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Impact of land use/land cover changes on surface water and soil-sediment export in the urbanized Akaki River catchment, Awash Basin, Ethiopia

Mekuria Argaw [a], Hamere Yohannes [b,*]

[a] Center for Environmental Sciences, College of Natural and Computational Sciences, Addis Ababa University, Addis Ababa, Ethiopia
[b] School of Civil and Environmental Engineering, Addis Ababa Institute of Technology, Addis Ababa University, Addis Ababa, Ethiopia

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ABSTRACT

The Akaki River catchment is undergoing rapid urbanization and substantial deforestation, leading to a decline in its hydrological conditions. Investigating how changes in land use and land cover (LULC) affect the hydrological cycle in urbanized catchments like the Akaki River in the Awash Basin is a priority in natural resource utilization and management. By analyzing satellite images and using the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) and Partial Least Square Regression (PLSR) models, this study examined the hydrological responses such as water yield (WY), sediment export (SE) and soil loss (SL) to the prevailing LULC changes in the catchments. The results showed an increasing trend of risks in surface runoff and sediment export from the catchments in the past three decades. The Analysis of Variance (ANOVA) test results showed significant variations in WY, SE, and SL across LULC types throughout the study period. The variables WY, SE, and SL increased by 35.25%, 8.11%, and 10.71%, respectively. The magnitude of change in SE, SL, and WY over the study period was substantially influenced by not only the change in LULC but also by the dynamics. Most importantly, settlements and farmlands were the main factors that influenced the hydrological components. These two LULC types attained greater variable importance for projection (VIP) and parameter weight (w) values of 1.31 and 0.61 for settlement and 1.19 and 0.56 for farmlands, respectively. The results of the study underlined the importance of regulating the rapidly changing LULC change and implementing conservation measures in order to attain a sustained hydrological and ecological balance in the Akaki River catchments,

1. Introduction

The ability of a natural landscape to offer critical services can be impacted by the conversion of natural systems to agricultural and urban environments, which ultimately poses a challenge to the sustainable production of ecosystem services (Sun et al., 2021). Changes in land use is one of the factors that affect ecosystem structure and functions (Polasky et al., 2011; Deng et al., 2013). Numerous studies have demonstrated the impact of land use change on the loss of ecosystem services (ESs) such as pollination, carbon storage, water provision, soil conservation, nutrient retention, timber production, agricultural and livestock production, and other cultural services (Polasky et al., 2011; Baral et al., 2014; Keller et al., 2015; Sun et al., 2021). The disruption of hydrologic-related ES

* Corresponding author.
E-mail address: hamere.yohannes@aau.edu.et (H. Yohannes).

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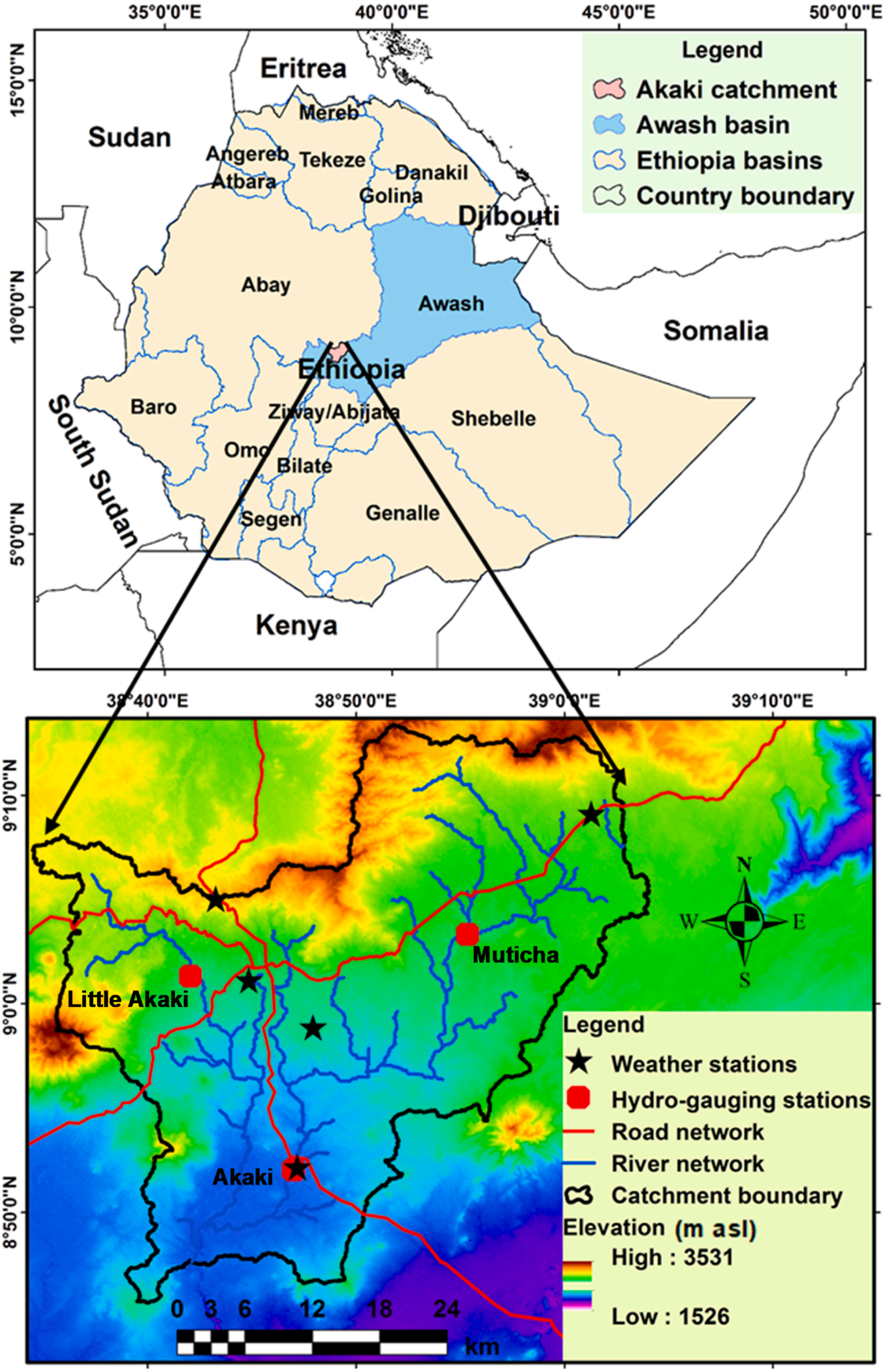

(caption on next page)

Fig. 1. Map of the study area.

triggered by increasing demands for land resources to produce food, water, and shelter has attracted the attention of scientific communities in recent decades (Gyamfi et al., 2016; Gao et al., 2017; Gebremicael et al., 2019). However, there are very limited methodological studies for simulating hydrologic ES and their spatiotemporal variations (Guswa et al., 2014).

