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Impact of Land Use Change on Lake Pollution Dynamics: A Case Study of Sapanca Lake, Turkey

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Abstract: Modeling non-point source pollution dynamics in inland lake basins is essential for safeguarding water quality, maintaining ecosystem integrity, protecting public health, and advancing long-term environmental sustainability. This study explores non-point pollution dynamics in the Sapanca Lake basin, Turkey, in association with the basin's land use, land cover, hydrology, pollutant sources, and water quality parameters. The required data were gathered via a three-year monitoring program, which was carried out at 12 sampling stations around the lake, as well as using the collecting field measurements and GIS databases. Stepwise multiple regression analysis was employed to determine the best relation between non-point pollutants and land features. The results showed that urbanization and population density have significant correlations with the total nitrogen (TN) and total phosphorus (TP) in the study areas. Rivers crossing pristine areas, such as forests and uncultivated lands, demonstrated better water quality, thereby positively contributing to the lake ecosystem conservation. The highest nutrient loads were observed in streams that flow through highly urbanized sub-basins, followed by predominantly agricultural areas. This is likely due to runoff from urban environments, leaching from cultivated land, and contributions from livestock and tourism facilities. Conversely, densely forested regions exhibited the lowest levels of nutrient loads, highlighting their capacity for nutrient retention. The peak levels of non-point source pollution (TN = 5.22 mg/L and TP = 0.53 mg/L) were recorded in catchments with the highest degree of urbanization, whereas the lowest values (TN = 0.28 mg/L and TP = 0.04 mg/L) were found in the least urbanized areas. These findings emphasize that nutrients primarily impact water quality because of increasing urban and agricultural activities, while forested land plays a vital role in preserving lake water quality. To ensure sustainable water quality in lake basins, it is essential to strike a careful balance between protective measures and utilization policies, prioritizing conservation efforts.

Keywords: total nitrogen; total phosphorus; Sapanca Lake; land use change; water quality

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1. Introduction

Aquaculture and agricultural activities, expanding urban areas, and land use/land-cover (hereinafter referred to as LULC) change are principal anthropogenic activities that degrade surface water quality [1–3]. On the other hand, population growth and socio-economic development steadily escalate the need for more freshwater resources. Therefore, surface water (sea, wetlands, etc.) and groundwater conservation and reclamation plans play a vital role in achieving sustainable water resource development [4,5].

Among different anthropogenic pollutants, non-point pollution sources are of greater concern in surface water conservation as their impacts, level, and distribution cannot be easily determined [6,7]. Generally, changes in LULC increase non-point pollutant loading into nearby ground or surface water bodies. For instance, agricultural activities can contribute nutrients like nitrogen and phosphorus, leading to eutrophication, while urban areas often introduce heavy metals and hydrocarbons [8]. LULC changes can also alter surface runoff patterns, infiltration rates, and groundwater recharge, which affect the transport and dilution of pollutants in surface water bodies. Increasing soil erosion and sedimentation are the other side effects of LULC change that occur due to deforestation and land clearing activities, leading to higher sediment loads in rivers and wetlands. This can reduce water quality, harm aquatic habitats, and increase the cost of water treatment [9–13].

Land use impacts the surrounding ecosystems that play a role in filtering and regulating water quality, such as wetlands and riparian zones. Changes to these areas can degrade their ability to maintain clean water. Recent studies have shown that LULC changes often intensify the impacts of climate change, such as altered extreme weather patterns and increased drought and flood events, which can further degrade soil and water quality [14]. Accordingly, understanding the relationship between LULC changes and surface water quality is essential for informed decision-making, allowing policymakers to implement sustainable land and water resources management practices and mitigate adverse effects on aqua systems.

Various statistical and empirical modeling techniques could be applied to determine the impact of LULC changes on lakes/wetlands pollution levels [14,15]. While the former requires extensive data, the latter is considered less complex and more user-friendly [16]. For example, statistical analyzing based on principal component analysis and multiple linear regression has shown that successive historical changes in LULC have raised the salinity rate in Lake Wilcox [17].

Identifying sources of water quality degradation is required for developing strategies to preserve and enhance the health of wetlands. The primary objective of this study is therefore, to investigate the relationship between LULC changes and nonpoint pollutants in a vital freshwater resource of Turkey, Lake Sapanca. This endeavor marks the first attempt to delineate such a relationship in the study area, offering valuable insights that will be applicable to other freshwater resources.

2. Materials and Methods

2.1. Study Area

Turkey receives an average annual precipitation of approximately 574 mm, equating to a total of 450 billion cubic meters per year [18]. The Lake Sapanca basin (see Figure 1), with an area of 311 km^2, is located between the Sakarya and Kocaeli provinces (latitude 40°41′–40°44′ N and longitude 30°09′–30°20′ E). The lake is one of the primary sources of fresh water in northwestern Turkey. Its location is on the main transportation lines that connect Europe and Asia. There are many residential, agricultural, and tourist facilities within the lake basin. It consists of 12 sub-basins that differ between urban areas, native forest, and agricultural land. The basin's annual average temperature and average precipitation are 14.3 °C and 720 mm, respectively.

