005; Shaw et al., 2011), and impairment of social well-being (Barbier, 2015; Mutoko et al., 2015; van Jaarsveld et al., 2005). This is because goods and services with no monetary value are unlikely to be considered in the conservation decision-making process. Although efforts are being made worldwide to include ES in spatial planning, governance, and development discourse (Alamgir et al., 2016) to advance the appreciation of ecosystem services, we have done little at the local level. The valuation aims to determine the value of non-marketed ecosystem services individually or collectively. The overarching goal is to raise awareness towards changing the communities "free" or "zero value" mindset on ecosystem goods and services (Mwaura et al., 2016). The mere listing of the ES without the assignment of currency units forms the basis for the ES assessment (Costanza et al., 2017). However, an explicit assessment of ecological services would improve informed decisions, particularly if trade-offs exist (Braat & de Groot, 2012; de Groot et al., 2010), and highlight the costs of ecosystems and biodiversity loss (Di Franco et al., 2021).

Forest ecosystems such as Elgeyo and Nyambene are essentially critical to the role they play in providing goods and services to society, particularly to the forest bordering communities. The science of ecosystem services is still a new concept in Kenya and most studies have extensively used unit transfer (Seppelt et al., 2011). Using such techniques has not shown the variability of ES supply and flux across different forest types, land cover, environmental gradients, and vegetation attributes (Alamgir et al., 2016). Since ES supply and flux vary by the landscape, vegetation type, and their respective properties, it becomes necessary to verify ES values explicitly at the local ecosystem level (Baral et al., 2014; Burkhard et al., 2012; de Groot et al., 2002, 2010; García-Nieto et al., 2013; Muller & Burkhard, 2012; van Oudenhoven et al., 2012). This, therefore, required the assessment of ecosystem services and aggregated values for the two watersheds (Elgeyo and Nyambene) in Kenya because of the lack of data on their ES values. The contribution of such a study will raise awareness by making visible the monetary value of ES originating from such critical ecosystems in the country. Likewise, the results will feed into the growing assessment database in Kenya with reported aggregate unit values ranging from US$1000 to about US$16,000 per ha per year (Kipkoech et al., 2011; Langat, 2016; Langat et al., 2019; Langat & Cheboiwo, 2010; Mwaura et al., 2016; Mwaura & Muhata, 2009).

Overall, the aim of the study was making visible the monetary values of regulatory ecosystem services and the indirect role in local and international climate and economy; Besides revealing the link between indirect use values and livelihoods of particularly forest communities; Essentially, to pursue and advocate for the consideration of ES in development agenda and decision-making process; Equally, creating an awareness of indirect benefit drawn from watersheds globally and the need for their sustainable conservation.

2. Materials and Methods

2.1. The Study Area

Conducted the study in two of the selected watersheds (Elgeyo and Nyambene) in Kenya. The Elgeyo ecosystem covers 108,194 ha, including the state forest (24,354 ha) and adjacent farmland within the five-kilometre buffer zone (83,840 ha). The state forest comprises eight forest blocks, namely Kaptagat, Kipkabus, Kessup, Kapchorua IV, Tingwa Hills, Tumeya, Kapchorua I, and Metkei (**Figure 1**). The state forest comprises an exotic forest (40%), a native forest (38%), and