Due to the absence of land use policy and mismanagement of land resources, the Ethiopian highlands experienced severe level of soil erosion and sedimentation of hydrological infrastructure, particularly artificial reservoirs for water supply and power generation (Wassie, 2020; Degife et al., 2021; Kenea et al., 2021; Regasa et al., 2021; Gebretekle et al., 2022). This is a common phenomenon in the Akaki River catchment, which has experienced rapid urbanization and high rate of deforestation. Hence, it is crucial to comprehend how LULC changes affected the hydrological components so as to use it for watershed management planning and for developing better strategies to tackle or minimize the effects. The Akaki River catchment has been the subject of numerous hydrological investigations. For instance, previous studies by Berga (2011), Hordofa (2019) and Zeberie (2020) used the Soil and Water Assessment Tool (SWAT) model to assess the hydrological responses of land use change and investigated sediment yield and conservation techniques. However, the studies failed to consider the long-term hydrological effects of LULC changes. They are also limited in their ability to show spatial distribution of water yield and soil-sediment export simultaneously, and rely heavily on data-intensive models, which are not fit for the conditions in Ethiopia. The use of data-intensive models, such as the Water Erosion Prediction Project (WEPP) and SWAT models, was a common approach in many studies on predicting surface runoff, soil loss, and sediment production (Gassman et al., 2014; Swarnkar et al., 2018). Such methods are less applicable for the sub-Saharan regions including Ethiopia, because of limited availability of required data and low reliability (Haregeweyn et al., 2012; Degife et al., 2021). The Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model provides a reliable and adaptable techniques for assessing water resources and related processes (Guswa et al., 2014). The model relies on freely accessible global or local data, delivers spatially explicit information with comparatively less data inputs, and can be quickly tailored to a particular scenario (Sharp et al., 2020). The model has been applied globally (e.g., Gao et al., 2017; Qi et al., 2019) and locally (e.g., Sahle et al., 2019; Aneseyee et al., 2020; Degife et al., 2021; Yohannes et al., 2021). The InVEST hydrological model has been widely used to predict water-related ESs. The site-specific analysis is crucial to managing the negative effects because the erosion process relies on the soil type, climate, terrain, and management strategies (Degife et al., 2021).

Incorporating ecological models in hydrological analysis has practical and scientific value for water-related ecological and environmental management planning to ensure water security and informed decision-making (Guswa et al., 2014; Gao et al., 2017). To examine hydrological changes at the catchment scale, numerous research combined the partial least square regression (PLSR) model with hydrologic models (e.g., Fang et al., 2015; Woldesenbet et al., 2017; Gashaw et al., 2018; Shawul et al., 2019; Gebremicael et al., 2019; Chisola et al., 2020). In this study, PLSR model was integrated with InVEST model results in order to evaluate the impact of LULC change on hydrological components and processes. The main goal of this study is determining analyzing the trend of LULC changes in the past three decades, quantifying and mapping of the associated spatiotemporal changes in water yield, sediment export and soil loss in the catchment.

2. Materials and methods

2.1. Description of the study area

The Akaki River catchment is located within the western margin of the Ethiopian rift valley at the northwest Awash River basin. It is part of the upper Awash River basin (Amare, 2019). The catchment is situated between 35°35′E - 39°5′E longitudes and 8°48′N - 9°12′N latitudes, covering an area of 1444.06 km^2 (Fig. 1) forming a bowl like shape, with Addis Ababa City in its center. It is bounded in the north by the Entoto ridge system, to the east by mount Yerer, to the south by mount Bilbilo and mount Guji, to the southwest by mount Furi, to the west by mount Menagesha and Wechecha volcanic ridges, and to the southeast by the Gara Bushu hills (Amare, 2019). The topography is undulating and forms plateaus with elevations ranging from 2062 m above sea level (m a.s.l) at the lower part of the Akaki plain to the highest peak of 3448 m at the Mount Entoto.

The artificial surface water supply reservoirs within the study area include Legedadi, Gefersa, Dire, and Abba Samual. The Akaki River catchment has an extensive drainage system formed from two major tributaries such as the Big Akaki river, which drains the entire eastern sub-catchments, and the Little Akaki, which drains the entire western sub-catchments, both draining towards the major outlet at the bottom, the Abba Samuel reservoir (Yohannes and Elias, 2017). The catchment has a mean annual temperature of 15.8 °C and mean annual precipitation of 1126 mm (Fig. 2) (NMA, 2021). The major soil types are Vertisols (68%), Nitosols (11%), and Luvisols (9%), with few traces of Cambisols, Leptosols, and Xerosols (MoWIE, 2021a). The main cultivated crops include wheat, teff, barley, beans, other grains and vegetables in the urban and peri-urban areas (Daba and You, 2020).

2.2. Land use/land cover change detection

2.2.1. Image preprocessing and classification

Landsat images for the years 1991, 2001, 2011, and 2021 were freely obtained from the United States Geological Survey (USGS) website (http://earthexplorer.usgs.gov). The images were taken in the dry season with a cloud cover of less than 5%. Dark Object Subtraction 1 (DOS1) was performed to reduce the atmospheric distorting effects, thereby converting the brightness value of each pixel

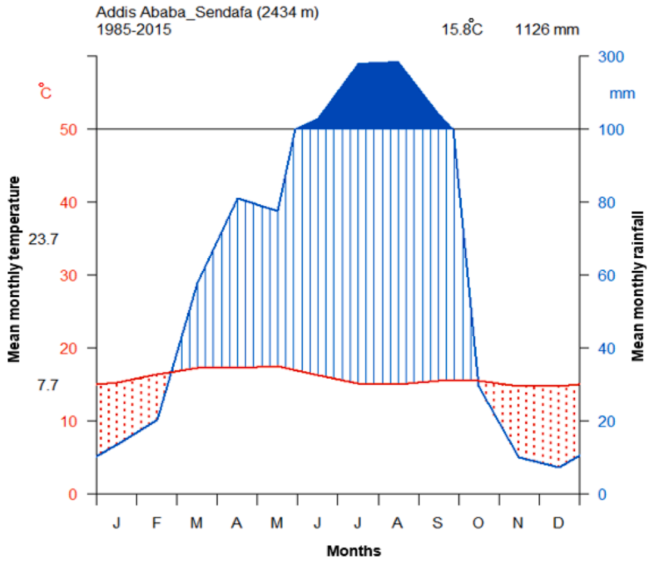

Fig. 2. Mean rainfall and temperature in the Akaki catchment between 1985–2015 (Source: NMA (National Meteorology Agency) of Ethiopia, 2021).

to reflectance value, before classifying the images (Chavez, 1988; Congedo, 2016). Image classification was undertaken using the hybrid classifies system, unsupervised followed by supervised techniques to achieve better classification accuracy (Teferi et al., 2010; Appiah, 2016). The unsupervised classification relies on the spectrum and texture information to extract image features (Ma et al., 2020). Thus, the Iterative Self-Organizing Data Analysis (ISODATA) clustering algorithm (Teferi et al., 2010; Mwabumba et al., 2020) was undertaken to determine spectral classes that serve as the baseline for ground truth data collection. .

The Supervised classification using a random forest (RF) classifier was followed, as this method is proven to be outperforming for urban land cover classification that utilizes clear and unclear observations, handles contaminated Landsat satellite data, and works well even when the dataset contains some noise (Hu et al., 2018). The LULC classes were identified based on the spectral characteristics of the images obtained from unsupervised classification, Google Earth images, field surveys, and familiarity with the study area. Stratified random sampling was adopted to select 375 sample sites as the region of interest (ROI) for each image classification purpose (75 per LULC class). The signature spectral separability test was undertaken using the *Jeffries-Matusita distance index* to ensure the accuracy of the classification process (Richards and Jia, 2006; Mwabumba et al., 2020). The area LULC were classified into Five classes, which are Farmland, Forest, Grassland, Settlement and Water body and these classes were selected based on author prior knowledge about the area, field survey, satellite imagery and google earth map observation. The description of the identified LULC types is presented in Table 2.