The water body area of the lake is 47 km^2 with maximum depth is 55 m. The first observations of the limnological features of the lake show shallow shores covered by extensive vegetation. It is a typical warm monomictic lake, characterized by complete mixing from the surface to the bottom during February and March, which facilitates nutrient enrichment in the surface waters and oxygenation of the bottom layers. Lake Sapanca is characterized by low concentrations of dissolved inorganic ions, making its water suitable for drinking, industrial applications, and agricultural irrigation. However, the lake faces significant environmental pressures due to urbanization, which has led to habitat degradation along its shores. This is primarily driven by the increasing human population and associated anthropogenic activities, highlighting the need for effective management and conservation strategies to preserve its ecological integrity and water quality. Although there is no direct waste discharge, chemical pollutants of domestic and agricultural origin enter the lake via runoff [19].

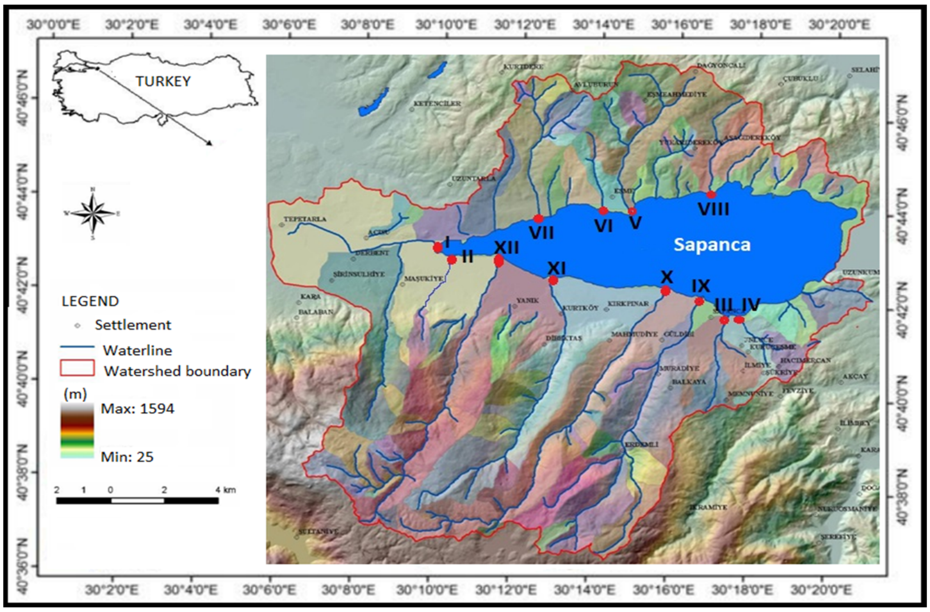

Figure 1. Location of the Lake Sapanca basin in the northwest of Turkey with 12 sub-basin streams and sampling sites in each stream from I to XII.

The Lake Sapanca basin hosts two principal aquifer systems with distinct geological and hydrological characteristics. The southern aquifer comprises karst formations of marble and recrystallized limestone from the Permo–Triassic and Upper Jurassic–Lower Cretaceous periods. This karst aquifer is characterized by spring discharges ranging from 1 to 19 m^3/s, predominantly sourced from fractures within fault zones and schist–marble contacts. The northern aquifer system, dating to the Quaternary period, has developed within alluvial deposits and alluvial fans. The alluvial fill reaches a maximum thickness of approximately 60 m, with the fans varying between 60 and 90 m in thickness. Groundwater flow in both aquifers predominantly converges toward the lake, indicating a strong hydrological connection [19]. Additionally, as depicted in Figure 1, surface runoff is channeled into the lake through numerous intermittent and perennial streams, with larger catchment areas concentrated in the southern and western sections of the basin.

2.2. Water Sampling, Analytical, and Statistical Analyses

Monthly samples were collected from 12 main streams in the lake basin (Table 1). Samples were taken at stream mouth (see Figure 1) for three years. At each point, the cross-sections and depths between the channels and the flow were measured precisely. As the dependent water pollution variables, total nitrogen (TN) and total phosphorus (TP) samples from the pollutants dispersed in the laboratory were analyzed in the first 24 h. Other analyses were carried out by a cadmium reduction method, ammonium-N (ISO 11732), nitrate-N (ISO 11905), nitrite-N diazotization (EN 26777), and Kjeldahl nitrogen by the Kjeldahl method (ISO 11905-1). The TP was determined by the standard ascorbic acid method.

In this method, persulfate digestion was applied to soluble reactive phosphorus [20]. Quality assurance/quality control was applied to all the sampling and analytical processes.

Table 1. Main features of sampling sub-basins.

Number	Name	Area (km^2)	Stream Length (km)	Dominant Land Cover
I	Balıkhane	34.6	14.1	Urban
II	Kasabasın	8.2	2.1	
III	Keçi	7.8	5.7	
IV	Sarp	7.8	3.3	
V	Maden	13.4	6.0	Agriculture
VI	Kurudere	4.9	2.3	
VII	Değirmen	15.3	6.0	
VIII	Harmanlı	5.2	2.7	
IX	Yanık	33.2	14.2	Forest
X	Kurtköy	27.1	12.7	
XI	Mahmudiye	22.0	17.2	
XII	Istanbul	28.1	14.2	

Statistical analyses were conducted to clearly assess the impact levels of pollutants within the basin and to explore the relationships among relevant parameters. This approach unveiled the confidence intervals of the estimates [21,22]. To this end, a stepwise multiple regression analysis was utilized to identify the optimal fit between the dependent variables TN and TP and the categories of land use, which included forest, cultivated land, urban land, low-density settlement areas, grassland, water bodies, and population density, our independent variables. The experimental data were analyzed using Statgraphics Centurion version XVI (Statpoint Technologies Inc., Warrenton, VA, USA). An alpha (α) level of 0.05 (equivalent to 95% confidence) was adopted to ascertain statistical significance in all analyses.