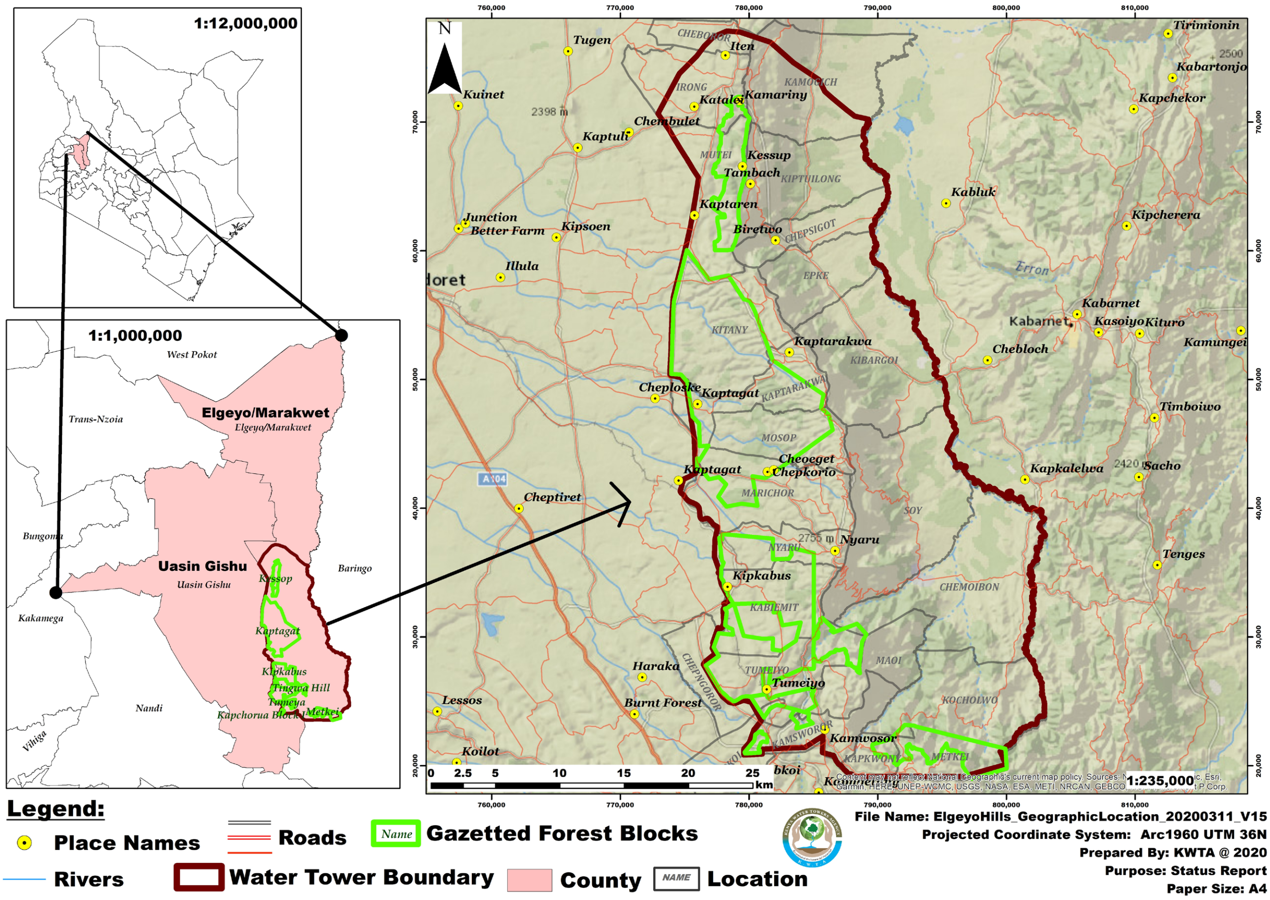

Figure 1. Map showing Elgeyo ecosystem alongside Kenya's and Elgeyo Marakwet county's map (Source: KWTA GIS database).

open grassland and scrubland (22%) (KWTA, 2020b). Largely, Elgeyo Marakwet County with a small section in Uasin-Gishu County with a population of 0.5 million and 1.2 million, respectively (KNBS, 2019). It extends from 35˚20'' to 35˚45''East and 0˚10' to 0˚20'North. Precipitation is binomial with a mean of 1200 mm, highest between March and May and lowest in August and October. Temperatures range from 11.2˚C to a high of 33˚C (KALRO, 2020). The study estimates the highest point in the ecosystem at 3350 m above sea level, while the slope varies between 2˚ and 60˚ (County Government of Elgeyo Marakwet, 2018; The Republic of Kenya, 1980; KWTA, 2020a).

The Nyambene ecosystem is part of the Tana and Ewaso-Nyiro watersheds and covers 30,313 ha comprising the state forest (5427 ha) and farmland within the five-kilometre buffer zone (24,886 ha). The state forest is predominantly indigenous and divided into four management blocks, including Nyambene, Kilimandingiri, Keiga, and Thuuri (KWTA, 2020c). The Nyambene extends from 0˚17'N to 0˚8'N, and from 37˚48'E to 37˚52'E within Meru County and traversed by the sub-counties of Igembe South, Igembe Central, Tigania East, Tigania West, and Tigania Central (**Figure 2**). The five sub-counties have a population of 691,298 (173,743 households) (KNBS, 2019). The precipitation regime is binomial with long rains between March and May and short rains in October and

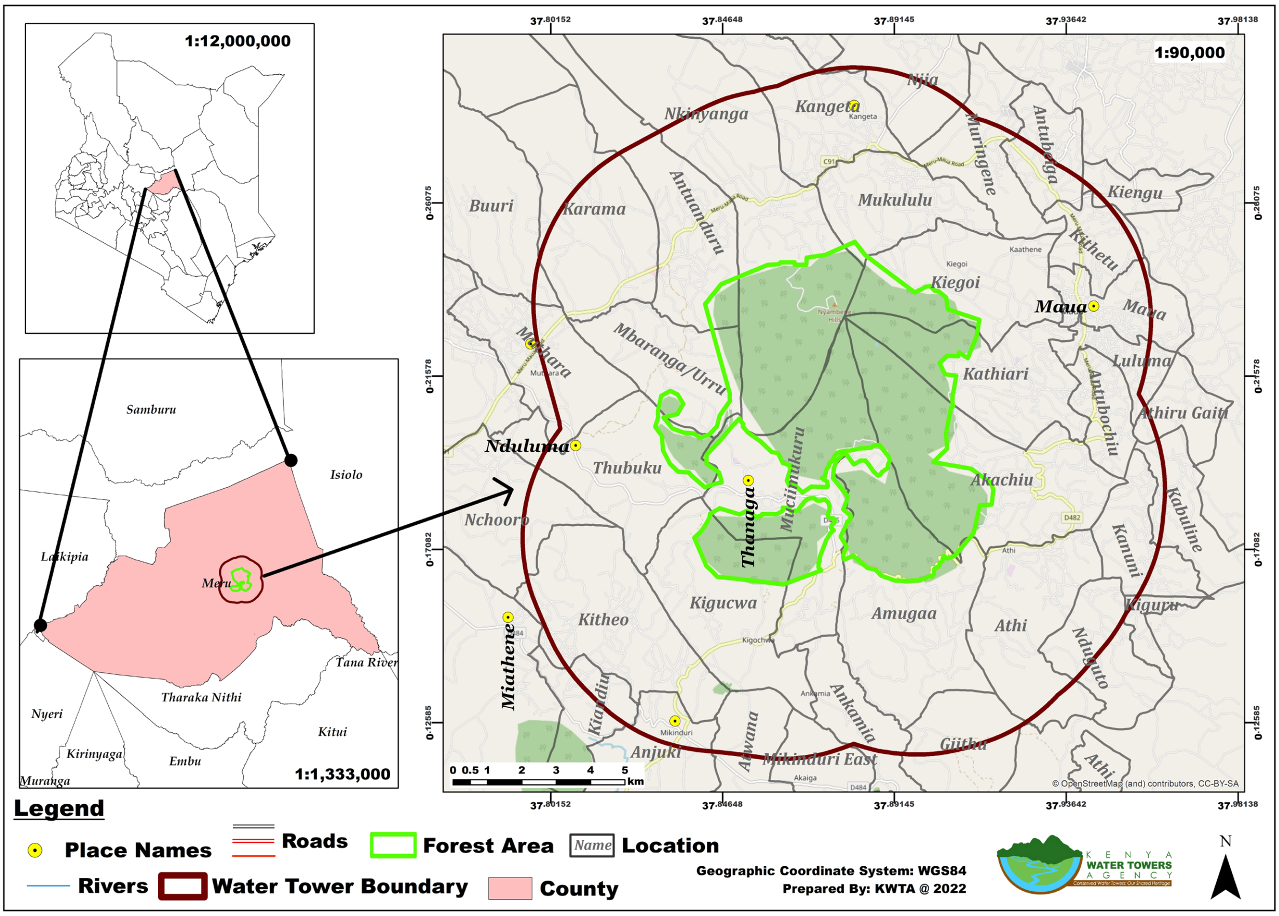

Figure 2. Map of Nyambene water tower alongside Kenya's and Meru county's map (Source: KWTA GIS database).