2.2.2. *Accuracy assessment*

Accuracy assessment is essential to ground truth in the results of the LULC maps derived from remotely sensed data (Foody, 2002; Congalton et al., 2009). Thus, the ground truth information using ground control points (GCPs) was collected from field surveys and Google Earth images. The Global Positioning System (GPS) was used to collect 250 coordinates (minimum of 50 points per class) following Congalton et al. (2009) for the year 2021 LULC (Supplementary material, Appendix 1). For the earlier years (1991, 2001, and 2011), the same number of GCPs were collected from Google Earth images. Then, the quantity and allocation disagreement between classified maps and reference ground truth information (Pontius and Millones, 2011) were evaluated to examine the classification accuracy (Supplementary material, Appendix 2). The magnitude of the change from one LULC category to the other was examined using cross-tabulation. Image classification was performed in QGIS Desktop 3.18.3 and final mapping was done in ArcMap 10.3.

The temporal change was estimated using Eq. 1:

$$Change \quad in\% = \frac{Area \quad of \quad final \quad year - Area \quad of \quad intial \quad year}{Area \quad of \quad intial \quad year} \times 100 \tag{1}$$

Table 1
Description of satellite imageries used for LULC classification.

Year	Satellite	Resolution (m)	Path/row	Date of Acquisition
1991	Landsat 5, TM	30	168/54	1991-01-19
2001	Landsat 5, TM	30	168/54	2001-12-16
2011	Landsat 5, TM	30	168/54	2011-01-10
2021	Landsat 8 OLI_TIRS	30	168/54	2021-01-21

Table 2
Description of LULC types in the Akaki catchment.

LULC Type	Description
Farmland	Cultivated land used for annual and perennial crop growing.
Forest	The area is covered by dense trees, including evergreen, mixed, and plantation forests (*Eucalyptus, Junipers, and Conifers*).
Grass land	Areas with grass cover, land with little or no grass, and other small-sized plant species.
Settlement	Urban and other residential buildings, industrial areas, institutions, transportation, roads, and scattered houses.
Water body	Areas with man-made reservoirs, which remains waterlogged and swampy throughout the year, are the rivers and main tributaries.

2.3. InVEST model setup and simulation

The Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) was used to model the hydrological components in the Akaki River catchment. The InVEST model is primarily designed to evaluate the impact of land use change on ESs (Leh et al., 2013; Sharp et al., 2020). The model has various modules such as water yield, carbon storage and sequestration, coastal blue carbon, crop production, nutrient and sediment delivery ratio, recreation and tourism, urban flood risk, and habitat quality models to simulate several ESs (Sharp et al., 2020). In this study, water yield (WY), sediment export (SE), and soil loss (SL) were selected to examine the impact of LULC change on the hydrological changes in the Akaki River catchment. These hydrological parameters were chosen due to the significant issue of surface runoff, soil erosion, and sediment export in the study area.

2.3.1. The annual water yield model

The InVEST annual water yield model, based on the Budyko curve, determines water yield from precipitation minus storage and evapotranspiration losses (Zhang et al., 2008; Sharp et al., 2020). This study used the model to determine the amount of water that runs off from a given pixel that does not evapotranspire based on the cell vegetation characteristics (Leh et al., 2013; Sharp et al., 2020). The inputted variables were long-term average annual precipitation and reference evapotranspiration (ET_0) for the period of 1985–2015, root restricting layer depth (soil depth), plant root depth, plant available water content (PAWC), plant evapotranspiration coefficients (K_c), LULC and rainfall seasonality factor (Z parameter) to calculate the average water yield at each grid cell.

The ordinary kriging interpolation technique was used to map a 30 m raster grid dataset of precipitation and ET_0 (Zhang et al., 2008). Based on weather data derived from five stations (Addis Ababa Bole, Addis Ababa observatory, Akaki, Intoto, and Sendafa), the ET_0 was calculated using the 'modified Hargreaves' Equation (Droogers and Allen, 2002). The missing data on temperature and rainfall were estimated by taking the average of the neighboring stations as no substantial difference in mean climate, and the disappeared value has less than 10% (Tang et al., 1996). The soil data for the area was acquired from the Africa soil information services (AfSIS) database (AfSIS, 2015) at a spatial resolution of 250 m. Therefore, the soil depth, PAWC, and plant root depth were resampled to 30 m using the nearest neighbor method (Worqlul et al., 2017). The value of K_c for each LULC class was assigned following FAO and InVEST user guide (Allen et al., 1998; Sharp et al., 2020). The Z parameter was computed using the number of rain events per year following the procedures in Donohue et al. (2012). The total WY volume per hectare was computed for each sub-watershed (Sharp et al., 2020).

2.3.2. Sediment delivery model

The InVEST Sediment Delivery Ratio (SDR) model provided an advantage in quantifying and mapping the amount of soil loss and sediment export from each pixel and joined to streams and reservoirs (Sharp et al., 2020). Thus, the SDR model was used to predict the average annual rate of soil loss and sediment export. The soil erosion rate is determined by topography, rainfall intensity, soil characteristics, and land use types (Nelson et al., 2009). The sediment export in specific grid cells is computed from the rate of soil loss and sediment delivery ratio (Sharp et al., 2020). The model employs the Universal Soil Loss Equation (Wischmeier and Smith, 1978) on a given pixel to calculate the soil loss rate. The SDR model is parameterized using the digital elevation model (DEM), rainfall erosivity (R-factor), soil erodibility (K-factor), soil cover (C-factor), support practices (P-factor), LULC types, and other model default values of maximum SDR, Borselli k and IC_0. Borselli k and IC_0 are calibration parameters that define the relationship between the index of connectivity and the sediment delivery ratio. And the model manual suggested default values while running SDR module.

A 30 m resolution DEM of the Shuttle Radar Topography Mission (SRTM) for the year 2014 was downloaded from the USGS data portal (https://earthexplorer.usgs.gov/srtm/). The climatic factor (R-factor) was computed following Hurni (1985), adapted for the Ethiopian climate and the map was prepared using ordinary kriging (Zhang et al., 2008). Following Sharpley and Williams (1990), the soil erodibility factor, K-factor, was determined using soil texture and soil organic carbon, which were downloaded from the AfSIS database (AfSIS, 2015) and the computation employed using a raster calculator in ArcMap (v 10.3). C-factor represented the impact of land use on soil loss rate. The C-factor value for each LULC was assigned using the computed annual average NDVI value for each land use (Van der Knijff et al., 2000). The rate of soil loss under specific support practices was determined by assigning P-factor values (Wischmeier and Smith, 1978). The amount of sediment exported to the stream and potential soil loss in ton/ha/yr at each sub-watershed was computed as output.

2.3.3. Model validation

Validation verifies the performance of InVEST model for the simulation of hydrological components (Redhead et al., 2016). The model was validated using measured daily stream flow data (1990–2015), and sediment data (1990–2010) obtained from three