3. Results

3.1. Land Use Proportion

The land use of the lake basin was classified into eight categories, forest, grassland, cultivated lands, natural lands, low-intensity settlements, urban land, and roads based on the sub-river basin, as indicated in Figure 1. The results revealed that forest cover dominated the catchments of the IX, X, XI, and XII streams. The proportion of cultivated land is more than half of the total land cover at V, VI, VII, and VIII (Figure 2). Considering both LULC, the sub-basins are grouped into forest, cultivated land, and urban development areas. Mixed horticulture and fruit and vegetable cultivation are the main types of agriculture on the cultivated land. Ornamental plant cultivation dominates low-density settlement areas. A greater proportion of the urban regions occurred in III and IV, followed by low-density settlements in sub-basins I and II. These four sub-basins dominate the population; therefore, natural land is replaced by urban areas and road cover. There is no cultivation area in forest sub-basins IX and XI and the urban-dominated sub-basin III.

In the Lake Sapanca basin, the settlement areas reached 1142 hectares with 3.86% in 1995. Settlement areas have grown with the destruction of agricultural and forest areas. Compared to 1985, there was a 70% growth (470 hectares). In 2005, LULC changes continued to be experienced in agricultural and forest areas, and the difference became more evident, especially in forest areas. The settlement area, accounting for 6.0% of the basin, has expanded by 612 hectares since 1995, reaching a total of 1754 hectares in 10 years, reflecting a 28% increase [23]. In 2020, the settlement area within the basin expanded to

2450 hectares. The population increase in the research area exceeding 20 percent in the last ten years is clear evidence of rapid urbanization in the Lake Sapanca basin [24,25].

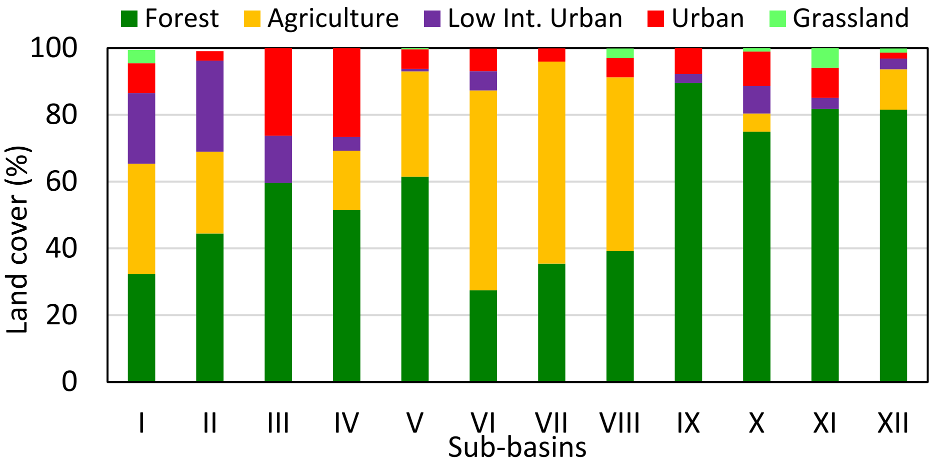

Figure 2. Percentage land use within each sub-basins of the Lake Sapanca watershed.

3.2. Stream Water Quality

A summary of the characteristics of the sub-basins, stream discharge, and water concentrations of TN and TP is presented in Table 2. The TN concentrations ranged from 0.28 to 5.22 mg/L, while TP concentrations varied between 0.04 and 0.60 mg/L. Both parameters exhibited significant differences across the various sub-basins ($p < 0.01$). The measured annual average precipitation was 980 mm. Streamflow demonstrated strong seasonal and temporal variations throughout all studied sub-basins. High flows were recorded during the period from April to May and low flows were observed from August to September (Figure 3). From August to October, discharge in all study areas and streams located north of the V, VI, VII, and VIII sub-basins decreased significantly. Some streams ceased to flow in this period (Table 2). The highest discharge was recorded at station I, which exhibited the least variation.

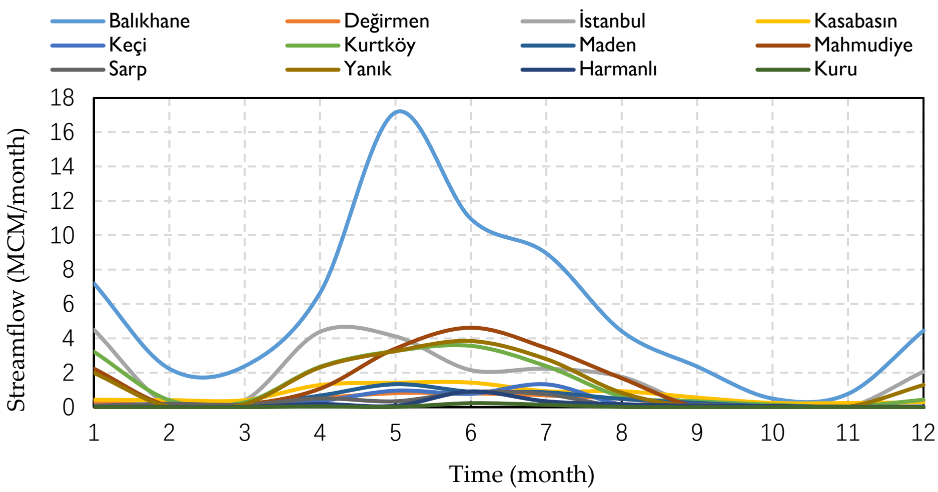

Figure 3. Monthly streamflow variation at each sub-basin (water year from October (1) to September (12)). MCM stands for million cubic meters.