November and a mean of 1700 mm. The altitude of the area ranges from 1000 m to 2528 m above sea level, while temperatures range from 13.7˚C to 28.7˚C. Endowed with floral diversity, over 200 springs, and a significant number of streams and rivers that serve as water sources for populations within the watershed and further downstream (KWTA, 2020c).

2.2. Research and Sampling Design

The study adopted a cross-sectional design with the actual assessment based on ecosystem service type, data, and benefit cohorts. Based on the classification of the Millennium Ecosystem Assessment (MEA) and the TEV framework, the ES data collection regrouped into two perspectives: ecological and economic values. The study sourced ecological data using GIS and remote sensing supported with field sampling and substantiated with secondary data, while the economic data leading to monetary allocation used traditional valuation techniques such as market prices, cost-based, stated and revealed preference techniques, and benefits transfer (Baral et al., 2017). However, the study focused on regulatory and support services and used a hybrid approach with both biophysical and socio-economic attributes (Mengist et al., 2020).

2.3. Data Collection

2.3.1. Assessment of Ecological Values

The valuation of RES involved biophysical quantification and attribution of the monetary unit using non-market valuation techniques. The technique used was based on study size, data needs, availability, available resources, topics, and expertise (Baral et al., 2017; Burkhard et al., 2010, 2012; Häyhä et al., 2015; Paudyal et al., 2015). The assessment began with land use, land cover, RES profiling and quantification, attribution of shadow prices to products, and estimation of the total.

2.3.2. Land Use Classification

The study used Geographic Information System (GIS) and Remote Sensing (RS) techniques with a spatial resolution of 30 m to generate land cover data for the two ecosystems. The assessment began with image generation, image processing, classification with a random forest classifier, and creation of corresponding classified maps (LC1990, LC2000, LC2010, LC2020). Four Landsat path/array satellite images from three types of sensors from the United States Geological Survey (USGS) website, https://earthexplorer.usgs.gov/. Processed images during the dry season of the years, i.e. between January and March, to ensure cloud-free and improved image display. Processed the data using Arc GIS 10.7 and R Studio 1.4.1106 and ENVI 5.3 and projected the generated images onto the Universal Transverse Mercator (UTM) coordinate system, data Arc1960, Zone 36 North. Corrected for geometric errors from the sources using ground control points derived from a 1:50,000 scale topographical map. The other three previous versions (L5 TM, L7 ETM+, L7 ETM+) of Landsat imagery (1985 TM, 2001 ETM+, and 2010 ETM+) were then each referenced by performing the frame-to-frame registration method using the latest version corrected Landsat 8 OLI /TIRS 2022 image. The study adopted the IPCC Scheme II classification, which considers ten (10) classes, namely, dense forest, moderate forest, open forest, wooded grassland, open grassland, perennial cropland, annual cropland, wetland, open water bodies, and barrens.

The process began by delineating the training site with polygons, encoding the land cover, and enhancing the image features using true and false colour composites. The study performed validation of the predefined land cover Landsat imagery training site through field visits to 100 assessment points per ecosystem, Google Earth imagery, and historical land cover data. The study applied a random forest classifier with an accuracy of 0.8 based on the class confusion matrix to create a spectral signature and classification of all pixels in the generated image. Finally, we applied an image filter to smooth the classification results by removing "salt" and "pepper" noise from the classified maps. The final land cover maps were used to generate and analyse the LCLU class area size (ha) using the "Tabulae" area algorithm in Arc GIS version 10.7, which intersects the imagery in the respective study area.

2.3.3. Quantification and Economic Valuation of RES

1) Water flow regulation and Water Purification

The study opted for the water storage method of replacement costs, as shown (1), as widely accepted (Kibet et al., 2019; Langat, 2016; Xi, 2009) based on the avoided cost principle. The land cover size was determined using 2019 Landsat imagery, while the precipitation amount was based on average annual precipitation data sourced on request from the Kenya Metrology Database (MoE&F, 2020). Sourced runoff reduction coefficients from secondary databases of ecosystems with similar ecological characteristics (Kateb et al., 2013; Okelo et al., 2009) and relative land cover coefficients (Blume et al., 2007; Goel, 2011; Karamage et al., 2018; Kauffman et al., 2007). The unit costs of the water regulation were determined by the unit costs of the replacement system (artificial dam) (US\$3/m^3) based on a replacement cost principle (Eytan & Spuhler, 2020; The Ministry of Water and Irrigation and World Bank Kenya, 2005; Wu et al., 2010).

$$V_{WP} = \sum_{i=1}^{N} A_{LC} \times P_C \times RR_{Coef.} \times C_{Sur.} \quad (1)$$

V_{WP} represents the economic value of the watershed; A_{LC} represents the area (ha) of land cover; P_C represents the average annual rainfall that the ecosystem receives; RR_{coef}. Runoff reduction coefficient of the respective land cover (estimated by the precipitation runoff coefficient of the respective land cover/land use subtracted from the runoff coefficient of the bare area); C_{Sur} represents the unit cost per cubic meter of the replacement water reservoir.