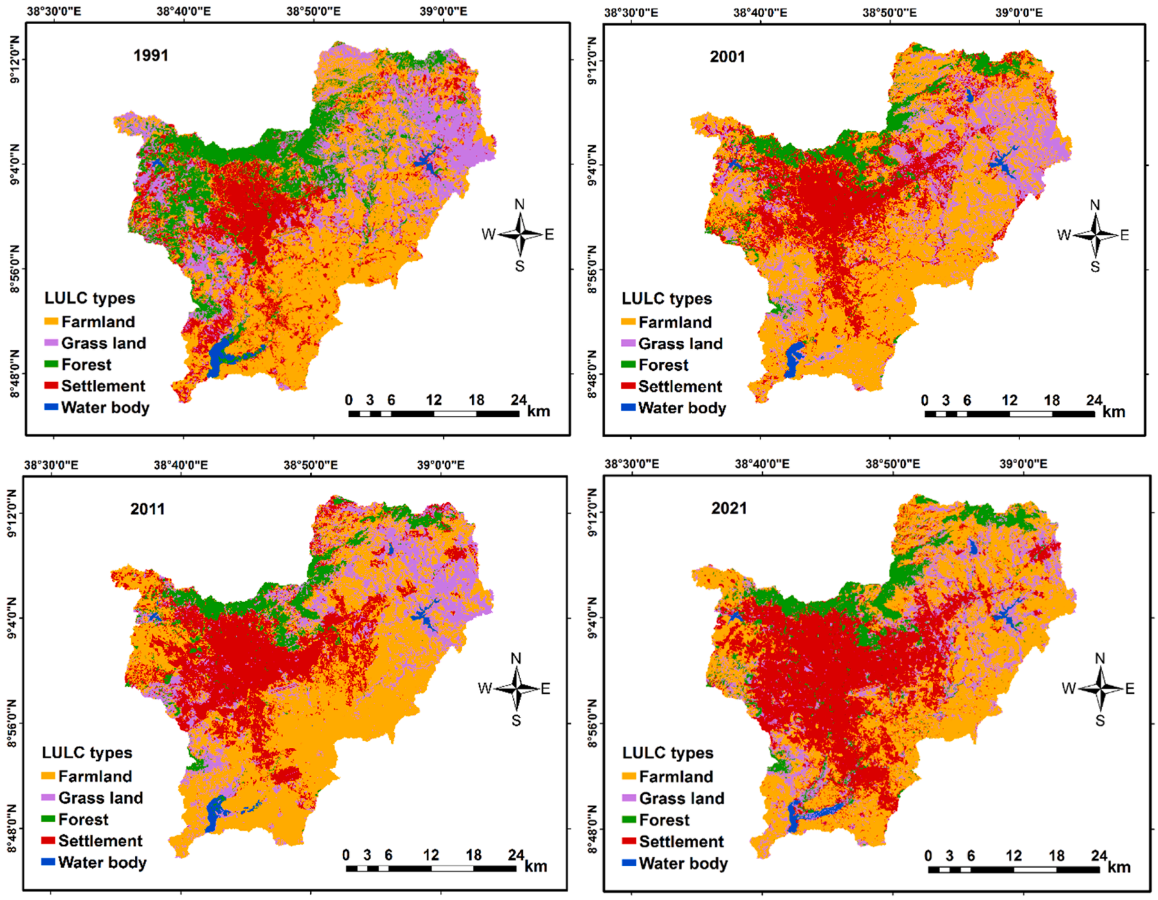

Fig. 3. LULC maps of the years 1991, 2001, 2011, and 2021 for the Akaki catchment.

gauging stations (Little Akaki, Akaki, and Muticha) (MoWIE, 2021b). The Akaki catchment lacks continuous records of suspended sediment load data and data inconsistencies between stations. Therefore, following Sinha et al. (2019), the available average dataset for the same time window was selected to generate continuous sediment data using the power law function (sediment-discharge rating curve) that basis on the consistent relationship between discharge and suspended sediment concentration (Walling, 1978; Asselman, 2000). The accuracy level of the model was assessed using standard statistical methods, including Nash-Sutcliffe simulation efficiency (NSE), percent bias (PBIAS), and root mean square error-based standard deviation (RSR) (Yohannes et al., 2021).

2.4. The hydrological impact of LULC change analysis

Understanding the response of hydrological components to LULC change is essential for catchment water resource management planning in the changing environment (Gashaw et al., 2018; Garg et al., 2019). The impact of individual LULC on selected hydrological components was analyzed using the partial least square regression (PLSR) model. The PLSR is a robust multivariate regression for selecting significant predictors when there is multicollinearity, numerous predictors, and several dependent and independent variables (Carrascal et al., 2009; Chisola et al., 2020). Moreover, the PLSR analysis is least affected by data distribution (Gebremicael et al., 2019). The selection of variables with the best predictive power is based on the variable importance for projection (VIP), and the

Table 3
The LULC area coverage between 1991 and 2021.

LULC	1991 Area (ha)	Area (%)	2001 Area (ha)	Area (%)	2011 Area (ha)	Area (%)	2021 Area (ha)	Area (%)
Farmland	60386.9	41.82	72798.76	50.41	69358.77	48.03	60132.69	41.64
Forest	25010.5	17.32	11160.00	7.73	11570.40	8.01	14646.69	10.14
Grass land	32349.4	22.4	26910.00	18.63	25755.48	17.84	20962.53	14.52
Settlement	25050.4	17.35	32112.00	22.24	36324.54	25.15	47284.62	32.74
Water body	1609.12	1.11	1425.51	0.99	1397.07	0.97	1379.79	0.96

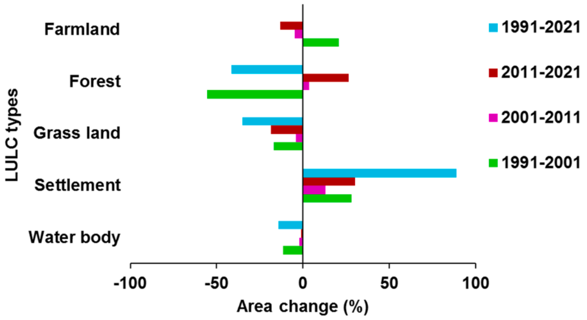

Fig. 4. Area change in LULC (%) between 1991 and 2021.

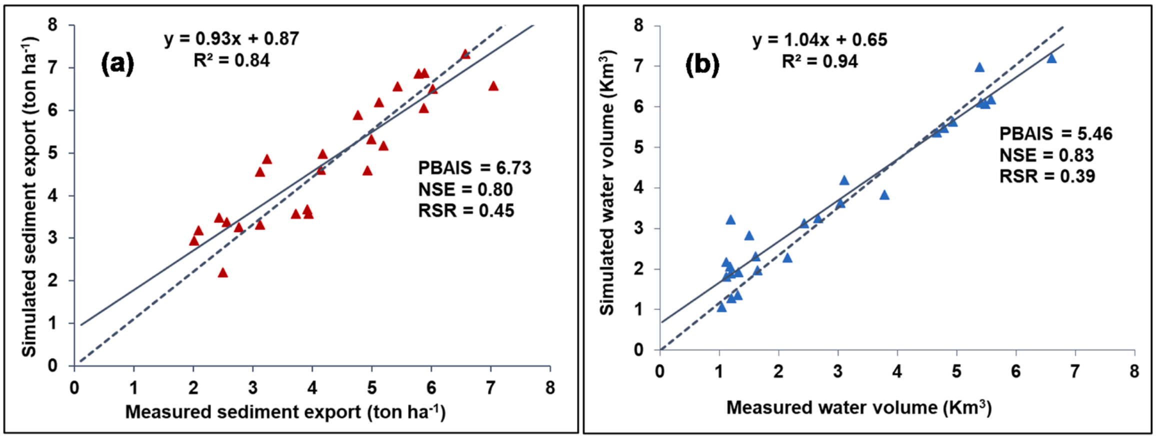

Fig. 5. Validation of InVEST hydrology model for Akaki catchment.

Table 4
The summary result of the analysis of variance for hydrological components over the years.

Parameter (unit)	df	Mean square	F-stat	Sig.
Sediment export (ton ha^{-1})	3	20.82	3.73	0.022*
Soil loss (ton ha^{-1})	3	519.38	2.99	0.048*
Water yield (m^3 ha^{-1})	3	2733124.20	3.08	0.044*

* Indicates significance at $p < 0.05$, df: degree of freedom

loading weights (w). The VIP value indicates the importance of a predictor (LULC classes) for the dependent variables (the hydrological components) in the projection. The factor with a VIP value of >1 was deemed the most influential predictor to explain the dependent variable. Variables with VIP > 0.8 also significantly contribute to the change of response variables (Wold et al., 2001). The 'w' of the factor indicates the magnitude and direction of the relationship between the predictor and response variables. The squares of w values more than 0.2 i.e. ($w^2 > 0.2$) indicated that the PLSR components are mainly weighted on the corresponding variables (Wold et al., 2001).