Monthly variations in TN and TP concentrations are illustrated in Figure 4. The TN results indicate that concentrations in urban-dominated areas consistently exceeded surface water thresholds. In contrast, stream concentrations from cultivated land were elevated but remained within the limits, particularly during periods of high-water discharge. The increased concentrations observed in these areas, compared to forests and grasslands, can be attributed to effluents from urban sources and diffuse runoff from agricultural practices.

Notably, ammonium-N was the predominant form found in streams within urban areas, highlighting the impact of human waste, while nitrate-N prevailed in agricultural sources, reflecting the nitrification leaching from applied fertilizers. In this region, nitrogen fertilizers such as urea, ammonium nitrate, and diammonium phosphate are primarily used.

Table 2. Stream flow discharges based on three-year averages with coefficient of variation (CV), total nitrogen (TN), and total phosphorus (TP) in river discharge from different land use types.

Number	Discharge (L/s)	CV (%)	TN (mg/L)	TP (mg/L)
I	2248	64	1.40	0.17
II	277	87	1.81	0.13
III	126	134	5.22	0.53
IV	101	115	4.32	0.60
V	152	114	1.70	0.07
VI	14	199	1.94	0.24
VII	127	105	0.97	0.08
VIII	60	168	1.73	0.07
IX	476	101	0.28	0.04
X	458	98	0.44	0.04
XI	468	91	0.48	0.05
XII	582	96	0.56	0.16

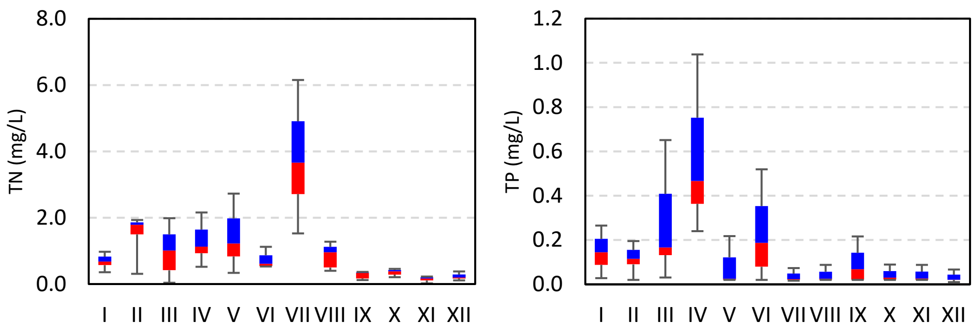

Figure 4. Streamflow variation at each sub-basin (water year from October (1) to September (12)).

Like the stream water TN concentrations, the TP concentrations were also significantly affected by land cover. The TP was much higher in streams in urban areas (I, II, III, and IV) than in the agriculture-dominated land and forest land streams ($p > 0.01$). Compared to the forest land stream water, the TP concentration was 1.5 times higher at the cultivated land sites and 5.0 times higher at the urban land sites. Moreover, the water TP concentrations were above the surface water TP limits at sites where anthropogenic impacts occurred, predominantly in high urban areas with higher standard deviation, such as III and IV.

Nitrate was identified as the predominant form of inorganic nitrogen, having concentrations ranging from 0.02 to 6.60 mgL^{-1}. The sub-basins IX, X, XI, and XII, with a higher proportion of forest cover, exhibited the lowest nitrate concentrations. Conversely, nitrogen levels were significantly higher in areas with intense urbanization. Streams crossing the agriculture-dominated regions typically showed higher nitrate concentrations during the dry seasons, when water discharge was reduced. At urban sites, ammonium concentrations ranged from 0.040 to 2.15 mgL^{-1}, with the highest levels recorded at stream IV, which also showed a higher standard deviation. This sub-basin is in an area of extensive urban development (Table 1), highlighting the impact of anthropogenic activities.

The concentrations of TN and TP in stream water exhibited considerable variability according to land use. Streams dominated by urban areas, and to a lesser extent those influenced by agriculture, displayed higher concentrations and greater variation (measured as the coefficient of variation (CV) compared to forested sites (Figure 4 and Table 2).

Notably, TN and TP concentrations increased during the dry summer months, leading to an elevation in the standard error of these variations. Consequently, stream discharge from urban-dominated basins was higher than that from agricultural lands. This indicates that the inflow of TN into Lake Sapanca from these streams predominantly originates from urban-dominated areas. While TN concentrations in streams from cultivated land were also elevated, their overall contribution to the lake was minimal, due to their lower discharge levels (Figure 5).

