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Research article

Implications of land use/land cover dynamics on urban water quality: Case of Addis Ababa city, Ethiopia

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ABSTRACT

Water resources are often at the center of urban development but, as the city expands, the environmental pressure on its water resources increases. Therefore, in this study, we looked into how various land uses and changes in land cover affect the water quality in Addis Ababa, Ethiopia. Land use and land cover change maps were generated from 1991 to 2021 at intervals of five years. On the basis of the weighted arithmetic water quality index approach, the water quality for the same years was likewise divided into five classes. The relationship between land use/land cover dynamics and water quality was then evaluated using correlations, multiple linear regressions, and principal component analysis. According to the computed water quality index, the water quality decreased from 65.34 in 1991 to 246.76 in 2021. The built-up area showed an increase of over 338%, whereas the amount of water decreased by over 61%. While barren land exhibited a negative correlation with nitrates, ammonia loadings, total alkalinity, and total hardness of the water, agriculture and built-up areas positively correlated with water quality parameters such as nutrient loading, turbidity, total alkalinity, and total hardness. A principal component analysis revealed that built up areas and changes in vegetated areas have the biggest impact on water quality. These findings suggest that land use and land cover modifications are involved in the deterioration of water quality around the city. This study will offer information that might help reduce the dangers to aquatic life in urbanized environments.

1. Introduction

Clean and safe water is a crucial resource for the improvement and maintenance of human health and wellbeing [1,2]. However, despite its significance, water management issues affect most communities worldwide, making clean water a scarce resource for many. Anthropogenic activities in close proximity to water sources have an impact on the water quality since land and water ecosystems are connected by surface runoff, stream networks, and groundwater systems [3–5]. Deforestation and other factors, such as the presence of agriculture adjacent to water resources, can affect the overall water quality by increasing sedimentation and nutrient additions in waterbodies [6–8]. Changes in land use/land cover (LULC) dynamics also have an impact on water resources through their contribution to processes like the introduction of invasive fauna and flora species into the water, and siltation [9,10]. As a result, urban areas significantly threaten the water supply, flow dynamics, and water quality as they expand [11,12].

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The city of Addis Ababa the capital city of Ethiopia has also not been spared from water quality problems [13]. There has been an increase in wastewater from households, industries and commercial areas without the establishment of compatible waste management systems. Huge amounts of trash have also been dumped straight into the city's watersheds due to inadequate sewage lines and sewage treatment facilities [14]. Consequently, the various water resources in the city have suffered considerable negative effects. This has led to a rise in the demand for clean and safe water [15–17]. Previously vegetated areas are rapidly sealed off by built-up areas, the growing intensity of land use continues to reduce the water quality [18–22].

It has become extremely difficult to maintain the water supply and quality while balancing the rapid infrastructure development in the face of these changes. According to studies, a 10% increase in imperviousness can result in an increase in surface runoff since it reduces infiltration [23]. Thus, fast urbanization can modify the hydrology, topography, geology, and water quality of river basins, changing how they behave [24–26]. Land uses such as agriculture and built up areas have been shown to influence soil moisture and climatic processes such as temperatures and precipitation. The intensity of the precipitation can be reduced as result of the developmental activities whilst the temperatures increase with increased impervious surfaces [27]. One major problem is that most developing nations lack the resources necessary for efficient urban planning. Hence, by the time a plan is completed, the circumstances that supported it are no longer true [28]. In order to incorporate water and sanitation planning into the urban planning process, a more proactive, adaptable, and reactive style of planning is required. This permits, if necessary, the adoption of efficient interventions to enhance water quality and stream ecosystem health [29,30].

International research has been conducted to evaluate how LULC alterations may affect water quality. Among others, these investigations include those by Refs. [31–33]. Ref. [34] when quantifying spatio-temporal water quality in the Mokopane area of South Africa found that land use significantly impacts surface water quality, with built-up land having the most negative impact on water quality than the other land use classes. Anthropogenic activities (wastewater discharge, industrial activities etc.) alongside natural processes such as weathering of rocks were found to be playing a vital role in the observed water quality. Other studies have also shown anthropogenic activities to influence the hydrochemistry of the water through the alteration of parameters such as concentrations of fluoride and nitrate [35]. There hasn't been much research done in Addis Ababa city that looks at how water quality changes over time and across the entire city. Because the information that is currently accessible only provides a snapshot of the urban water quality for a brief period of time, it is unknown what has been happening in the city's watersheds over time as a result of the fast urbanization [36]. Moreover, research doesn't go into enough detail on the subject and the data that is available is scattered [37]. The city's population's health is still at risk from declining water quality, especially for those who live downstream and in areas with a dearth of public water supplies [38,39]. According to earlier research [40,41], the Gerfesa, Legedadie, and Dire reservoirs' water quality and quantity in Addis Ababa has deteriorated, with an increase in siltation, algal blooming, pathogens, and heavy metals in the water [41,42]. According to Ref. [41], the city's rapid changes in land use and land cover over the past several decades, along with incorrect exploitation and inadequate natural resource management of the land, rivers, and vegetation, are to blame for the depreciation of its water resources. To minimize potential threats on water quality, it is essential to comprehend how LULC changes affect water quality [43,44]. Therefore, by giving knowledge that could help reduce concerns caused by urban growth to aquatic ecosystems and subsequently their

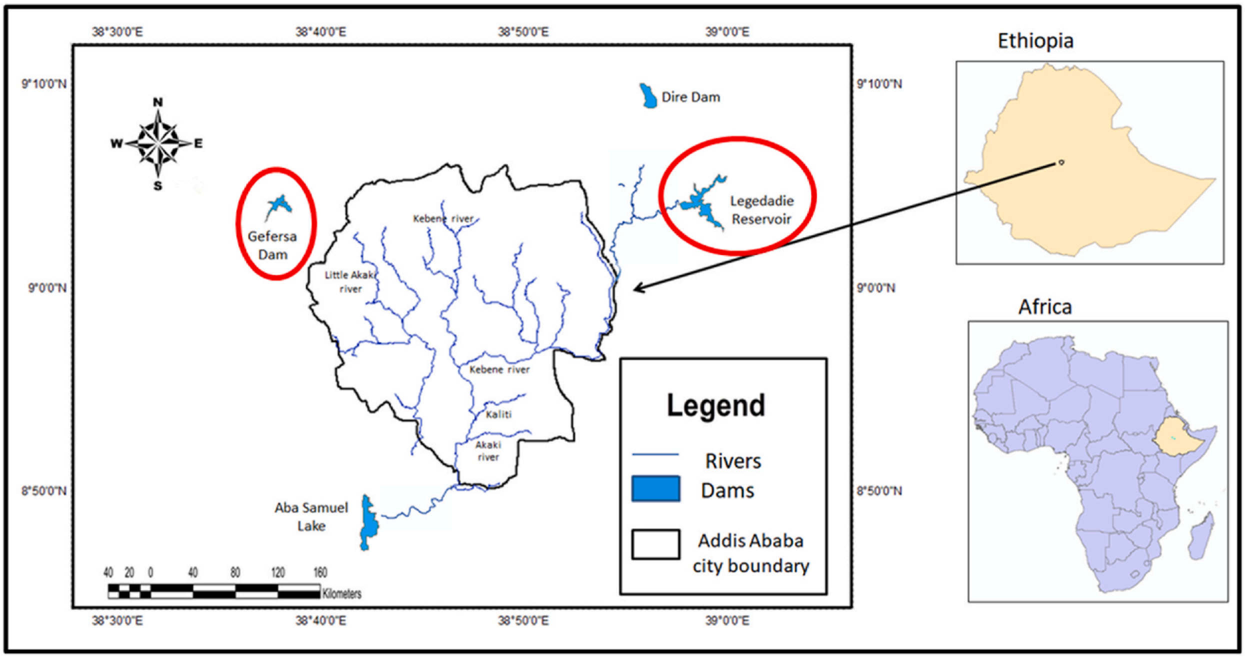

Fig. 1. Map of the study area showing the water resources of Addis Ababa and the sampling sites circled in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