The function of the water purification ecosystem was based on the avoided water treatment costs, according to formula (2). The amount of purified water was based on the estimated annual precipitation kept by the two ecosystems. The unit cost of the purification function was based on the unit cost of constructing and maintaining a backup facility (municipal water treatment plant) (Jahanifar et al., 2017). This was based on the assumption that the destruction of the forest ecosystem would cause water quality degradation, which would require the construction of a municipal wastewater treatment plant to replace the ecosystem function.

$$V_{WQ} = Q_{WC} \times \rho \quad (2)$$

where V_{WQ} represents the economic value of regulating the water quality of the ecosystem; Q_{WC} is the amount of water stored and purified by the ecosystem, represented by total household consumption; ρ represents the unit cost of US\$0.3/m^3 (Fuente et al., 2015) of the replacement water treatment mechanism.

2) Soil conservation and Erosion control

The study assumed the relative soil loss of land cover to be the unit cost of impact mitigation given by formula (3) on the avoided cost principle (Bishop, 1999; Nahuelhual et al., 2007). The land cover size was determined from the 2019 land cover Landsat imagery, while the study sourced the corresponding land cover soil erosion reduction coefficient from the secondary database (Hurni, 1988; Kateb et al., 2013; Tessema et al., 2020). The unit cost of the ecosystem's soil erosion control unction was based on the replacement cost of dredged water reservoirs. Here, the study estimates hydroelectric power generation dam dredging at US$3.34 per tonne of sediment (Adeogun et al., 2016).

$$V_{SC} = \sum LC_A \times SE_{RC} \times C_{Proxy} \quad (3)$$

where V_{SC} represents the economic value of forest soil protection; LC_A is the respective land cover area (ha); SE_{RC} is the soil erosion reduction coefficient based on land cover soil erosion coefficients (Hurni, 1988; Tessema et al., 2020); C_{proxy}: the proxy unit cost estimated at KES 351 (USD 3.34) per tonne of sediment (Adeogun et al., 2016).

3) Soil Nutrient Conservation

The assumed loss of in situ soil minerals (nitrogen (N), phosphorus (P), and potassium (K)) attributed to the relative soil loss across the different land covers and the unit replacement costs formula (4), as commonly applied (Nahuelhual et al., 2007). Soil mineral content across different land covers was determined by field sampling and laboratory analysis, while the study equated the unit value of soil nutrient protection function to a surrogate (artificial fertiliser) relative unit cost based on a replacement cost principle (Gizaw et al., 2021).

$$EV_{SNC} = \sum CS_{LC} * SN_{LC} * \delta_{SNF} * P_{CF} \quad (4)$$

where EV_{SNC} is the economic value of soil protection; CS_{LC} is soil conserved (kg/ha) of the respective land cover; SN_{LC} is the soil nutrient content (%) (N, P, K) in the forest soil; and δ_{CF} is the ratio of commercial fertilisers (1/51%, NPK-17-17-17); P_{CF} is the unit price of the commercial fertilisers (KES 60/kg).

4) Tree carbon quantification

The study used a generalised improved pantropical mixed species model (5) to estimate the above-ground biomass (AGB). Tree biomass assessment targeted two main carbon pools (stem and root biomass) for each tree with a DBH ≥ 5 cm. Field-based sampling with a nested concentric plot design was used to measure tree dimensions (including tree height, diameter at breast height, and crown diameter). The outer circle radius of 15 m was used to record and measure trees with DBH ≥ 20 cm, while a 10 m radius was used to measure trees with DBH ≥ 10 < 20 cm, and a radius of 5 m was used to record and measure parameters for trees with a DBH ≥ 5 cm while a 2 m radius was used to measure trees with a DBH < 5 cm and seedlings.

$$AGB = 0.0673 \times \left(\rho D^2 H\right)^{0.976} \quad (5)$$

where AGB is the above-ground weight of the tree (kg), ρ is the wood density, D is the diameter at breast height in cm, H is the tree height, while α and β are the model coefficients.

The study estimated the total tree biomass to be a proportion of 1.25 to the total biomass (Chavan & Rasal, 2010). Aggregated carbon accounts for approximately 47% of total biomass (Aalde et al., 2006; Domke et al., 2019). Sourced the respective wood densities from the wood density database (Zanne et al., 2009).

Wood-specific gravity was an important predictor of AGB, considering a wide range of vegetation types (Chave et al., 2014). The market prices were then used to estimate the economic value of the aggregated ecosystem carbon.

5) Soil carbon quantification

The study estimated soil carbon stocks from the proportion of soil organic carbon (SOC) and soil organic matter (SOM) levels processed. The study determined the organic matter (OM) content using the loss on ignition method (LOI) while organic carbon (OC) was based on a ratio of 1:0.58 (SOM: SOC). Carried out a soil sample preparation before processing. Samples were oven dried, crushed in a mortar and pestle for homogenisation, then sieved with a 2 mm sieve to remove debris and stones, which were weighed separately. After sieving, the soil samples underwent a dry burning process required for carbon analysis to remove residual moisture. Placed the two samples, each weighing 10 grams, in a pre-weighed crucible and then burned at 550˚C for a minimum of 8 hours and then cooled before recording their weights. The difference in weight of the soil before and after heating represented the moisture and organic matter content, while the residue represented the ash. The study estimated the soil organic carbon (SOC) based on a factor of 0.58 as given in formula (6), and carbon per unit area based on SOC and the respective soil coefficients as given in formula (7).

$$S_{OC} = \frac{\left(\left(IS\omega\right) - \left(SR\omega\right)\right) \times 0.58}{IS\omega} \quad (6)$$

where S_{OC} is soil organic carbon (%); $IS\omega$ is the initial weight of the soil sample; $SR\omega$ is the weight of soil residue after incineration;

$$T_{OC} = \left(\rho_s \times D_s \times S_{OC}\right)100 \quad (7)$$

T_{OC} is total organic carbon (Mg of C per ha); ρ is the bulk density (g/cm); D is the soil tread depth (cm).

In mass calculations, the study weighed soil samples for wet weight, air-dried at approximately 40˚C for 48 hours, with an aliquot of each sample taken after weighing the air-dried samples. The samples were further oven-dried at 105˚C for twenty-four hours and recorded their weights were. The study recorded three weights for each sample (i.e., total soil weight, the weight of the aliquot before oven drying at 105˚C, and the weight after oven drying at 105˚C) allowing the calculation of bulk density.