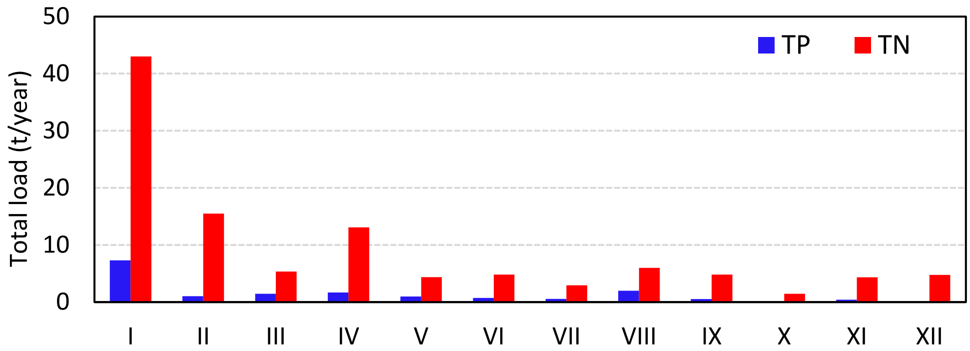

Figure 5. Annual TN and TP contribution to Lake Sapanca by different sub-basin streams.

Various traditional approaches to pollution control, such as coagulation, biofiltration, and adsorption, have demonstrated significant potential for effectively removing pollutants. However, these methods often involve substantial land requirements, high energy consumption, and elevated maintenance and operational costs. Additionally, they carry a considerable risk of generating secondary pollution [26]. Microbial and ecological remediation techniques are particularly useful for mitigating eutrophication. Following this, physical methods and chemical processes, including filtration, ventilation, and UV radiation, can be implemented. Agricultural pollution can be effectively managed by constructed wetlands, buffer strips, and floodplains [27,28].

3.3. Modeling Results

Stepwise linear regression was applied to determine the model that best formulated the relationship between stream-borne pollutants and land use at the sub-basin scale. In the regression model, the independent variables were land cover variables, such as forest, cultivation land, urban land, low-intensity settlements land, and grassland. The results of backward stepwise multiple regression modeling for TN indicated that, as shown in Equation (1), ($R^2 = 0.81$, $p < 0.01$), proportional land coverage (%) of the urban area and cultivated land have a significant role in stream water TN variation.

$$TN = -0.575 + 0.022 \times \text{cultivated land} + 0.183 \times \text{urban land} \quad (1)$$

Equation (1) suggests that a higher proportion of urban areas (%) and cultivated land would lead to increased TN levels in the streams. In contrast, natural ecosystems, such as forests and grasslands, were identified as the least significant variables affecting TN, indicating that they positively contribute to the concentration of TN in stream water. Furthermore, the stepwise multiple regression analysis revealed that land cover significantly impacts stream water TP, as well as the results of Equation (2).

$$TP = -0.103 + 0.023 \times \text{urban} + 0.002 \times \text{cultivated} + 0.003 \times \text{low-density settlement} \quad (2)$$

Based on the equations, urban land, cultivated land, and low-density settlement areas had a significant impact on stream TP concentration ($R^2 = 0.88$, $p < 0.01$). To explore the relationship between land use and nonpoint source pollution, Pearson correlation analyses were performed (Table 3). In regions with high urban density, a strong correlation (>95%) was found between TN and TP, with the highest correlation rates observed in urban areas. Conversely, forested regions, grasslands, and nearby streamflow areas were shown to negatively affect nonpoint source pollution levels (TN and TP).

Table 3. Pearson correlation coefficient between land use/land cover types and total nitrogen (TN), and total phosphorus (TP) concentration in stream water.

Parameter	TN	TP
Streamflow	−0.262	−0.150
Forest area	−0.317	−0.181
Grassland	−0.359	−0.364
Agricultural land	−0.061	−0.189
Low-density settlement	0.220	0.166
Urban area	0.848 *	0.913 *
Population density	0.660 *	0.697 *

Note: * Strike sign denotes strong linear correlation.

4. Discussion

Previous studies have indicated that LULC changes and increasing population density in urban and agricultural areas significantly degrades surface water quality [29,30]. This issue can be partially mitigated through the installation of sewer networks that effectively collect wastewater from urban regions, alongside the implementation of optimal agricultural practices in cultivated areas [9]. However, challenges remain, as domestic and industrial effluence, stormwater runoff, and diffuse pollution continue to adversely affect water quality. The present study highlights that changes in LULC within the sub-basins have a negative impact on river flow and lake water quality. Despite maintaining a relatively high percentage of forest areas in many sub-basins, it is evident that transitions to agricultural and urban land uses lead to unfavorable changes in seasonal discharge patterns and nutrient concentrations [31].

Between 30% and 50% of the world's surface waters are currently adversely affected by non-point sources of pollution, predominantly stemming from agricultural activities. In the United States, over two-thirds of total pollution arises from non-point sources, with agricultural pollution accounting for the majority, ranging from 68% to 83% [32]. A similar situation is observed in Europe, where agricultural activities contribute to 85% of the total nutrient inflow (TN and TP) into the North Sea [33]. In China, emissions from agricultural sources represent 57.2% and 67.4% of the TN and TP, respectively [34]. Intermittent streams are described as waterways that experience a break in flow during the rainy season and can completely dry up in high-altitude regions during the dry season [35].