protection, this work has the potential to fill in some of the research gaps [45]. The data from this study can be used to determine the city's water supplies over time and forecast how they will vary as the environment changes [46]. In the context of infrastructure development, basin development, and water quality, such information is crucial for directing management planning and modeling assessments of the potential future for the city.

This study therefore looked at whether changes in urbanization rates and land use over the previous 30 years had any substantial impact on water quality at various sites along Addis Ababa's water resources. The specific goals were to: (1) Analyze the temporal variability of biophysico-chemical water quality parameters in Addis Ababa's water resources; (2) To assess the spatial and temporal changes in LULC in Addis Ababa between 1991 and 2021; and (3) To establish the relationship between the various LULC classes and water quality parameters. The results will be crucial for LULC activities as well as for planning and managing drinking water quality in the city. The findings of this study can also be used to guide management actions by policy and decision-makers such the Addis Ababa Water and Sewerage Authority (AAWSA), Ministry of Lands, Housing, and Urban Development (LHUD), Environmental Protection Agency (EPA), and other stakeholders. The knowledge gained from this research will also help advance our understanding of the connection between LULC changes in urbanized environments and the rapid degradation of water quality that is common in many developing nations.

2. Materials and methods

2.1. Study area description

This study was conducted in Addis Ababa (Fig. 1) located in the central highlands of Ethiopia, between 8°48′ and 9°6′ North latitudes and 38°38′ and 38°54′ East longitudes, at an altitude range of 3100 m above sea level (a.s.l.) to 2200 m.a.s.l. at the lower portion of Akaki plain [47]. This city has 10 administratively separate sub-cities and is 540 km^2 in size. Addis Ababa is located in the upper Awash Basin, and the Awash and Abay Rivers' watershed boundaries from its northern border. Based on the types of water resources and geographic locations, the city's water supply sources can be divided into four groups. The Gefersa Dam I, II, and III clusters, the Legedadi surface water subsystem, which consists of the Legedadi and Dire Dams, the Akaki groundwater system, and the spring water sources at the base of Entoto Mountain constitute these clusters [48].

2.2. Water quality data collection and analysis

AAWSA provided the surface water quality data for the Legedadie and Gerfesa dams, which provide water to Addis Ababa city, for the period of 1991–2021. Water samples are analyzed at AAWSA on a monthly basis (three times per month) all year round. Starting in 1991 and continuing to the present, this data was gathered on a monthly basis throughout each year at 5 years intervals, amounting to 252 samples of data. Using Excel and R-studio, missing data was filled in. AAWSA is equipped with a network for monitoring all water sources supplying the city with water, including ground, surface, and wastewater, as well as a well-established recognized laboratory for conducting necessary water analyses. Additional information on water quality was collected from published and unpublished government reports, reports from the Ethiopian Central Statistical Agency, and reports from the Environmental Protection Agency. Turbidity, pH, total dissolved solids, total alkalinity, total hardness, ammonia concentration, nitrite, nitrate, phosphate, fluoride, iron, chloride, sulfate, manganese, and reactive silica were among the parameters of interest. These variables represented the water's chemical, physical, and biological characteristics.

Dissolved oxygen, water temperature, pH, Oxygen, and conductivity are measured in situ using a Multimeter probe (model HQ40d) at all sampling sites. Turbidity is measured using a turbidity meter (T100 Oakaton). Phosphate, nitrate, and sulfate (PO_4^{-3}, NO^{-3}, SO_2^{-4}) are determined using UV/visible spectrophotometer (model T90) following the sodium salicylate method for analysis of nitrates from the water samples, ascorbic acid method (after persulfate digestion) for total phosphorus and turbidimetric method for SO_2^{-4}. Soluble

Table 1
Means ± the standard deviation of each water quality parameter obtained from the descriptive statistics.

Parameters	1991	1996	2001	2006	2011	2016	2021
Turbidity (NTU)	138 ± 27.7	161 ± 20.6	175 ± 40.1	161 ± 22.2	347 ± 42	268 ± 53.8	398.2 ± 174
pH	7.67 ± 0.13	7.36 ± 0.32	7.47 ± 0.23	7.18 ± 0.22	7.34 ± 0.33	7.35 ± 0.32	7.58 ± 0.27
TDS (mg/L)	52 ± 3.59	58.7 ± 5.43	59.8 ± 5.84	61.4 ± 5.37	59.6 ± 6.76	59 ± 5.48	60.8 ± 5.71
EC (μS)	104.8 ± 2.76	120.9 ± 10.1	123.3 ± 11	128.5 ± 13.3	124.7 ± 13	122.9 ± 14.7	126.1 ± 12.6
Total Alkalinity (mg/L)	45.7 ± 4.04	49.6 ± 4.85	51.5 ± 5.55	52.6 ± 5.7	50.6 ± 8.17	49.8 ± 4.97	66.4 ± 46.9
Total Hardness (mg/L)	54.1 ± 5.47	60.3 ± 16	64.8 ± 17.8	63.2 ± 16.8	64.1 ± 11.9	60.4 ± 15.9	74.6 ± 27.3
NH_3 (Ammonia) (mg/L)	0.001 ± 0.001	0.034 ± 0.007	0.014 ± 0.004	0.041 ± 0.02	0.018 ± 0.01	0.033 ± 0.01	0.15 ± 0.16
NO^{2-} (Nitrite) (mg/L)	0.004 ± 0.002	0.011 ± 0.01	0.006 ± 0.003	0.007 ± 0.005	0.027 ± 0.03	0.006 ± 0.004	0.045 ± 0.03
NO^{3-} (Nitrate) (mg/L)	0.34 ± 0.21	0.58 ± 0.28	0.86 ± 0.41	0.55 ± 0.37	0.55 ± 0.33	0.62 ± 0.32	2.75 ± 3.01
SO_4^{2-} (Sulfate) (mg/L	1.78 ± 0.55	1.51 ± 0.83	1.15 ± 1.34	6.9 ± 1.2	8.8 ± 0.78	1.55 ± 0.81	10.2 ± 17.5
PO_4^{3-} (Phosphate) (mg/L)	0.08 ± 0.03	0.4 ± 0.44	0.38 ± 0.04	0.36 ± 0.34	0.32 ± 0.31	0.03 ± 0.02	0.6 ± 0.59
F^- (Flouride) (mg/L)	0.15 ± 0.11	0.15 ± 0.04	0.15 ± 0.1	0.27 ± 0.13	0.018 ± 0.01	0.15 ± 0.11	0.02 ± 0.01
Fe (Iron) (mg/L)	0.12 ± 0.86	1.35 ± 0.87	0.13 ± 0.09	0.16 ± 0.12	1.64 ± 0.45	1.36 ± 0.88	1.81 ± 0.04
Mn (Manganese) (mg/L)	0.05 ± 0.02	0.15 ± 0.17	0.23 ± 0.21	0.15 ± 0.13	0.19 ± 0.14	0.14 ± 0.16	0.3 ± 0.24
Cl (Chloride) (mg/L)	6.03 ± 1.13	5.38 ± 1.29	5.08 ± 1.73	5.1 ± 1.2	5.64 ± 0.73	5.44 ± 1.37	5.06 ± 1.61