The study used the market pricing function (Pearce, 2001) as shown (8) to determine the value of forest carbon sequestration in contrast to the climate change damage function (Ferarro et al., 2011) with the potential value overestimation.

$$V_{FCR} = \sum\nolimits_{n=1}^{\infty} A_{LC} \times Q_C \times \varepsilon_C \quad (8)$$

where by V_{FCR} is the economic value for climate regulation, A_{LC} is the area (ha) of the respective land cover, Q_C is the amount of carbon dioxide sequestered by the respective land cover per unit area, while ε_C represents the average global carbon market price per unit of carbon.

Prices in global compliance markets currently range from less than US$1/mg of CO_2e to US$30/mg of CO_2e (AU$1-29/mg of CO_2e). While considering the voluntary markets, average prices range from US$1/mg of CO_2e to $5/mg of CO_2e or (AU$1-6/CO_2e) (World Bank Group, 2020). However, the study used $5 per tonne of CO_2 as the prevailing price for carbon traded in Kenya in the Voluntary Carbon Standard (VCS) REDD+ market.

2.4. Data Analysis

Descriptive statistics in Statistical Package for the Social Sciences (SPSS) were used to summarise data on measures of central tendency, spread, and variance. Carried out a normality test, and based on the test outcome, the study ran both Analysis of Variance (ANOVA) and Friedman's test for significance testing across the land cover.

3. Results and Discussions

3.1. Land Cover Land Use

The dominant land cover/use in the eight state forest blocks of the Elgeyo ecosystem in 2019 was a dense forest at 41% (natural and exotic), followed by cropland at 36%, and grassland at 22% grassland and scrubland. The dominant land cover in the Nyambene state forest was dense forest (92%) and cropland (6%) (**Table 1**).

Table 1. Land cover/land use size with respective loss.

Land Cover	Elgeyo		Nyambene	
	Area (ha)	Proportion (%)	Area (ha)	Proportion (%)
Dense Forest	8065.38	31.97	4775.00	87.99
Dense Exotic Forest	2366.65	9.38	236.84	4.36
Wooded Grassland	3487.06	13.82	96.04	1.77
Bushland/Scrubland	2021.73	8.01	-	-
Crop Land	8747.30	34.68	241.77	4.45
Perennial Cropland	448.06	1.78	71.41	1.32
Vegetated Wetland	52.79	0.21	-	-
Other lands	21.08	0.08	3.62	0.07
Open water	15.81	0.06	2.27	0.04
Fallow Land	-		-	-
Total	**25225.86**	**100.00**	**5426.94**	**100.00**

3.2. Watershed Protection

The study found that with a mean annual rainfall of 1200 mm (Elgeyo) and 1400 mm (Nyambene), the two ecosystems store about 70 million and 39 million cubic meters of rainwater annually, respectively. This translates to about 5400 m^3 and 7200 m^3 per hectare per year for Elgeyo and Nyambene. Using an average construction unit cost of US$3 per·$m^3$ of artificial water reservoir (dam) replacement, the study estimates the watershed protection values at KES15.6 billion (US$146.2 million) and KES8.6 billion (US$81 million) for the Elgeyo and Nyambene ecosystems, respectively. These correspond to KES 620,200/(US$5796.3) and KES 1,600,000/($14953.30) per hectare per year for Elgeyo and Nyambene, respectively (**Table 2**). The study's estimates were higher compared to a study in the Mau East ecosystem (Langat, 2016), which reported a watershed protection value of KES 127893.11 (US$1421.03) $ha^{-1}·yr^{-1}$, and a study in Indonesia which estimated water flow regulation and maintenance services value at US$1880 $ha^{-1}·yr^{-1}$ (range of $707 - 3110 $ha^{-1}·yr^{-1}$) (Aulia et al., 2020). Similarly, the study estimates were higher than the study value in China (Xi, 2009) between US$540 and US$560 per hectare per year. The study attributes discrepancies to the difference in runoff coefficients, mean annual precipitation, forest cover, and unit cost of the replacement reservoir, which vary by ecosystem and jurisdiction. The replacement unit cost only considered the costs for the construction of the reservoir, but not the operating and administration costs of the reservoir. Likewise, the study only considered the water conservation value for state forests and not the forest value for adjacent community agricultural land.

3.3. Water Quality Regulation

Based on their respective annual rainfall, the two ecosystems potentially store about 70 million·m^3 and 38 million·m^3 of water for Elgeyo and Nyambene, respectively. Using the replacement cost of US$0.3/$m^3$ (Fuente et al., 2015) as relative unit costs, the study estimates the water purification function of the two ecosystems at KES 2.2 billion (US$20.6 million) and KES 1.2 billion (US$11.2 million). This corresponds to KES 87862.3 (US$821.14) per hectare per year and KES 226340.86 (US$2115.34) per hectare per year for the Elgeyo and Nyambene ecosystems, respectively (**Table 3**). The study estimates for Elgeyo were within compared to a study in China (Xi, 2009) which ranged from US$999.55 to US$1149.84 in water quality improvement per hectare per year. However, the area estimates for the Nyambene ecosystem were slightly higher compared to the reference study. Likewise, the results also contradicted the results of a study in Mau East with an estimated water quality regulation value of US$12 per hectare per year. The study attributes the difference to the different water data used in the Mau East case, where it used domestic water data, as opposed to the potential precipitation storage used in the study. While attributes the difference to the study in China to the percentage of land cover and land use and inevitable price fluctuations.

Table 2. Watershed protection valuation.