The impact of nitrogen and phosphate pollution has evolved due to the social and economic development of neighboring settlements. Calculating the pollutant footprint allows pollution levels to relate with human activities. Urbanized areas, regions with intensified commercial activities, and the nature of agricultural practices have become critical factors influencing diffuse pollution (TN and TP). It is essential for decision-makers to take footprint studies into account when addressing these issues [35].

Cultivated areas experienced dry conditions for 4 to 6 months during the summer months. Hydrological variability among sub-basins can be significant, influenced by factors such as spatial variation, vegetation, and the size of the drainage area. In our study, streams located in sub-basins with the highest forest cover (exceeding 75%) demonstrated permanent flow, reduced discharge variability, and the lowest concentrations of TN and TP, with less fluctuation (IX, X, XI, and XII). These trends can be attributed to the advantages of land cover [36]. Conversely, in regions where agricultural land constituted more than 40% of the sub-basin, streams exhibited intermittent flow and comparatively higher levels of TN and TP during periods of reduced discharge, particularly in the dry season. The stream discharge from urbanized areas and those with lesser agricultural influence showed higher TN and TP concentrations compared to streams from forest-dominated sub-basins (Figure 4). Often, TN and TP concentrations surpassed the thresholds of 5 mg L^{-1} and 0.65 mg L^{-1}, respectively, which are the class IV limits set by the Turkish National Quality Standards for Surface Waters. Furthermore, the elevated levels of TN and TP in stream water indicate runoff and discharge contributions, resulting in increased nutrient richness in urban sub-basins. This finding is supported by Nakane and Haidary [37], who highlighted the strong correlation between TN levels and urbanized areas, underscoring the detrimental impact of anthropogenic activities on natural water resources. However, this study adds a nuanced perspective by emphasizing localized hydrological and pollution dynamics.

Specifically, our findings demonstrate that streams draining forest-dominated sub-basins exhibit lower nutrient concentrations and more stable hydrological regimes than those influenced by agricultural and urban areas. This suggests the critical role of forest cover in mitigating nutrient enrichment and maintaining consistent discharge patterns. Conversely, agrarian sub-basins were characterized by higher levels of TN and TP, particularly during low flow periods in dry seasons. These patterns underline the pronounced seasonal and spatial variations in pollutant loading, reinforcing the importance of tailored land use management strategies for each sub-basin.

The analysis of TN and TP concentrations exceeding national water quality thresholds in urbanized areas highlights the urgent need for integrated urban and agricultural runoff management. This includes implementing practices such as riparian buffer zones, precision farming, and enhanced sewer networks, which can collectively minimize nutrient loading into surface waters. The pollutant footprint analysis further reveals that socio-economic activities in urban and peri-urban areas significantly exacerbate diffuse pollution. Addressing these challenges requires aligning water management policies with local land use practices and socioeconomic realities.

While the global prevalence of non-point source pollution is well-documented, our study elucidates the critical interplay of land cover, hydrological variability, and nutrient dynamics at a sub-basin scale. These findings are particularly relevant for regions like Lake Sapanca, where diverse land use patterns intersect with significant population growth and agricultural intensification. By highlighting specific sub-basin characteristics associated with optimal water quality, our study provides actionable insights for policymakers to prioritize forest conservation and sustainable land management practices.

5. Conclusions

The concentrations of TN and TP in stream water are critical indicators, providing valuable insights into the impact of anthropogenic activities on watershed ecosystems. Spatial variations in TN and TP across different LULC types within sub-basins offer a framework for analyzing the effects of urbanization, agriculture, and forest-dominated landscapes. This study highlighted that land use significantly influences water quality parameters. Specifically, urban and agricultural areas exhibited elevated TN and TP levels, which negatively affect stream and lake water quality. Among these, urbanization exerts a markedly greater impact compared to agricultural activities.

To protect and anticipate changes in lake water quality, it is crucial to minimize the proportion of urbanized areas within watersheds. The predictive model developed in this study can serve as a valuable tool for estimating nutrient loading in lake basins under varying conditions. While the current research focuses on existing land use and water quality conditions, future studies should assess the impacts of potential land use changes, climate change, and pollution control measures.

The implications of this research extend beyond Lake Sapanca, offering valuable insights into sustainable water management in other freshwater systems facing similar challenges. Future studies should explore the integration of socio-economic and climate change dimensions into LULC and water quality analyses to develop holistic approaches to freshwater conservation. Ultimately, our findings advocate for a balanced, data-driven approach to land use planning and water resource management, aimed at safeguarding freshwater ecosystems for current and future generations.

The present study was limited to developing a simple and cost-effective methodology to illustrate the common parameters affecting lake water quality and their connections to LULC changes at catchment scale. Future studies are suggested to establish the relation between water quality and river flow course at a higher resolution (pixel-scale) from upstream to downstream. To this end, using emerging remote sensing methods and satellite imagery may be implemented to enhance estimations' accuracy [38–40]. Such assessments could also facilitate the development of effective strategies to mitigate nutrient pollution and safeguard the ecological health of lake ecosystems.