reactive silica is estimated using molybdosilicate method and ammonia is determined by phenate method. Total alkalinity is assessed using the titration method and total dissolved solids by evaporating a pre-filtered sample to dryness, and then finding the mass of the dry residue per liter of sample. Descriptive statistics, including the annual means and standard deviations for the study years were calculated using the data analysis tool on Microsoft Excel and compiled according to the years of the study. Table 1 presents the means of each water quality parameter recorded over the years.

Following Refs. [14,49,50], the water quality from various time periods was divided into five groups. The entire water quality was then evaluated and rated using the water quality index approach, where ranges are utilized to represent water quality (Table 2) [51–53]. The WQI incorporates data from multiple physical, chemical and biological parameters that have a strong correlation with water quality, into a mathematical equation. 15 parameters were selected for water quality index in this study, including turbidity, pH, total dissolved solids, electrical conductivity, total alkalinity, total hardness, ammonia, nitrite, nitrate, sulfate, phosphate, flouride, iron, manganese and chloride. These variables were selected based on data availability from AAWSA covering the census years. The first step in calculation of the WQI involves marking of the water quality physic-chemical parameters with a weight (w_i) following their relative importance in water quality. The second step involved calculating the relative weight of each parameter, and then the last step involved computing the quality rating scale using the following equation [51,54]:

$$q_i = (v_i / s_i) * 100 \qquad (1)$$

where q_i is the quality rating; v_i is the concentration of each parameter in each water sample and S_i is the WHO recommendation of each chemical parameter. Therefore, the equation

$$WQI = \sum q_i w_i / \sum w_i \qquad (2)$$

was used to determine the actual WQI for each year. The analytical outcomes of the water analyses were compared to the suggested upper and lower bounds and benchmarks established by Ethiopia and the WHO.

2.3. Spatial datasets acquisition and pre-processing

For LULC change analysis, both primary and secondary data were collected. For ground truthing, an exploratory survey was carried out to better understand the city's predominate land uses. Ground truthing field survey was undertaken to Legedadie, Dire and Gefersa reservoirs. All land cover classes were identified and recorded across each reservoir. The GPS coordinates of each sampling site were also noted recorded. Google Earth Engine, a platform for online pre-processing of satellite images, enhancement, and classification based on machine learning algorithms, was used to acquire and process satellite data from the years 1991–2021 in order to classify the land coverings in this study [55]. For this investigation, we obtained images from the area's dry seasons (01 January to 31 May) in order to reduce the impact of cloud cover. The images used to map and identify the various land cover classes in the city were taken in the years 1991, 1996, 2001, 2006, 2011, 2016, and 2021, as indicated in Table 3. Landsat data were chosen for mapping land covers because of its continuous geographical resolution and temporal coverage.

2.4. Image classifications and land cover change

The composite and processed satellite images for the years 1991, 1996, 2001, 2006, 2011, 2016 and 2021 were classified independently using the Random Trees classification method in ArcGIS 10.5 and LULC time series maps produced. Classes were defined based on FAO's Land Cover Classification System (LCCS) as shown in Table 4. The training data was from field observations using GPS, Google Earth data and existing maps from the Geospatial Information Institute of Ethiopia. 70% of the points were used for training the algorithm, while 30% were put aside for accuracy assessment.

The accuracy of the LULC classifications was evaluated using error matrices and Kappa analysis techniques [56]. With 30% of the ground truthing data points acquired from the field in 2021 serving as the reference data, the error matrix for the land cover classifications on the Landsat 8 image of 2021 was built. Google Earth data points for the various land cover types were used for validating prior years. By using a confusion matrix to compare the findings of the land cover classification to the ground observations, the accuracy of each land-cover class was assessed. The confusion matrices were then used to derive the overall accuracy, the Kappa statistic, and the producer and user accuracy for each class [57]. The total accuracy is calculated by dividing the number of pixels in the image that were properly identified by the total number of pixels used in the classification procedure. The Kappa statistic measures how much better one classification is than another when compared to a random classification. The user's accuracy is calculated by dividing the number of samples of each class in the map by the number of correctly classified points for each class in the image. On the other hand,

Table 2
Water quality ratings [51].

WQI	Water quality rating	Class
0–25	Excellent	1
26–50	Good	2
51–75	Poor	3
76–100	Very poor	4
Above 100	Seriously polluted/Unusable	5

Table 3
Description of spatial datasets used in this study.

Satellite data	Acquisition date (Composite images)	Bands	Spatial resolution
Landsat 8	01 January-31 May 2021 01 January – 31 May 2016	Thermal bands (2) SWIR (2) NIR	30 m
Landsat 5 TM	01 January –31 May 2011 01 January – 31 May 2006 01 January – 31 May 2001 01 January – 31 May 1996	Thermal band (1) SWIR (2) NIR Visible bands (4)	30 m

Table 4
Description of the land cover classes identified in this study.

Class	LCCS standard	User class definition
Water	Natural and artificial water bodies	Lakes, artificial dams and rivers
Vegetation	Natural and semi-natural terrestrial vegetation	Trees, shrubs, grasses
Bare land	Bare areas	Clear ground/bare areas
Roads	Built-up areas/artificial surfaces	Built up areas/impervious surfaces
Agriculture	Cultivated and managed terrestrial areas	Cultivated terrestrial areas
Settlements	Built-up areas/artificial surfaces and associated areas	Built-up structures

the producer accuracy was calculated by dividing the number of sample points that were correctly classified into a given class on the map by the total number of points in the ground truth data that belonged to that class [57].

The change statistics were then compared against each other to determine the percentage area of each class that had changed between the time periods. The classified land cover maps were then used for the change detection analysis [58,59].