Land Cover/Use	Elgeyo		Nyambene	
	Water Conserved (m3)	Water Conservation Value (KES)	Water Conserved	Water Conservation Value (KES)
Dense Forest	34566564.2	7685875545.64	35813186.8	7963062092.16
Industrial Forest	10142986.9	2255293133.48	1776321.47	394965079.31
Wooded Grassland	6013916.68	1337194373.12	379161.17	84306486.60
Bushland	3486764.97	775282191.97	-	-
Perennial Cropland	772745.02	171819856.02	729679.64	162244267.23
Annual Cropland	15085939.12	3354358562.81	281924.17	62685838.91
Vegetated Wetland	225504.49	50140922.61	-	-
Open Water	67553.13	15020439.23	-	-
Other Land	-	-	16963.24	3771776.95
Total	**70361974.5**	**15644985024.9**	**38997236.5**	**8671035541.16**

Table 3. Ecosystem water purification function valuation.

Land cover	Elgeyo		Nyambene	
	Water Preserved (m3)	Water Purification Value (KES)	Water Preserved	Water Purification Value (KES)
Dense Forest	34566564.18	1088846771.7	35813186.8	1128115385.2
Moderate Forest	10142986.88	319504086.82	1776321.47	55954126.37
Wooded Grassland	6013916.68	189438375.32	379161.17	11943576.92
Open Grassland	3486764.97	109833096.68	-	-
Perennial Cropland	772745.02	24341468.25	729679.64	22984908.56
Annual Cropland	15085939.12	475207082.21	281924.17	8880611.31
Vegetated Wetland	225504.49	7103391.33	-	-
Open Water	67553.13	2127923.70	-	-
Other lands	-	-	16963.24	534342.14
Total	**70361974.48**	**2216402196.0**	**38997236.5**	**1228412950.5**

3.4. Soil Conservation

Using ex-situ soil sedimentation and unit dredging costs, the study estimates forest soil conservation for the two ecosystems at 1.34 million tons and 0.4 million tons of soil for Elgeyo and Nyambene, respectively, annually. This translates to the economic value of KES 478 million (US$4.4 million) and KES 130.7 million (US$1.22 million) respectively (Table 4). This equates to KES 18943.62

Table 4. Economic valuation of forest soil conservation.

Land Cover	Elgeyo		Nyambene	
	Total Soil Carbon (Mg)	Economic Value (KES)	Total Soil Conserved (Mg)	Economic Value (KES)
Dense Forest	556511.18	195335422.91	329475.10	115645759.53
Industrial forest	163299.01	57317951.01	16341.85	5735989.00
Wooded Grassland	226658.66	79557188.16	-	-
Bushland	137477.98	48254769.92	6530.64	2292254.02
Crop Land	244924.33	85968439.59	-	-
Perennial Cropland	27779.82	9750717.37	14989.51	5261317.73
Vegetated Wetland	3689.79	1295114.71	4991.51	1752021.60
Other Land	-	-	-	-
Open Water	1099.70	385994.70	253.29	-
Fallow land	-	-	147.49	-
Total	**1361440.5**	**477865598.37**	**372729.39**	**130687341.87**

(US$177.04) and 24081.21 (US$225.06) per hectare per year. The study results were consistent with the Shangyon-Mengla study (Xi, 2009) which ranged from US$49.86 to US$1096.39 per hectare per year. However, the results are inconsistent with the study carried out in Mau, Cherangany, and Elgon, which valued forest soil maintenance at US$11.27 to US$18.66 $ha^{-1}\cdot year^{-1}$ (Langat et al., 2019). The study would attribute the inconsistency with the latter to land cover fraction and corresponding coefficients, sediment ratio, and unit cost. For example, the study assumed that all lost soil found its way into the water reservoir, in contrast to the Mau, Cherangany, and Elgon studies, which assumed that only 50% made its way into the aquatic environment.

3.5. Soil Nutrient Conservation

The conservation value of soil nutrients used the respective mean soil loss per unit area (Gizaw et al., 2021; Kateb et al., 2013; Okelo et al., 2009) and the relative mineral unit (NPK) contribution to the relative mineral composition of the soils, multiplied by the respective unit costs of substitutes (commercial fertilisers). The study estimates the annual amount of nutrients conserved by the two ecosystems at 12277.54 tons and 3219.13 tons per year for Elgeyo and Nyambene, respectively. Using commercial fertilisers as a proxy, the study value for nutrient preservation function at KES 3.6 billion (US$33.3 million) and KES 935.4 million (US$8.74) annually for the Elgeyo and Nyambene ecosystems, respectively. This, respectively, corresponds to KES 141519.36 (US$1322.61) and KES 172442.02 (US$1611.61) per hectare per year (**Table 5**). Study results were

Table 5. Forest soil nutrient conservation value.

Land Cover	Elgeyo		Nyambene	
	Soil Nutrient Conserved (Mg)	Economic Value (KES)	Soil Nutrient Conserved (Mg)	Economic Value (KES)
Dense Forest	5063.48	1471388000.64	2950.88	857490379.30
Dense Exotic Forest	1435.25	417067439.23	151.20	43936572.24
Wooded Grassland	2057.72	597950303.93	59.53	17297375.02
Bushland	1248.09	362680647.54	-	-
Crop Land	2181.49	633915864.13	34.33	9975574.04
Perennial Cropland	247.43	71899758.49	22.45	6524256.03
Vegetated Wetland	34.47	10017201.26	-	-
Other Land	-	-	-	-
Open Water	-	-	-	-
Fallow land	9.60	2790441.41	0.75	217338.70
Total	**12277.54**	**3567709656.6**	**3219.13**	**935441495.34**

higher compared with the Mau, Cherangany, and Elgon watersheds valued at \$67.35, \$53.67, and \$89.41 $ha^{-1}\cdot yr^{-1}$, respectively (Langat et al., 2019). Higher than the study in Chile valued soil fertility conservation at US\$26.3 $ha^{-1}\cdot yr^{-1}$ (Nahuelhual et al., 2007), Anji County, Huzhou, Zhejiang, China, on forest soil conservation based on the eco-service unit method with a mean value of RMB436 (US\$69.8) $ha^{-1}\cdot yr^{-1}$ (Zhang et al., 2015). However, the estimates were slightly higher though within range with a study in the Xishuangbanna corridor in China with a mean value of US\$1103.61 $ha^{-1}\cdot yr^{-1}$ (Xi, 2009).