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References

1. Zhang, K.; Ye, Z.; Qi, M.; Cai, W.; Saraiva, J.L.; Wen, Y.; Liu, G.; Zhu, Z.; Zhu, S.; Zhao, J. Water Quality Impact on Fish Behavior: A Review from an Aquaculture Perspective. *Rev. Aquacult.* **2025**, *17*, e12985. [CrossRef]
2. Danandeh Mehr, A.; Akdegirmen, O. Estimation of urban imperviousness and its impacts on flashfloods in Gazipaşa, Turkey. *Knowl. Eng. Sci.* **2021**, *2*, 9–17. [CrossRef]
3. Jiang, L.; Lai, Y.; Guo, R.; Li, X.; Hong, W.; Tang, X. Measuring the impact of government intervention on the spatial variation of market-oriented urban redevelopment activities in Shenzhen, China. *Cities* **2024**, *147*, 104834. [CrossRef]
4. Yan, F.; Wang, X.; Huang, C.; Zhang, J.; Su, F.; Zhao, Y.; Lyne, V. Sea Reclamation in Mainland China: Process, Pattern, and Management. *Land Use Policy* **2023**, *127*, 106555. [CrossRef]
5. Zhang, T.; Song, B.; Han, G.; Zhao, H.; Hu, Q.; Zhao, Y.; Liu, H. Effects of coastal wetland reclamation on soil organic carbon, total nitrogen, and total phosphorus in China: A meta-analysis. *Land Degrad. Dev.* **2023**, *34*, 3340–3349. [CrossRef]
6. Huang, C.; Zhao, D.; Fan, X.; Liu, C.; Zhao, G. Landscape dynamics facilitated non-point source pollution control and regional water security of the Three Gorges Reservoir area. *China Environ. Impact Asses.* **2022**, *92*, 106696. [CrossRef]
7. Liang, Y.; Xiao, H.; Liu, X.; Hu, Q.; Xiong, J.; Li, W.; Tang, C. Variation in sources of inorganic nitrogen under different hydrological conditions in a floodplain lake: A case study of Bang Lake (Poyang Lake, Jiangxi Province, China). *Inland Waters* **2018**, *8*, 176–185. [CrossRef]
8. Partani, S.; Mehr, A.D.; Jafari, A. Enhancing nutrient absorption through the influence of mangrove ecosystem on flow rate and retention time in salt marshes. *Sci. Total Environ.* **2024**, *924*, 171518. [CrossRef]
9. Nunes, A.N.; De Almeida, A.C.; Coelho, C.O.A. Impacts of land use and cover type on runoff and soil erosion in a marginal area of Portugal. *Appl. Geogr.* **2011**, *31*, 687–699. [CrossRef]
10. Celebi, A.; Ozdemir, S. Mining wastewater management and its effects on groundwater and ecosystems. *Water Sci. Technol.* **2014**, *70*, 1481. [CrossRef]
11. Gilbert, P.M. Eutrophication, harmful algae and biodiversity—Challenging paradigms in a world of complex nutrient changes. *Mar. Pollut. Bull.* **2017**, *124*, 591–606. [CrossRef] [PubMed]