2.5. Analysis of relationship between LULC change and water quality

Using IBM SPSS version 25 software, the Pearson correlation coefficient was assessed to identify the association between LULC change and water quality measures. For the years 1991, 1996, 2001, 2006, 2011, 2016 and 2021, the average yearly concentration of each water quality measure for which LULC information is available was examined. The observed percentage of LULC change served as the independent variable, and the dependent variables employed were measures of water quality [4,33]. In order to assess if the link

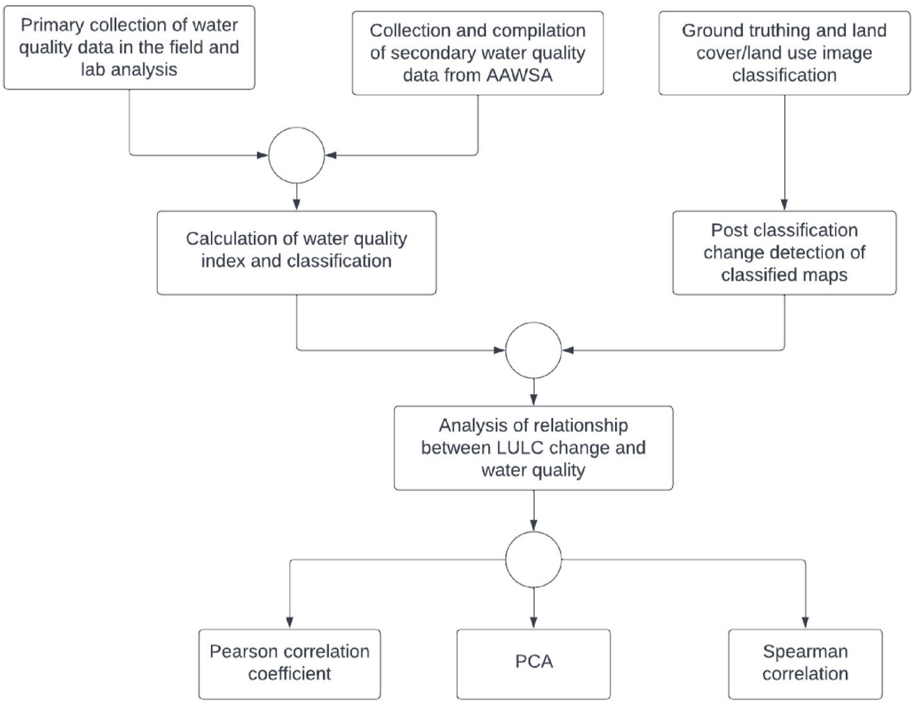

Fig. 2. Flow chart of the methodology.

was non-existent, weak, moderate, or strong, the study used ranges proposed by Ref. [33], where values between 0 and 0.09 denoted a lack of a relationship, 0.1 and 0.35 a weak relationship, 0.36 and 0.67 a moderate and 0.68 and 1 a strong relationship. Significant correlations were noted with asterisks. The physicochemical water quality parameters characterization and their relationship with land uses was further performed through a principal component analysis using the Spearman's correlation coefficient using the software XLStat-2023. Fig. 2 illustrates the flow chart of the methodology followed in this paper.

3. Results and discussions

3.1. Water quality classification

Table 5, shows the water quality classifications standards for 17 water quality parameters obtained from different sources.

The study's findings indicated that the water's turbidity varied during a 30-year period, with the greatest value (398.2 NTU) recorded in 2021 and the lowest value (138 NTU) in 1991 (Fig. 3a). Throughout the years of the census, the measured turbidity levels were significantly greater than the 0.2 NTU indicated by WHO criteria for safe water. According to earlier research, the reduced vegetation that is cut down to make room for settlements during urbanization is responsible for increased siltation, which results in higher turbidity. High turbidity can be associated with excess amounts of suspended organic matter and microorganisms such as bacteria. It could also be as a result of water coming into contact with surface runoffs [64]. According to research, turbidity of more than 1 NTU also affects the effectiveness of disinfection in water treatment plants [65]. Therefore, use of highly turbid water can be a health risk since excessive turbidity stimulates growth of pathogenic bacteria and can protect them from the effects of disinfectants [66]. It can also be ascribed to an increase in domestic and municipal sewage that is deposited untreated into the reservoirs. Electrical conductivity and total dissolved solids both exhibited an upward trend (Fig. 3a), with TDS consistently above the WHO-recommended 50 mg/L level. TDS include substances such as carbonates, bicarbonates, chlorides sulphates, phosphates, nitrates, calcium, magnesium, sodium and organic ions all of which determine the general nature of water quality. They affect the taste of drinking water if found at high concentration above recommended values [66]. The following variables also changed over the course of the study: sulfate, nitrate, iron, chloride, pH (Fig. 3b), fluoride, manganese, and phosphate (Fig. 3c), with sulfate, nitrate, iron, phosphate, and manganese exhibiting a positive trend and reaching a high in 2021. This increase in concentration could be attributable to increased sewage effluents and surface runoff from non-point sources like industry, where vegetated fields are rapidly transformed into built-up regions, as well as point sources like metropolitan areas, settlements, and agricultural land. The water's total hardness and total alkalinity both displayed a favorable trend (Fig. 3d). This growth can be linked to nutrient loading brought on by bad water resource management and unabated human activity.

3.2. Water quality index analysis

The water quality of Addis Ababa city was evaluated using the weighted arithmetic water quality index (WQI) approach (Table 6). The computed WQIs for the various years showed that Addis Ababa's physico-chemical water quality has been declining throughout the study period. The findings showed that Addis Ababa's water quality score exceeded 246 in 2021, a rise of 181 from the 65 reported in 1991. This is very high compared to results from other Ethiopian source waters of Hawassa town [67] which found that the drinking water quality index is still under marginal category with a WQI value of 49. Ref. [53] also found that the WQIs for the reservoir and tap water in Fiche town, Ethiopia were 25.031 and 40.676, respectively, and therefore safe for drinking. However, the results of this study are comparable to those of Bida town, Nigeria, where WQI of 171.85 was recorded; indicating that the drinking water is highly polluted [68]. The deterioration of water quality in Addis Ababa city over the years might be due to the fact that as a capital, the city harbors

Table 5
Ethiopian and international water quality classifications standards.

Parameters	Unit	1	2	3	4	5	Sources
Turbidity	NTU	<1	1 to 5	>5			[60]
pH		<6.5	6.5–8.5	>8.5	>8.5	>8.5	[61]
TDS	mg/l	<150	150–500	500–1500	>1500	>1500	[62]
EC	µS	<150	150–500	500–800	>800	>800	[60]
Total Alkalinity	mg/l	>50	50–250	>250	>250	>250	[14]
Total Hardness	mg/l	<60	60–180	180–300	>300	>300	[60]
NH_3 (Ammonia)	mg/l	0.02	0.02	0.02	0.02–0.2	0.2	[14]
NO^{2-} (Nitrite)	mg/l	<0.06	0.06–0.1	0.1–0.15	1	1	[14]
NO^{3-} (Nitrate)	mg/l	<10	10	20	20	25	[14]
SO_4^{2-} (Sulfate)	mg/l	<250	250	250	250	250	[14]
PO_4^{3-}(Phosphate)	mg/l	0–2				>6.1	[14] [63]
F^- (Flouride)	mg/l	<0.5	0.5–1.5	>1.5	>3	>3	[60]
Fe (Iron)	mg/l	<0.3	0.3–1	>1	>1	>1	[60]
Mn (Manganese)	mg/l	<0.1	0.1	0.1	0.5	1	[14]
Cl (Chloride)	mg/l					250	[53]
E. coli	CFU	<1	1 to 10	11–100	>100	>100	[60]
Total coliform	mg/l					10000	[61]