3.6. Climate Regulation (CO_2 Sequestration)

3.6.1. Forest Tree Carbon

Forest tree carbon assessments recorded different tree dimensions, tree biomass, and carbon across the land cover (**Table 6**). The mean tree carbon for Elgeyo varied significantly across land cover/land use with $F_{(7,47)} = 4.389$, $P < 0.05$, with a mean ± standard deviation of 56.06 ± 42.4 Mg carbon/ha, and a range of 0.43 ± 0.01 to 144.67 ± 20.93. The Nyambene also varied significantly across the land cover with $F_{(4,26)} = 7.205$, $P < 0.01$, with a mean ± standard deviation of 130.06 ± 103.66. The results, although higher than most carbons in dry forests, 31.13 ± 10.8 Mg/ha in Cameroon (Kemeuze et al., 2015), 21 Mg/ha in Miombo (Lupala et al., 2014), AGB 12.4 Mg/ha for Marsabit ecosystem (Muhati et al., 2018) is extremely lower than most estimates of mean tropical forest carbon of 183 Mg/ha (Sullivan et al., 2017). The estimates are also lower than the biomass of most tropical African forests and Borneo, which is reported to be between 395.7 and 445 Mg/ha (Lewis et al., 2013; Slik et al., 2010). Notwithstanding, the study estimates for Nyambene were significantly higher than the Elgeyo carbon estimate and consistent with the Taita Hills study, which found a mean of 92.59 and 211.5 Mg/ha (Omoro et al., 2013). The study could attribute the discrepancy to forest degradation, deforestation, and conversion to other land uses, as reported by Elgeyo and a well-preserved ecosystem with Nyambene (KWTA, 2020b).

The two ecosystems store about 1.4 million Mg and 0.7 million Mg carbon, which is equivalent to 5.2 million Mg CO_2e and 2.6 million Mg CO_2e, respectively. Trading the carbon for the two ecosystems in a voluntary REDD+ carbon market mechanism and at a flat price of US$5 per tonne of CO_2e, the two ecosystems would be worth about KES2.8 billion (US$25.8 million) and KES1.4 billion (US$12.9 million) for Elgeyo and Nyambene, respectively. This corresponds to KES 110071.01 (US$1028.7) and KES 255287.77 (US$2385.87) per hectare per year (**Table 7**). Estimates for Elgeyo were lower and consistent with the Mengla-Shangyon and Nabanhe-Mangao corridor studies (China) in Nyambene with a unit value of US$2195 per hectare per year (Xi, 2009). A similar scenario compared to the East Mau study that assessed carbon sequestration valued at $2782.47 per hectare per year (Langat, 2016). The study mainly attributed the difference between the degraded forest of Elgeyo and the fairly well-preserved forest of Nyambene. The study also attributes the discrepancy to the unit transfer and the unit price used, with US$10 used in the two reference studies, while US$5 per CO_2 was used in this study.

Table 6. Forest tree carbon statistics.

Land Cover type	No Trees/ha	DBH (cm)	Tree Height (M)	Tree Wood Density (g/cm3)	Biomass (tons/ha)	Elgeyo Tree Carbon (Ton/ha)	Nyambene Tree CO_2 (Ton/ha)
Dense forest	888.19	20.73	17.70	0.48	192.00	144.67	210.47
Moderately dense	547.97	22.03	17.36	0.41	144.08	80.14	151.34
Wooded grassland	268.93	24.86	16.09	0.49	109.95	82.16	84.47
Bushland	73.13	24.65	14.18	0.48	33.33	25.15	20.29
Cropland	-	-	-	-	-	-	
Degraded forest	88.46	32.08	20.56	0.46	55.82	36.00	24.07
Vegetated Wetland							
Others e.g. PELIS	169.86	6.15	5.55	0.40	0.89	0.43	
Open Water Bodies							
Glades	-	-	-	-	-	-	
Total	**274.91**	**21.71**	**14.72**	**0.41**	**89.35**	**56.06**	**130.06**

Table 7. Forest carbon valuation.

Land Cover type	Elgeyo		Nyambene	
	Total Tree Carbon (Mg)	Value (US$)	Total Tree Carbon (Mg)	Value (US$)
Dense forest	1166818.52	21411119.93	1004970.68	18441211.89
Moderate	189663.33	3480322.12	35843.36	657725.64
Grassland	286496.85	5257217.19	8112.59	148866.01
Bushland	50846.51	933033.45	-	-
Cropland	-	-	-	-
Degraded forest	16130.16	295988.44	1718.82	31540.41
Others e.g. PELIS	9.06	166.34	-	-
Total	**1414161.73**	**25949867.71**	**705610.96**	**12947961.18**
Unit Area Values	56.06	1028.70	130.02	2385.87

3.6.2. Soil Carbon

The results of the soil mineral assessment for the case of Elgeyo exhibited non-significant difference across the land cover. The findings ranged from 208.77 ± 41.29 to 220 ± 46.48 Mg SOC/ha with a mean ± standard deviation of 213.71 ± 43.23 Mg SOC/ha. However, the Nyambene ecosystem recorded significant differences among the land cover with $F_{(3,20)} = 3.986$, $P < 0.05$ ranging from 67.81 ± 37.71 to 170.61 ± 68.06 with a mean of 143 ± 50.87 Mg SOC/ha. Based on the respective mean SOC, the study estimates the aggregate soil carbon for the two ecosystems at 8.2 million and 0.87 million Mg SOC, respectively, and about 30.2 million and 3.2 million CO_2 for Elgeyo and Nyambene, respectively. At a unit price of US$5, the total value for CO_2 sequestered by the two ecosystems in the soils, at KES 16.1 billion (US$150.85 million) and 1.7 billion (US$15.95 million) respectively, for Elgeyo and Nyambene ecosystems. This equates to KES 639866.42 (US$5980.06) and KES 314662.39 (US$2940.77) per hectare per year (Table 8). This amount is much higher than forest tree carbon, demonstrating the significant potential of soils in this ecosystem to store significant amounts of soil carbon stock.