A cross-validation test is usually used to obtain the optimum number of components and measure the model's predictive power (Chisola et al., 2020). Thus, the proportion of variance in the matrix of independent variables (R_2X); the ratio of the variance in the matrix of dependent variables by the model (R_2Y), and cumulative goodness of prediction within a given number of factors (Q^2_{cum}) were calculated to determine model performance. If their values are > 0.5, it is considered as a good predictive ability of the model (Shi et al., 2013). In this study, Shapiro and Wilk (1965) normality test was used to infer whether the data are typically distributed. The independent variables used in this study were the LULC classes. The dependent variables were annual water yield, sediment export, and soil loss to explore the hydrological impact of individual LULC changes. Analysis of Variance (ANOVA) test was conducted to detect the significance of the difference in considered hydrological components over the study period and across LULC classes at a 5% confidence level, as the data are normally distributed, and the variances were homogenous (Appendix 3). The statistical analysis and PLSR modeling were conducted using the R software package (v.4.1.1) (R Core Team, 2021) and the XLSTAT tool (www.XLSTSAT.com).

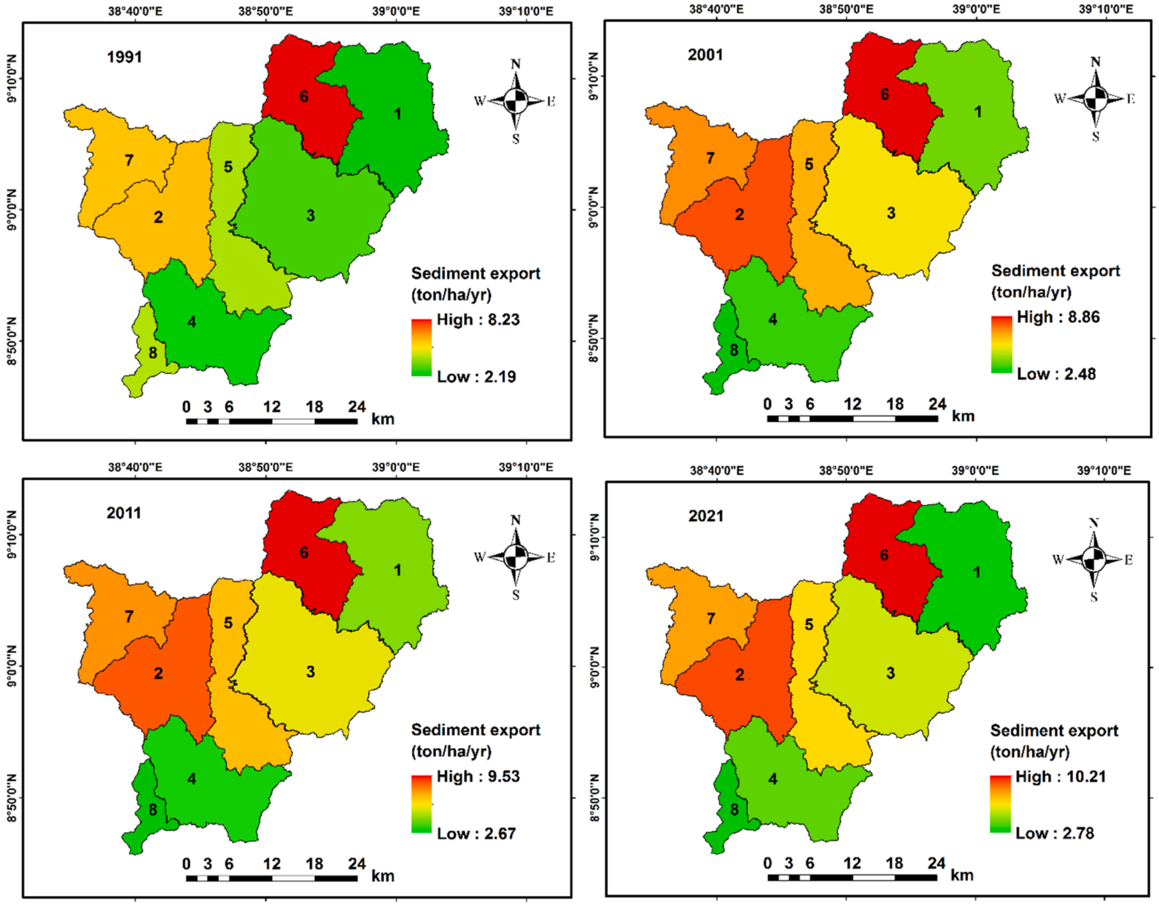

Fig. 6. Spatial distribution of sediment export (1991–2021).

3. Results

3.1. Land use/land cover change (1991-2021)

The LULC change and its spatial distribution in the period between 1991 and 2021 showed that the areas in the northern, northwestern, southwestern, and western parts of the upper catchment were covered with forests in the early periods (Fig. 3). The northern parts still maintain contiguous patches of forests along the ridges. Whereas, the areas in the southeastern and southern parts of the catchment are predominantly covered by farmlands, and the eastern parts by grasslands. The settlements covered and widely expanded towards the central and western parts over the study period.

Table 3 displays the magnitude of the area coverage for each LULC between 1991 and 2021. In the last three decades, the area under the settlement continually increased while grassland and water bodies decreased. The settlement increased from 17.35% in 1991to 32.74% in 2021 and expanded by 89% from 1991 to 2021. In 1991, the grassland relatively covered large area but gradually decreased in the later years by a magnitude of 35.19% during 1991–2021. Water body also shrunk by 14.25% in the period from1991 to 2021 (Fig. 4). The rate of change in farmland and forest areas varied during the study period. Farmland increased from 41.82% in 1991 to 50.41% in 2001, while it showed a declining trend in the later years with an area coverage of48.03% in 2011 and 41.64% in 2021 (Table 3). The area under forest cover shows a substantial decline between 1991 and 2001 by a magnitude of 55.37%. Although there as a gradual increase until 2021, the overall trend has showed a decline by a magnitude of 41.43% in the period from 1991 to 2021 (Fig. 4).

3.2. Validation of InVEST model

The result of the InVEST hydrology model validation shows a strong correlation with the measures of agreement R^2 (0.84), PBIAS (6.73), NSE (0.80), RSR (0.45) for sediment export, and R^2 (0.94), PBIAS (5.46), NSE (0.83) and RSR (0.39) for water yield (Fig. 5).