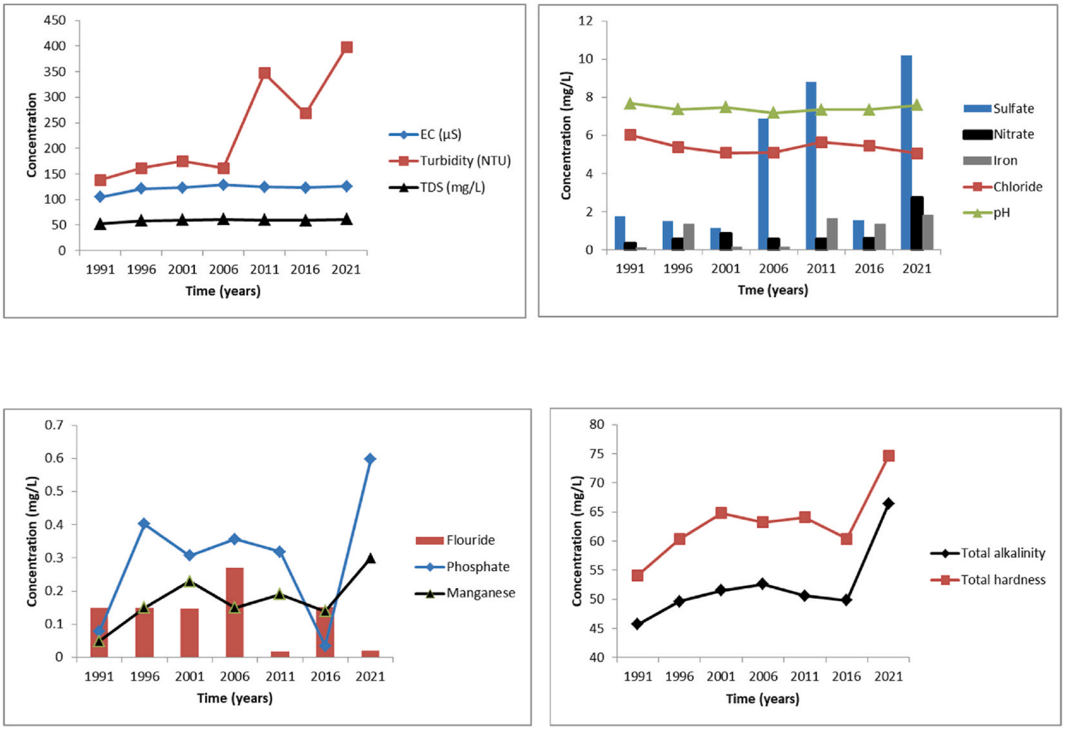

Fig. 3. a-d: Water quality parameters for Addis Ababa water resources recorded between 1991 and 2021.

over 65% of the country's businesses where more than 90% of those industries dump their trash into the neighboring rivers [38]. Where,

s_i = Standard value of i parameter [51].

$$k = 1/\sum(1/s_i) \tag{3}$$

$$q_i = (v_i/s_i) * 100 \tag{4}$$

v_i = Parameter value taken on ground.

Table 7 displays the classifications of water quality for the study years, 1991 to 2021. The classification change for water quality showed a significant decline in water quality between 1991 and 2021, going from a water quality index of 65.34–246.76. The categorization of the water quality shifted from poor to extremely poor during the period of 1991–2001, probably as a result of the fact that the water was already poor during that time. The period of 2016–2021 had the highest level of water quality degradation, with a water quality index score of above 246, according to records. 2021 had the worst water quality classification among all studied years and the surface water quality was shown to be seriously polluted and unusable.

3.3. Land-cover maps, changes and urbanization rates in Addis Ababa

Seven land cover classes were depicted on these maps of land cover for the years 1991, 1996, 2001, 2006, 2011, 2016, and 2021 (Fig. 4a–g). The classification results demonstrated remarkable accuracy, with a Kappa value of 80.6% and an overall accuracy of 91%. Users' and producers' accuracy varied widely between 80% and 100%.

The accuracy of classifications was assessed using error matrices to generate the user and producer's accuracy, overall accuracy and Kappa statistic and these are summarized in the supplementary file (S1). Supervised classification had the highest accuracy for the classifications. The overall accuracy for 2021 was 91% with a Kappa statistic of 80.6%. Users and producer's accuracy were constantly high ranging from 80% to 100%.

The change detection analysis across the city revealed a number of land cover changes as shown in the supplementary file (S2). Between 2016 and 2021, there was a significant rise in the area that was built up (settlements and roads), but the amount of water decreased. While the quantity of vegetated area fluctuated during the study period, the amount of bare land decreased most from 2016 to 2021. Agricultural areas also significantly decreased over the course of the study. Addis Ababa's settlements covered an area of approximately 72.6 km^2 in 1991, which increased to over 318.5 km^2 by 1996, an increase of over 338.7% (Table 8). Roads also showed an extensive increase of 219.2% (from 47.4 km^2 in 1991 to 151.3 km^2 in 2021). Between 2016 and 2021, the pace of urbanization peaked, converting over 349.8 km^2 of land to built-up areas (settlements and highways), bringing the total impervious surface area to

Table 6
Calculated WQI values for the period of study.

Parameters	s_i	$1/s_i$	Water quality ratings (q_i)								Water quality index (q_iw_i)						
			unit weight ($w_i = k/s_i$)	1991	1996	2001	2006	2011	2016	2021	1991	1996	2001	2006	2011	2016	2021
Turbidity	5	0.2	0.02254	2760	3220	3500	3220	6940	5360	7964	62.22	72.59	78.90	72.59	156.44	120.83	179.53
pH	8.5	0.12	0.01326	44.67	24.00	31.33	84.47	22.67	23.33	38.67	0.59	0.32	0.42	1.12	0.30	0.31	0.51
TDS	1500	0.0007	0.00008	3.47	3.91	3.99	4.09	3.97	3.93	4.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EC	800	0.001	0.00014	13.10	15.11	15.41	16.06	15.59	15.36	15.76	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total Alkalinity	250	0.004	0.00045	18.28	19.84	20.60	21.04	20.24	19.92	26.56	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Total Hardness	300	0.003	0.00038	18.03	20.10	21.60	21.07	21.37	20.13	24.87	0.01	0.01	0.01	0.01	0.01	0.01	0.01
NH_4^- (Ammonia)	0.2	5	0.56356	0.60	17.00	7.15	20.25	8.90	16.25	74.80	0.34	9.58	4.03	11.41	5.02	9.16	42.15
NO^{2-} (Nitrite)	1	1	0.11271	0.37	1.08	0.62	0.72	2.71	0.63	4.47	0.04	0.12	0.07	0.08	0.30	0.07	0.50
NO^{3-} (Nitrate)	25	0.04	0.00451	1.36	2.32	3.44	2.20	2.20	2.48	11.00	0.01	0.01	0.02	0.01	0.01	0.01	0.05
SO^{4-} (Sulfate)	250	0.004	0.00045	0.71	0.60	0.46	2.76	3.52	0.62	4.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PO^{4-} (Phosphate)	6.1	0.16	0.01848	1.30	6.59	5.03	5.85	5.21	0.57	9.79	0.02	0.12	0.09	0.11	0.10	0.01	0.18
F^- (Flouride)	3	0.33	0.03757	5.00	5.00	4.90	9.03	0.60	5.03	0.67	0.19	0.19	0.18	0.34	0.02	0.19	0.03
Fe (Iron)	1	1	0.11271	12.00	135.00	13.40	16.40	164.00	136.00	181.0	1.35	15.22	1.51	1.85	18.48	15.33	20.40
Mn (Manganese)	1	1	0.11271	5.00	15.00	23.00	15.00	19.00	14.00	30.00	0.56	1.69	2.59	1.69	2.14	1.58	3.38
Cl^- (Chloride)	250	0.004	0.00045	2.41	2.15	2.03	2.04	2.26	2.18	2.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total		8.87								**WQI(q_iw_i)**	65.34	99.85	87.83	89.22	182.84	147.50	246.76

Table 7
Water quality classifications for the census years.