The estimated total carbon from plants and soil for the two ecosystems is about 9.3 million and 1.8 million tonnes of carbon, respectively, which translates to 34.3 million and 6.5 million tonnes of CO_2e for Elgeyo and Nyambene, respectively. The study would estimate the aggregate value at KES 18.3 billion (US$171.3 million) and KES 3.5 billion (US$32.5 million) for the Elgeyo and Nyambene ecosystems, respectively. The results show the enormous economic opportunity that the two ecosystems offer, especially for climate protection efforts through forest protection. Although the unit estimates are lower compared to most of the literature, the study provides data that can elicit the establishment of programs such as payment of ecosystem service (PES) and REDD+. This can affect not only nature conservation but also the livelihoods of local communities and societies and thus a socio-economic situation conducive to development.

Table 8. Forest soil carbon valuation.

Land Cover	Elgeyo Soil Carbon (Ton/ha)	Nyambene Soil Carbon (Ton/ha)	Total SOC (Mg) Elgeyo	Total SOC (Mg) Nyambene	Total Value (US$) Elgeyo	Total Value (US$) Nyambene
Dense forest	209.33	170.61	1688327.9	814662.9	30980818.70	14949065.9
Moderate	212.57	152.00	1846290.0	35999.44	33879421.93	660589.64
Grassland	208.77	141.69	2671679.3	13607.74	49025315.63	249701.98
Bushland	220.21		1633869.1	-	29981497.19	-
Cropland			-	-	-	-
Degraded forest	213.52	67.81	351113.79	4842.27	6442937.97	88855.64
Others	218.76		16924.75		310569.08	
Glades	217.50		12622.21	-	231617.59	-
Total	**213.71**	**133.03**	**8220827.1**	**869112.4**	**150852178.1**	**15948213.2**
Unit Value			325.89	160.21	5980.06	2939.94

Table 9. Regulatory ecosystem services (RES) values.

Ecosystem Services	Elgeyo		Nyambene	
	Value (KES)	(%)	Value (KES)	(%)
Watershed protection	15644985024.48	37.81	8671035541.16	55.54
Water purification	2216402196.02	5.36	1228412950.51	7.87
Soil Conservation	477865598.37	1.15	130687341.87	0.84
Soil Nutrient	3567709656.63	8.62	935441495.34	5.99
Plant CO2 Sequestration	3358068386.79	8.11	2062360469.25	13.21
Soil Carbon	16116399974.10	38.95	2585396751.69	16.56
Total	**41381430836.39**	**100.00**	**15613334549.82**	**100.00**

3.7. Aggregate for the Selected Regulatory Ecosystem Service

The study estimates the total value of the six selected regulatory ecosystem services (RES) at KES 41.4 billion (US$386.7 million) and KES 15.6 billion (US$145.9 million) for Elgeyo and Nyambene, respectively. This equates to KES 1.64 million (US$15331.19) and KES 2.9 million (US$26887.9) per hectare per year. Elgeyo, the carbon sequestration value was about 47%, followed by a watershed protection value of 38% of the total. While Nyambene recorded the highest watershed protection value at about 58%, carbon sequestration at 26% of the total (Table 9) followed it. The study results were higher compared to a study in Taiwan that assessed forest ecosystem regulatory services at NT$400,976 (US$12976.57) per hectare per year (Lin et al., 2021). Equally, higher compared to a study in East Mau, valued at KES 641741.71 (US$5997.32) per hectare per year (Langat et al., 2019) and with the Nabanhe-Mangao and Mengla-Shangyong Corridor estimated at US$12947.71 and US$389248.33 $ha^{-1}\cdot year^{-1}$, respectively (Xi, 2009). The study attributes the discrepancies to the number of ES included in the study and the assumed unit price.

4. Conclusion

Kenya's watershed ecosystem covers 1.2 million hectares (MoE&F, 2018) which range from open to closed canopy forests. Extrapolating the study unit estimates to the country's watersheds, the regulatory ecosystem services would range between US$18.4 billion and US$30.5 billion. This equates to between 16.7% and 27.7% of Kenya's GDP in 2021, underscoring the importance of watersheds to the local and national economy.

The analysis of the study results revealed different unit area values for the two ecosystems, a clear indication that different vegetation structures differ in terms of stock and flow of ecosystem benefits. For instance, the Nyambene watershed, which is primarily native forest, recorded higher unit area values compared to the Elgeyo dominated by exotic forest. Based on the results, and since decision making involves trade-offs, converting natural forests to industrial forests would mean to reduce the benefits and vice versa. The study results revealed that native forest are more viable in watershed ecosystems than industrial forests, supporting the political debate. This will also answer the question of the type of seedlings used in the restoration of watershed ecosystem in the country. Even though not absolute, the study findings exhibit monetary units that can provoke ES and sustainable conservation discourse among stakeholders.

Equally, the study results show the potential economic value of particularly tradable products such as forest carbon sequestration. Taken together, such results would justify the need for increased investment, particularly in the conservation of the country's watersheds. This is besides complementing other local studies and would be crucial as society strives to incorporate ES assessment results in development discourse.

Recommendations

The study mainly employed surrogates in estimating monetary values because of data paucity of some RES. In that context, society should invest in long-term data collection aimed at building a national ES database. A well-resourced database will be important in future ecosystem services assessment with an aim of facilitating future forest resource accounting.

Equally, researchers should endeavour to improve assessment techniques and approaches aimed at generating more accurate, acceptable, and concise data to support policy discourse and sound decision making.

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Compliance with ethical standards

The study principally used the Geographical Information System (GIS) and Remote Sensing, validated by ground truthing, and didn't engage humans and animals in the study.

Data Availability

The reviewers can access the study data through this link https://datadryad.org/stash/share/SjPmjzw6O57u-yeanQC9X5nR4paf85s2f-cSve9flFg or upon request via the email address of the relevant corresponding author

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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