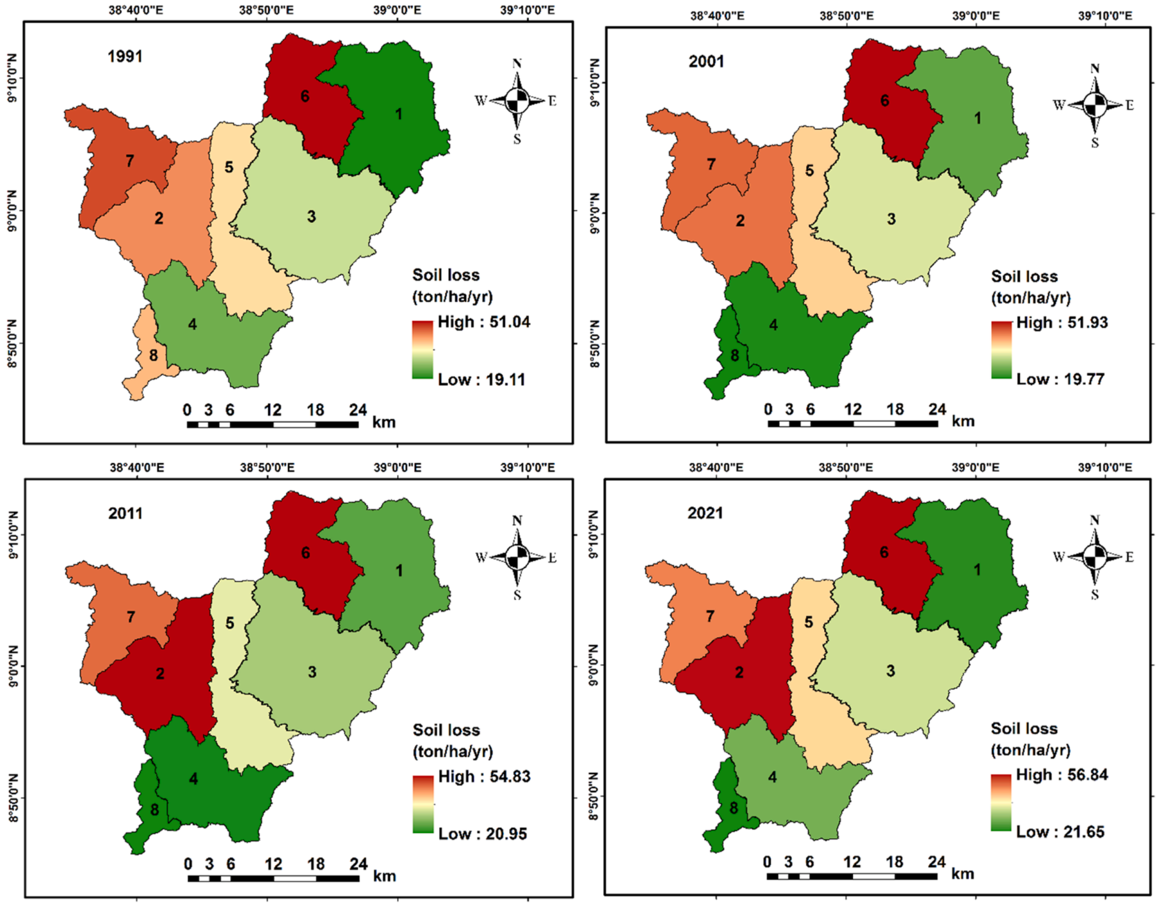

Fig. 7. Spatial distribution of soil loss (1991–2021).

3.3. Spatio-temporal changes of hydrological components in the Akaki catchment

3.3.1. Statistical analysis of the change in hydrological components over the years

The summary of results from the ANOVA test revealed a significant difference in all hydrological components across the years at $p < 0.05$ (Table 4).

3.3.2. Sediment export

The total annual sediment exported from the catchment was 7.6 million tons in 1991 with a slight increase in 2021 by a magnitude of one million tons. Accordingly, the mean annual SE was estimated to be 5.43 tons/ha/yr with an overall increase annual rate by 35.25% between 1991 and 2021. Relatively high amount of SE was generated in SW-6, SW-2, and SW-7 with a mean annual rate of 9.24 ton/ha/yr, 7.43 ton/ha/yr, and 6.94 ton/ha/yr, respectively (Fig. 6). The land use types in these sub-watersheds were dominated by farmlands and settlements, which might have contributed to the high values.

3.3.3. Soil loss

The total soil loss increased from 54 million tons in 1991 to 58 million tons in 2021. The mean annual rate of soil loss was 35.93 tons/ha/yr with an overall increase by 8.11% between 1991 and 2021 (Fig. 7). High annual rate of soil erosion was recorded in SW-6 (55.12 ton/ha/yr), SW-2 (48.38 ton/ha/yr), and SW-7 (45.88 ton/ha/yr), which are dominated by farmlands and settlements.

3.3.4. Water yield

The total annual water yield varied from 0.92 Km^3 in 1991 to 0.98 Km^3 in 2021. Mean annual WY was estimated at 6408.38 m^3/ha and increased by 10.71% between 1991 and 2021. The spatial distribution of WY showed a similar pattern of high in the western and low in the eastern part of the catchment (Fig. 8). Table 5 presents the water balance components of each sub-watershed (SW) in the Akaki catchment. SW-2 (7691.08 m^3/ha), SW-7 (7676.56 m^3/ha), and SW-5 (7112 m^3/ha) produced high WY during the study period. The mean actual evapotranspiration (AET) and potential evapotranspiration (PET) ratio were estimated as 458.32 mm/yr and 671.79 mm/yr, respectively for the entire study period. The highest AET and PET values were recorded in SW-7 and SW-6 with mean

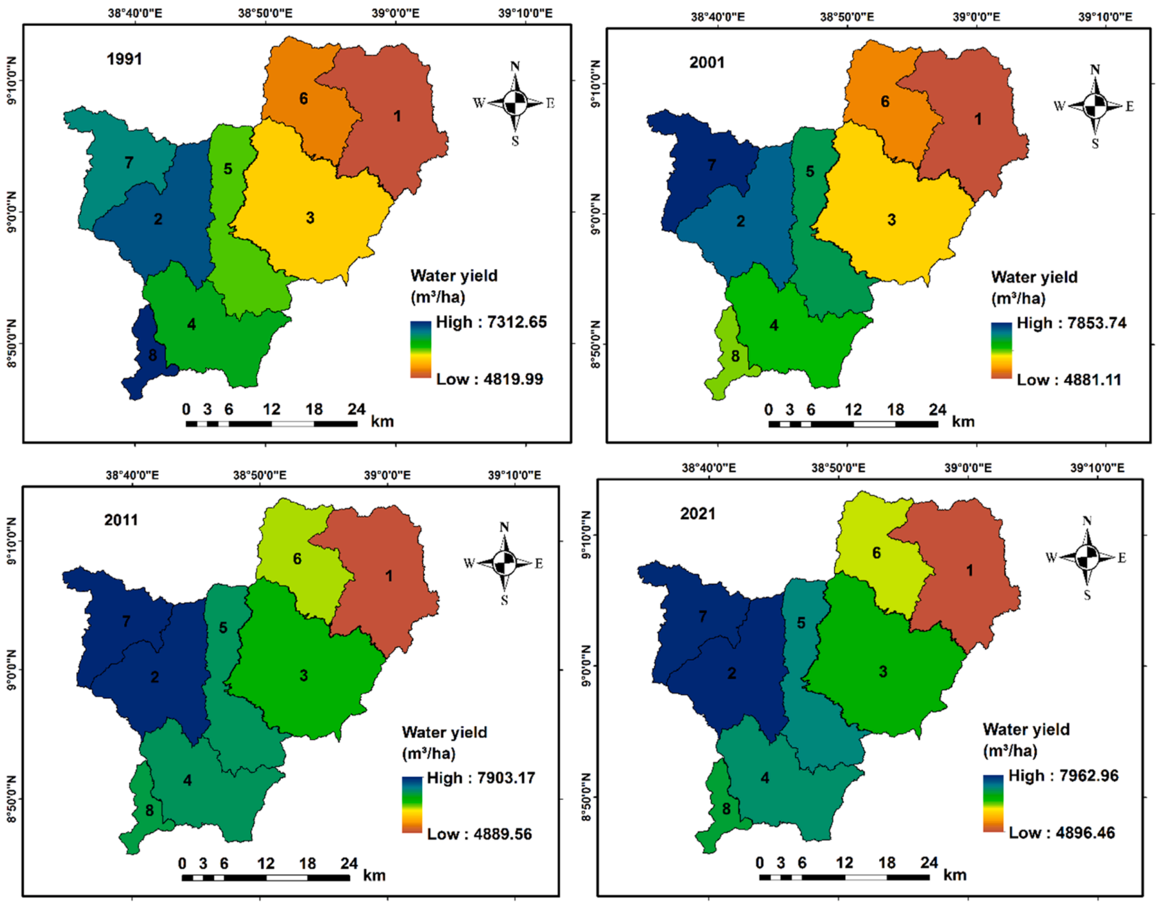

Fig. 8. Spatial distribution of water yield (1991–2021).