Census year	WQI (q_iw_i)	Water quality rating	Class
1991	65.34	Poor	3
1996	99.85	Very poor	4
2001	87.83	Very poor	4
2006	89.22	Very poor	4
2011	182.84	Seriously polluted/unusable	5
2016	147.50	Seriously polluted/unusable	5
2021	246.76	Seriously polluted/unusable	5

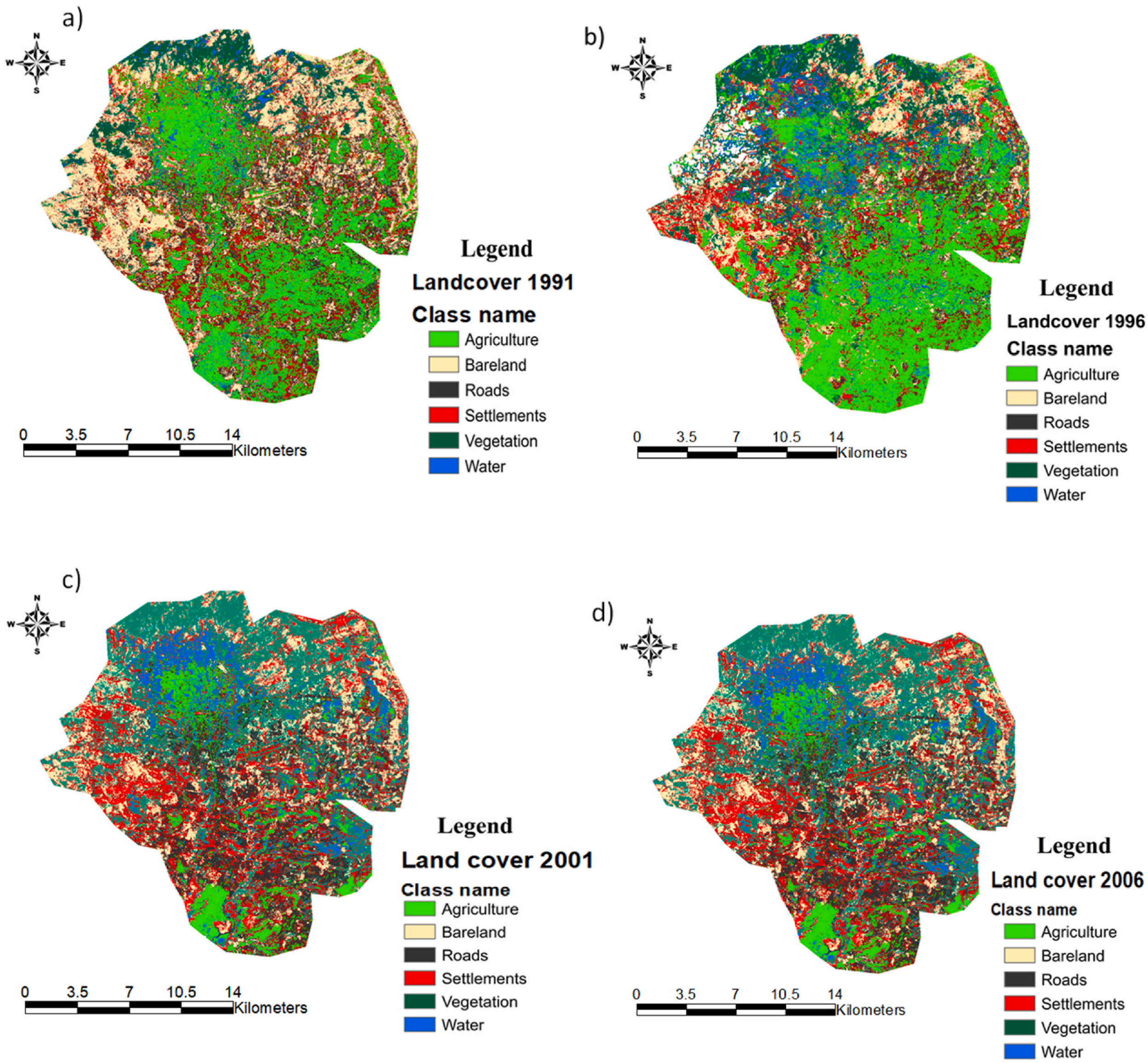

Fig. 4. a-g. Land cover classification maps of the Addis Ababa for the years (a) 1991, (b) 1996, (c)2001, (d)2006, (e)2011, (f) 2016 and (g) 2021.

469.8 km^2. Water, bare land, and agricultural areas all had significant declines during the research period, falling by 61%, 99.8%, and 91.9%, respectively.

Comparing the classification maps from 1991 to 2021 allowed for the identification of the city's overall net altered area and the kind of change that had taken place (Fig. 5). Agricultural and bare terrain areas had the most areal loss. Roads came in second place in