Table 5
The mean value of water balance components of Akaki catchment at the sub-watershed scale.

Sub-watershed	Area (ha)	Precipitation (mm/year)	PET (mm/year)	AET (mm/year)	Water yield (mm/year)
SW-1	23776.5	961.91	721.25	475.41	485.68
SW-2	20047.2	1212.09	596.17	442.87	769.11
SW-3	31670	1125.75	645.85	463.24	662.50
SW-4	19068.4	1115.73	550.67	406.29	709.23
SW-5	17210.7	1153.53	583.68	425.50	711.43
SW-6	14955.8	1106.45	789.86	488.03	618.01
SW-7	13394.9	1290.34	852.13	523.24	767.66
SW-8	4282.79	1134.61	634.73	442.01	709.41

values of 523.24 mm/yr and 488.03 mm/yr for the AET and 852.13 mm/yr and 789.86 mm/yr for the PET. Whereas the AET and PET were lower in the SW-4 and SW-5 with mean values of 406.29 mm/yr, 425.50 mm/yr for AET and 550.67 mm/yr, and 583.68 mm/yr for PET (Table 5).

3.4. *The impact of LULC changes on hydrological components*

The ANOVA result shows that there is a statistically significant difference in the mean value of SE (F-value = 3.56 and P-value = 0.031 at $p < 0.05$), SL (F-value = 4.37 and P-value = 0.015 at $p < 0.05$) and WY (F-value = 42.81 and P-value = 0.000 at $p < 0.01$) among the LULC classes. As shown in Table 6, the mean of SE, SL, and WY increased for all LULC classes except for forest land. The mean SE in forest areas showed a slight decline from 6.21 ton/ha in 2001 to 6.15 ton/ha in 2011 and increased in the later periods. The mean value of the SL in the forest lands increased continually between 1991 and 2011, with a slight decrease in 2021 by a magnitude of 0.3% (Table 6). The highest average SE, SL, and WY were recorded in settlements with the value of 6.38 ton/ha, 41.35 ton/ha, and

Table 6
Mean annual sediment export, soil loss, and water yield among LULC Types.

Year	LULC*	Sediment export (ton/ha)	Soil loss (ton/ha)	Water yield (m^3/ha)
1991	FL	4.72	34.61	6516.72
	Fo	5.14	37.36	5017.06
	GL	4.54	33.12	6130.31
	ST	5.23	38.56	7870.53
	WB	3.15	28.75	4742.57
2001	FL	5.50	35.98	6583.65
	Fo	6.21	39.37	5939.47
	GL	5.15	33.44	6203.40
	ST	6.17	40.71	7991.26
	WB	3.88	28.99	4961.56
2011	FL	5.97	36.06	6619.69
	Fo	6.15	40.10	6299.45
	GL	5.16	33.76	6325.33
	ST	6.78	42.13	8259.70
	WB	3.96	29.23	5186.93
2021	FL	6.76	37.27	6672.58
	Fo	6.43	39.99	6318.07
	GL	5.88	34.79	6337.69
	ST	7.35	43.99	8953.09
	WB	4.42	30.35	5238.54

*FL: Farmland, Fo: Forest, GL: Grass land, ST: Settlement and WB: Water body

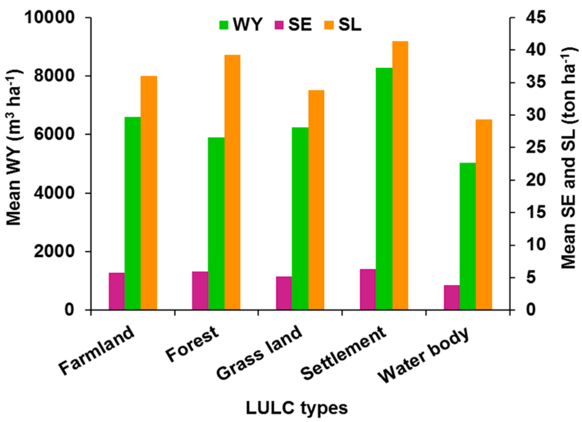

Fig. 9. Mean value of water yield (WY), sediment export (SE), and soil loss (SL) of LULC classes over the past 30 years.

Table 7
Summary of PLSR model quality for hydrological components in the Akaki catchment.

Variable	Comp.	R^2Y	R^2Ycum	R^2X	R^2Xcum	Q^2	Q^2cum
Total	1	0.84	0.84	0.75	0.75	0.82	0.82
	2	0.11	0.95	0.18	0.93	0.53	0.92
Sediment export	1	0.8	0.8	0.77	0.77	0.79	0.79
	2	0.12	0.92	0.15	0.92	0.62	0.9
Soil loss	1	0.83	0.83	0.79	0.79	0.81	0.81
	2	0.1	0.93	0.11	0.90	0.29	0.91
Water yield	1	0.92	0.92	0.81	0.81	0.86	0.86
	2	0.03	0.95	0.14	0.95	0.81	0.94

8268.65 m^3/ha, whereas the lowest was observed in water body scoring 3.85 ton/ha, 29.33 ton/ha and 5032.4 m^3/ha, respectively (Fig. 9).

Table 7 presents the summary of the PLSR analysis, which demonstrates the potential of the model to explain selected hydrological component changes. The first two PLSR components cumulatively account for 92%, 90%, and 95% of the total variability in the SE, SL, and WY, respectively.

The monoplot of correlation displays the relationship between dependent variables (Y) and independent variables (X) using the correlation coefficient of the two PLSR components on the t1 and t2 axes indicated in Fig. 10. The angle and length of the line in the

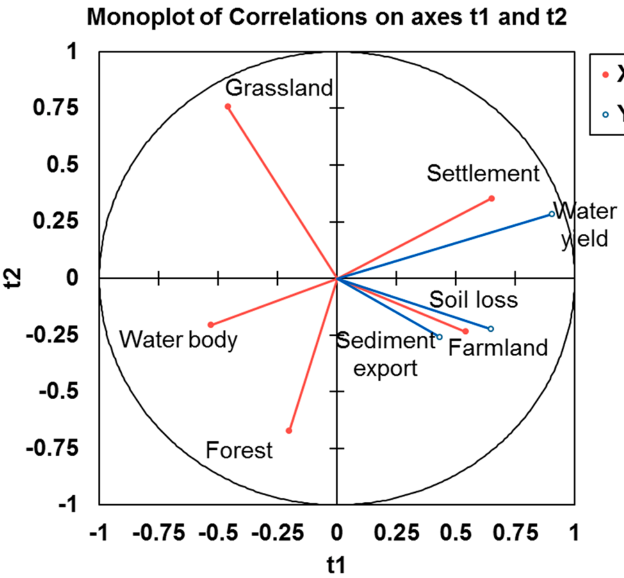

Fig. 10. Correlation circle of change in LULC classes and hydrological components with (t1:t2), X represents independent variables, Y represents dependent variables.

Table 8
PLSR weight and variable importance of each LULC for hydrological components.