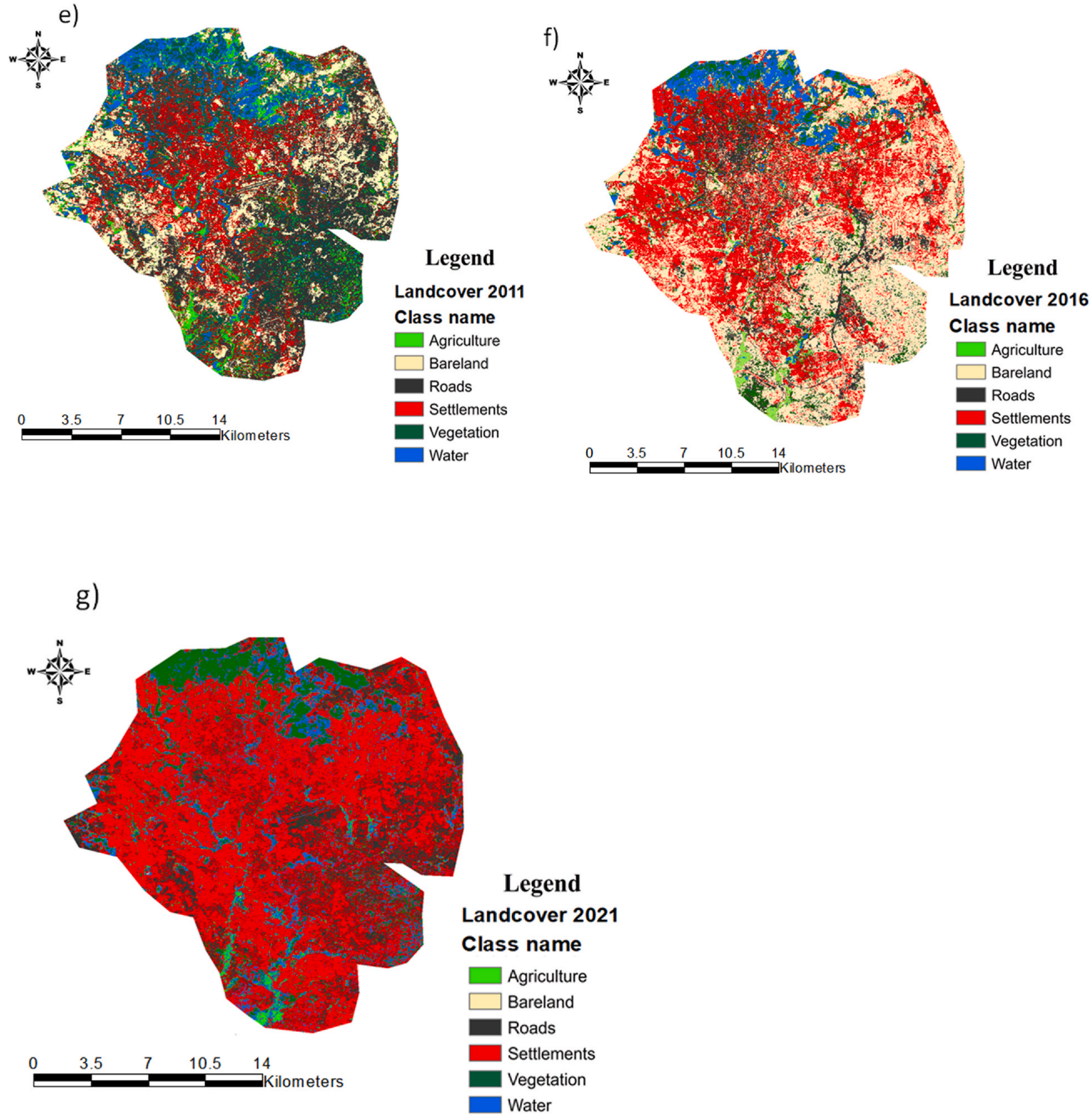

Fig. 4. (*continued*).

Table 8
Land-cover changes that occurred between 1991 and 2021.

Land cover class	1991 area (km^2)	2021 area (km^2)	Change in area (km^2)	% change from original area
Water	30.3	11.8	−18.5	−61.1
Vegetation	50.7	57.8	7.1	14
Settlements	72.6	318.5	245.9	338.7
Roads	47.4	151.3	103.9	219.2
Bare land	117.6	0.27	117.33	−99.8
Agriculture	145	11.8	133.2	−91.9

terms of area, after settlements. The area of the city that was covered by water decreased significantly as well.

3.4. Impacts of LULC change on water quality

The resultant land cover classifications were matched with the water quality metrics. A high association was found between changes in water quality measures and changes in land cover, such as an increase in built-up area, a decrease in bare land, and agricultural activity (Table 9). Turbidity, for instance, revealed a highly substantial positive association with agriculture, settlement, and roadways. This implies that the water becomes increasingly turbid as the amount of built-up area increases. The total alkalinity of the water was shown to increase as built-up area (settlements and roads) increased, as shown by the positive correlations of 0.892 and 0.852, but barren land was shown to decrease the total alkalinity of the water, as shown by the negative correlations of −0.833. A decrease in barren land had a negative association with the overall hardness of the water, whereas an increase in settlements and road classes had a positive significant link with the total hardness of the water. Ammonia, nitrite, and nitrate concentrations were affected by changes in the amount of bare land and built-up area. The nitrate concentrations' positive relationships with roads and settlements suggested that these LULC alterations were the primary sources of nitrate in the city's water supplies. Additionally, it was discovered that roads and manganese levels in water correlated positively, suggesting that expanding road networks will raise manganese levels in water (Table 9).

Fig. 6 reveals a strong positive correlation between the water quality classifications and built up area (roads and settlements). As the percent of land area within Addis Ababa city becomes increasingly urban, the water quality classifications become progressively worse. The strength of the correlation is indicated by the high R^2 value of 0.8411 and a significant p value of 0.0165 at 95% confidence level.

This can be attributed to the fact that the increase in built up area comes with an encroachment of people from the rural areas to the city resulting in dense population [16]. Increased population growth also means increased waste generation [69]. Since Addis Ababa does not have proper sewage lines connection, most of this waste in dumped directly into the rivers [38]. The city's sewer network coverage is very limited and has been estimated to account for only 7.5% of the built-up areas. Also only parts of the older sections of the city are connected to the central sewer system hence both residential and business premises use septic tanks which are also not so efficient [70]. The principal component analysis accounted for 68.95% of the cumulative variance of the data set in the first two axes (F1: 54.65% and F2: 14.30%) (Fig. 7). The principal component analysis test indicated that turbidity, total dissolved solids, total alkalinity, total hardness, ammonia concentration, nitrite, nitrate, phosphate, iron, sulfate, manganese, and reactive silica were all impacted by land uses such as settlements, roads and vegetation changes.

The operation of town industrial enterprises which may lack the resources and technology to deal with industrial waste contribute to the degradation of water quality in the city. This is because most of the time, these are run by residents with little or no education regarding environmental protection and they dump untreated wastes directly into the rivers crossing Addis Ababa and in the ditches designed for runoffs [38,71]. The changing trends to the proportion of different land uses that came with urbanization may also explain some of the reasons for Addis Ababa's water quality problems. In particular, the rapid increase in built up area results in a decline in vegetated areas which increase the rate of sedimentation making the water turbid. Also the increase in impervious areas from built up areas increases the rate at which non-point source pollutants are carried into the water resulting in further degradation of the quality [72].

4. Conclusions and recommendations

This study assessed the link between LULC changes and the quality of water in Addis Ababa city over a period of 30 years. The general findings of the study showed an increase in nutrient concentration (nitrate, phosphate, iron, manganese and sulfate), turbidity, electrical conductivity, TDS, and total hardness and total alkalinity in the water. The results of the study revealed that land use, particularly the increase in built up area is an important contributor and explaining factor regarding the quality of water in Addis Ababa. Thus, the management of land with respect to sustainable development and mitigation of the problems are clearly issues to be addressed with practical evidences. The findings of this paper suggest that land use planning policies need to work in together with water managers and users (city dwellers, industries, etc.) to come up with strategies to improve Addis Ababa's water quality. Controlling the rate, form, and type of urbanization can play a vital role in protecting valuable urban water resources. The LULC change analysis results suggest that water resources are more vulnerable and this is worsening with time, hence there is an urgent need for further monitoring to conserve them. No single approach can be enough to control the quality of water in a big city like Addis Ababa. In other words, multiple disciplines need to come together to form an integrated management strategy. The information provided in this study can be used as a baseline for formation of such management strategies. Consistent monitoring of changes to water quality will assist in identifying how land use planning can help to ensure the preservation of water resources [14]. The study also recommends that proper land use planning and management are essential to improve and sustain the quality of water in the city's water resources.

Based on the results of this study, it is evident that the city of Addis Ababa has undergone extraordinary growth over the years, which has put immense pressure on the water resources resulting in the deterioration of the water quality. This has made it extremely difficult to maintain the water supply and quality while balancing the rapid infrastructure development. With the relationship between urbanization, climate change and environmental change having such a profound impact on water security, urban actors need to look for actions and responses to curb their impacts and address all the gaps and challenges that the Addis Ababa water supply system faces (Romero-Lankao & Gnatz, 2016) hence the importance of studies like this one. It is therefore necessary to examine the connection between LULC and changes in water quality that cause water scarcity, even if the Ethiopian government executes its laws to control

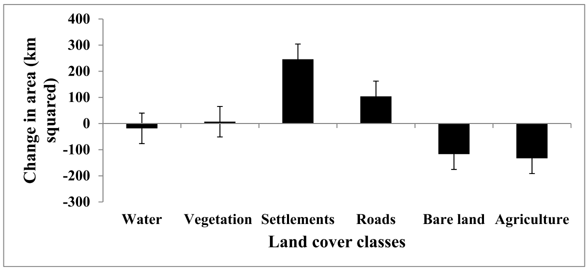

Fig. 5. Net changes of the Land cover classes during the period 1991 to 2021.

Table 9
Pearson correlation for water quality parameters change and LULC change, n = 7.

Water quality	Water	Vegetation	Agriculture	Bare land	Settlements	Roads
Turbidity (NTU)	−0.585	0.584	0.899**	−0.386	0.846*	0.917**
PH	−0.197	−0.113	−0.02	−0.25	0.246	−0.001
TDS (mg/L)	−0.22	0.124	−0.307	−0.383	0.376	0.633
EC (μS)	−0.231	0.177	−0.363	−0.325	0.371	0.639
Total Alkalinity (mg/L)	−0.714	0.074	−0.493	−0.833*	0.892**	0.858*
Total Hardness (mg/L)	−0.569	0.211	−0.501	−0.774*	0.788*	0.891**
N (Ammonia) (mg/L)	−0.725	0.014	−0.494	−0.807*	0.924**	0.794*
N (Nitrite) (mg/L)	−0.559	0.519	−0.632	−0.739	0.841*	0.831*
N (Nitrate) (mg/L)	−0.69	0.007	−0.843	−0.825*	0.904**	0.809*
SO4 (Sulfate) (mg/L	−0.639	0.663	−0.586	−0.569	0.664	0.74
PO4 (Phosphate) (mg/L)	−0.237	0.184	−0.04	−0.942	0.492	0.517
F- (Flouride) (mg/L)	0.206	−0.63	0.623	0.369	−0.573	−0.596
Fe (Iron) (mg/L)	−0.203	0.434	−0.702	−0.302	0.655	0.633
Mn (Manganese) (mg/L)	−0.386	0.183	−0.425	−0.721	0.67	0.826*
Cl (Chloride) (mg/L)	0.26	0.274	0.056	0.543	−0.365	−0.522

* Correlation is significant at 0.05 level,
** Correlation is significant at 0.01 level.

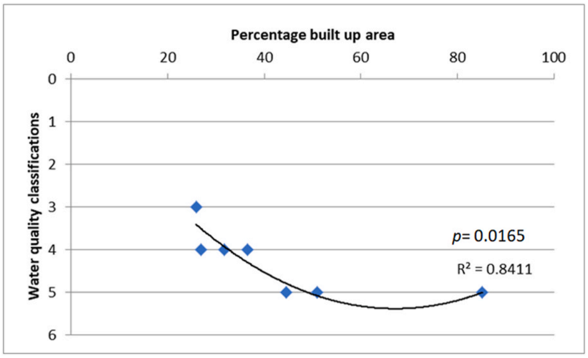

Fig. 6. Changes in water quality with changes in the proportion of urbanized land.

pollution of water resources. This study adds to the understanding of LULC changes in a catchment that is rapidly developing and experiencing rapid water quality degradation, which is typical of many developing countries. It also offers information to policy makers and land use planners in the watershed which they can use to develop an adaptive path to meet future water demand and lessen the vulnerability of municipal water supply systems to shortages by characterizing impacts of urban development patterns on future conditions of water quality. This is necessary for sustainable water management and smart urban growth. Hence, to improve the framework for maintaining the health of water resources, research like this one are vital at the local and state levels. Such information is crucial for directing management planning and modeling assessments of the potential future for the city to track the progress towards achieving Sustainable Development Goals 6 on clean and safe water for everyone.

The topic of water quality is wide and encompasses many variables. This study focused on some selected parameters that are considered key in the determination of drinking water quality based on WHO standards. However, the study was limited in that it did not consider other important water quality parameters such as total coliforms and heavy metals in the computation of the water quality index. It is therefore recommended that further research should consider additional water quality parameters such as heavy metals and

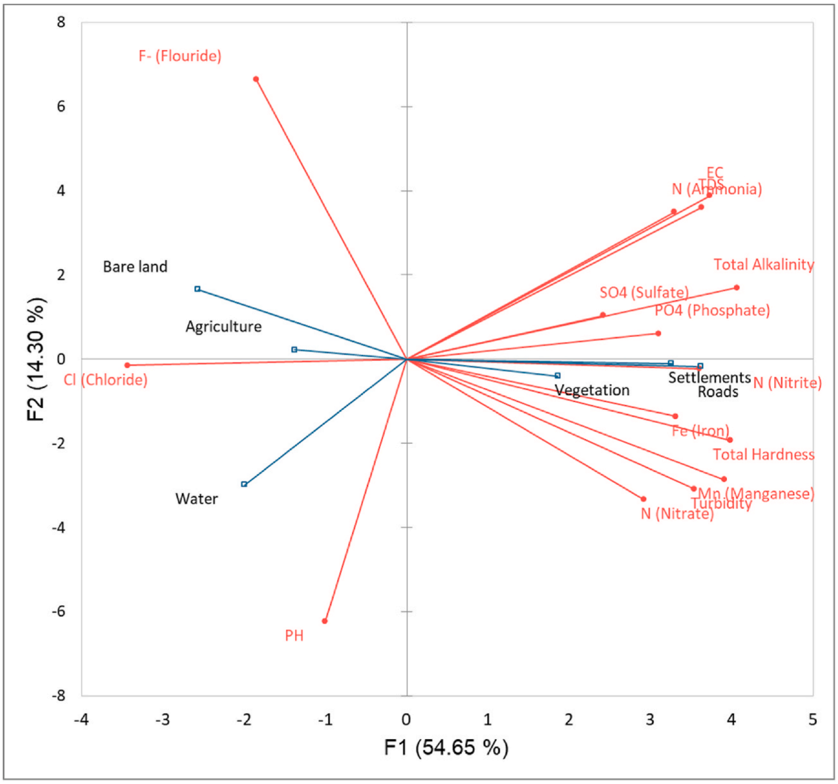

Fig. 7. Principal component analysis showing relationship between LULC variables and water quality parameters.

microbiological parameters and how they have been changing with land use/land cover changes.

Author contribution statement

Thandile T. Gule: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Brook Lemma: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Binyam Tesfaw: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

Data will be made available on request.

Declaration of interest's statement

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e15665.

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