Variable	Sediment export		Soil loss		Water yield		Total	
	VIP	w	VIP	w	VIP	w	VIP	w
Farmland	1.45	**0.65**	1.37	**0.61**	1.25	**0.56**	1.19	**0.58**
Forest	0.81	-0.36	0.68	-0.3	0.85	-0.38	0.92	**-0.45**
Grass land	0.9	-0.4	0.95	-0.43	0.56	-0.26	1.08	**-0.48**
Settlement	1.11	**0.51**	1.31	**0.59**	1.45	**0.65**	1.31	**0.61**
Water body	0.54	-0.31	0.52	-0.29	0.68	-0.31	0.80	-0.38

Bold-faced values are $w^2 > 0.2$, indicating the predictor variables are significant for response variables change

correlation circle indicate the degree of correlation among the variables. Therefore, the monoplot exhibits that the change in the settlement is directly correlated with water yield. Moreover, the farmland change strongly correlates with soil loss and sediment exports. The value of variable influence (VIP) and the weight (w) of each LULC on the change of hydrological components are displayed in Table 8. Farmland and settlement significantly contributed to SE, SL, and WY changes, which are explained by higher VIP and w values. In contrast, the shift in water body has the least contribution to hydrological changes. The overall VIP value for LULC with vegetation cover, namely grassland and forest, were 1.08 and 0.92, respectively, suggesting that their contribution to the changes in surface hydrology critically is important.

4. Discussion

The LULC in the Akaki River catchments, particularly the upper and middle parts, were subjected to anthropogenic changes in the last three decades. Many of the driving factors are linked to urban expansion, establishment of satellite towns and increasing rate of population growth due to in-migration. Since the metropolitan city of Addis Ababa has been expanding rapidly, the industrial infrastructure has also been growing steadily and aggravated the conversion of grasslands and forest lands to settlements, built up areas and impervious surfaces. Unlike the other LULC types, the change in farmlands was insignificant. However, earlier studies claim that settlements in the catchment expanded at the expense of cultivated lands (Worako, 2016). The overall LULC change trend showed that forest and farmlands did not change steadily and the trend was dynamic and expressed in tradeoffs among the land use land cover types. The increase in forest cover in the later years could perhaps be resulted from the upper catchment rehabilitation campaign as part of the national tree planting campaigns in the late 1990s and the climate resilience initiative in the late 2000s. On the contrary, the decline of farmlands was partly attributed to the absence of appropriate land use and allocation policies for the peri-urban areas, where proliferation of villages, settlements and industrial expansion since the late 1990s (Worako, 2016).

In general, the observed changes in LULC in the study catchments were largely driven by population growth, urbanization, industrialization, and expansion of commercial activities in Addis Ababa and the surrounding sub-urban areas (Worako, 2016). According to the national census data of the 1998 the population of Addis Ababa city was about 1,412,600 in 1984 and it increased to a little more than 2 Million in 1994 Census and it was projected to reach 3.3 Million by 2015 (Schmidt et al., 2018). The trend is an indicator that a rapid growth of the City population increased by 132% during the last three decades, resulting in rapid urbanization, in-migration and increased demand for land resources, which generally threatened the critical ecosystems and the environment.

This study showed spatial and temporal changes in the main hydrological components such as the WY, SE, and soil SL, mainly due to changes in the LULC. The mean WY, SE, and SL increased by 10.71%, 35.25%, and 8.11%, respectively, from 1991 to 2021. In the urbanized areas, the land surface imperviousness increased rapidly, resulting in decreased infiltration rate and rainfall retention capability, leading into an increase in the runoff coefficient and sediment delivery to the stream network (Mariye et al., 2022). Similar results of an increase in surface runoff and soil loss due to urbanization were reported in several studies (Birhanu et al., 2016; Pumo et al., 2017; Nampak et al., 2018; Li et al., 2018; Wang et al., 2018; Bulti and Abebe, 2020; Leta et al., 2021). For instance Birhanu et al. (2016) reported that urbanization contributed to an increased pick flow by 25% during 1993–2002 in Addis Ababa City. Another study by Bulti and Abebe (2020) in Adama city also reported that the runoff depth is increased by 9.5% in the city administration during 1995–2019. Nampak et al. (2018) also exhibited mean soil loss increased by 31.77 ton/ha/yr from 2005 to 2015 due to urban expansion.

Though urbanization is considered as a shift to modern life style, it may drive many serious environmental problems such as climate change, pollution, agricultural productivity decline, and general ecological deterioration (Wang et al., 2018).

The surface runoff and soil-sediment export were observed to be high in farmlands in the Akaki catchments, as it is commonly the case in the Ethiopian highlands (Hurni et al., 2015; Belayneh et al., 2019). The high vulnerability of farmlands to runoff erosion is generally attributed to the undulating topography, high rainfall, and intensive farming practices coupled with poor soil conservation intervention (Belayneh et al., 2020). Similarly, high surface runoff and soil-sediment export from cultivated lands were reported by Aneseyee et al. (2020) in the Winike watershed, Omo-Gibe Basin. They reported that cultivated fields generated the highest soil erosion rate, increasing from 10.02 ton/ha/yr to 43.48 ton/ha/yr during 1988–2018. Another study by Woldemariam and Harka (2020) found that annual actual soil loss changed from 75.85 ton/ha/yr to 107.07 ton/ha/yr during 2000–2018 in the Erer sub-basin, Wabi-Shebelle Basin. And similar study by Yohannes et al. (2021) also reported that the total WY and SE increased by 30.29% and 98.69%, respectively, between 1972 and 2017 in Beressa watershed, Blue Nile Basin of Ethiopia. The presence of adequate soil management practices has been reported to have significantly reduced soil erosion (Zhang et al., 2020). In the Akaki catchment, the decline in forest area cover and grassland cover in the period from 1991 to 2021 could be the main reason for the susceptibility of the catchment to surface runoff and soil loss as a result of accelerated soil erosion. The finding in this study agrees with previous research findings conducted in Ethiopia and elsewhere (e.g., Dinka and Klik, 2019; Moisa et al., 2021; Chen et al., 2018; Shang et al., 2019). For instance, the study by Dinka and Klik (2019) in Lake Basaka catchment found that about 86% of forest coverage and 46% of grasslands were lost during 1973–2015. Another study by Moisa et al. (2021) in Temeji watershed, Western Ethiopia found that high soil loss is observed when grass and forest land were converted into cultivated land with mean soil loss of 88.8 ton/ha/yr and 86.9 ton/ha/yr in 2020.

5. Conclusion

Over the past three decades, the Akaki River catchment has witnessed significant alteration in the LULC. The analysis revealed that there was a significant change in LULC from 1991 to 2021, which greatly accelerated surface runoff and soil-sediment export in the catchments. The increasing urbanization of the nearby towns is related to the observation of a significant increase in settlement expansion. The expansion of industrial infrastructure and conversion to agriculture are the main causes of the loss in forest cover. The amount of sediment exported to water bodies has been observed to have progressively increased over the last three decades as a result of soil cover decline. The variations in land use and land cover during the various time periods significantly affected the hydrological components used to illustrate the effects of the LULC changes. For instance, all LULC types had a rise in the mean value of SE, SL, and WY during the study period (1991–2021). The increase in surface runoff and soil-sediment export in the Akaki river watershed was considerably sparked by changes in farming and habitation patterns. This may result in the distribution of important hydrological cycles and impairs the functions of the ecological and environmental systems. The findings of this study suggest that it is necessary to manage and regulate the LULC change in the Akaki River catchments. In addition, soil and water conservation interventions are crucial, especially those sub-watersheds that generated significant amount of sediments and runoff.

CRediT authorship contribution statement

Argaw Mekuria: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Yohannes Hamere:** Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2024.101677.

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