12. Chen, C.F.; Chen, Y.M.; Lin, J.Y. Assessing the effects of migratory waterbird droppings on potential lake eutrophication using water quality models: A case study of Yangming Lake on Kinmen Island, Taiwan. *Inland Waters* **2023**, *13*, 182–196. [CrossRef]
13. El-Khoury, A.; Seidou, O.; Lapen, D.R.; Que, Z.; Mohammadian, M.; Sunohara, M.; Bahram, D. Combined impacts of future climate and land use changes on discharge, nitrogen and phosphorus loads for a Canadian river basin. *J. Environ. Manag.* **2015**, *151*, 76–86. [CrossRef] [PubMed]
14. Bai, X.; Zhang, S.; Smith, P.; Li, C.; Xiong, L.; Du, C.; Xue, Y.; Li, Z.; Long, M.; Li, M.; et al. Resolving controversies surrounding carbon sinks from carbonate weathering. *Sci. China Earth Sci.* **2024**, *67*, 2705–2717. [CrossRef]
15. Li, Y.; Wang, H.; Deng, Y.; Liang, D.; Li, Y.; Shen, Z. How climate change and land-use evolution relate to the non-point source pollution in a typical watershed of China. *Sci. Total Environ.* **2022**, *839*, 156375. [CrossRef]
16. Shen, Z.; Liao, Q.; Hong, Q.; Gong, Y. An overview of research on agricultural non-point source pollution modelling in China. *Sep. Purif. Technol.* **2012**, *84*, 104–111. [CrossRef]
17. Radosavljevic, J. Land Use Changes and Salinization: Impacts on Lake Phosphorus Cycling and Water Quality. Ph.D. Thesis, University of Waterloo, Waterloo, ON, Canada, 2023.
18. Çavdar, P.S. A Tool of Sustainable Control of Groundwater Resources: Underground Dams. *Arch. Adv. Eng. Sci.* **2024**, 1–7. [CrossRef]
19. Ersoy, S.; Güreşen, A.; Aktan, Y. Spatio-Temporal Dynamic of Submerged aquatic macrophytes in Lake Sapanca. *Turk. J. Bot.* **2020**, *44*, 552–562. [CrossRef]
20. Özdemir, A. Determination of protection zones in drinking water basins: A case study from Turkey, Sapanca Lake Basin. *Environ. Earth Sci.* **2020**, *79*, 178. [CrossRef]
21. APHA. *Standard Methods for the Examination of Water and Wastewater*, 21st ed.; APHA: Washington, DC, USA, 2005.
22. Ustaoglu, F.; Tepe, Y. Water quality and sediment contamination assessment of Pazarsuyu Stream, Turkey using multivariate statistical methods and pollution indicators. *Int. Soil Water Conserv. Res.* **2019**, *7*, 47–59. [CrossRef]
23. Temiz, T.; Sonmez, O.; Dogan, E.; Oner, A.; Opan, M. Evaluation of the effects of land-use change and increasing deforestation in the Sapanca Basin on total suspended solids (TSS) movement with predictive models. *Acta Geophys.* **2022**, *70*, 1331–1347. [CrossRef]
24. Kaçmaz, M.; Döker, M.F. Land Use and Spatial Change in Sapanca Lake Basin. *Turk. J. Geogr. Sci.* **2021**, *19*, 161–194. [CrossRef]
25. Kart Aktas, N.; Yıldız Donmez, N. Effects of urbanisation and human activities on basin ecosystem: Sapanca Lake Basin. *J. Environ. Prot. Ecol.* **2019**, *20*, 102–112.
26. Akıner, M.E.; Akıner, I. Water Quality Analysis of Drinking Water Resource Lake Sapanca and Suggestions for the Solution of the Pollution Problem in the Context of Sustainable Environment Approach. *Sustainability* **2021**, *13*, 3917. [CrossRef]
27. An, J.; Li, N.; Wang, S.; Liao, C.; Zhou, L.; Li, T.; Wang, X.; Feng, Y. A novel electro-coagulation-Fenton for energy efficient cyanobacteria and cyanotoxins removal without chemical addition. *J. Hazard. Mater.* **2019**, *365*, 650–658. [CrossRef]
28. García, D.; de Godos, I.; Domínguez, C.; Turiel, S.; Bolado, S.; Muñoz, R. A systematic comparison of the potential of microalgae-bacteria and purple phototrophic bacteria consortia for the treatment of piggery wastewater. *Bioresour. Technol.* **2019**, *276*, 18–27. [CrossRef]
29. Kakade, A.; Salama, E.; Han, H.; Zheng, Y.; Kulshrestha, S.; Jalalah, M.; Harraz, F.A.; Alsareii, S.A.; Li, X. World eutrophic pollution of lake and river: Biotreatment potential and future perspectives. *Environ. Technol. Innov.* **2021**, *23*, 101604. [CrossRef]
30. Krawczyk, B.; Szczukocki, D.; Szczepańska, M.; Czarny, K.; Seliger, P.; Skrzypek, S. Spatial water quality estimation of artificial lakes in Central Poland. *Int. J. Environ. Pollut.* **2018**, *63*, 206–224. [CrossRef]
31. Yan, B.; Fang, N.F.; Zhang, P.C.; Shi, Z.H. Impacts of land use change on watershed streamflow and sediment yield: An assessment using hydrologic modelling and partial least squares regression. *J. Hydrol.* **2013**, *484*, 26–37. [CrossRef]
32. Weber, A.; Fohrer, N.; Miler, D. Long-term land use changes in a mesoscale watershed due to socioeconomic factors-effects on landscape structures and functions. *J. Ecol. Model.* **2021**, *140*, 125–140. [CrossRef]
33. Arabi, M.; Govindaraju, R.S.; Hantush, M.M.; Engel, B.A. Role of Watershed Subdivision on Modeling the Effectiveness of Best Management Practices With SWAT. *J. Am. Water Resour. As.* **2016**, *42*, 513–528. [CrossRef]
34. Zhang, X.; Chen, P.; Dai, S.; Han, Y. Analysis of non-point source nitrogen pollution in watersheds based on SWAT model. *Ecol. Indic.* **2022**, *138*, 108881. [CrossRef]
35. Wu, M.; Zhang, X.; Reis, S.; Ge, S.; Gu, B. Pollution controls in Lake Tai with the reduction of the watershed nitrogen footprint. *J. Clean. Prod.* **2022**, *332*, 130132. [CrossRef]
36. Nie, W.M.; Yuan, Y.P.; Kepner, W.; Nash, M.S.; Jackson, M.; Erickson, C. Assessing impacts of land use changes on hydrology for the upper San Pedro watershed. *J. Hydrol.* **2011**, *407*, 105–114. [CrossRef]
37. Nakane, K.; Haidary, A. Sensitivity analysis of stream water quality and land cover linkage models using Monte Carlo method. *Int. J. Environ. Res.* **2010**, *4*, 121–130.
38. Zhou, G.; Li, J.; Tian, Z.; Xu, J.; Bai, Y. The Extended Stumpf Model for Water Depth Retrieval from Satellite Multispectral Images. *IEEE J. Sel. Top. Appl.* **2024**, *17*, 6779–6790. [CrossRef]

39. Zhou, G.; Jia, G.; Zhou, X.; Song, N.; Wu, J.; Gao, K.; Huang, J.; Xu, J.; Zhu, Q. Adaptive High-Speed Echo Data Acquisition Method for Bathymetric LiDAR. *IEEE Trans. Geosci. Remote* **2024**, *62*, 5703017. [CrossRef]
40. Xiong, C.; Tao, H.; Liu, S.; Liu, G.; Wen, Z.; Shang, Y.; Wang, Q.; Fang, C.; Li, S.; Song, K. Using satellite imagery to estimate CO_2 partial pressure and exchange with the atmosphere in the Songhua River. *J. Hydrol.* **2024**, *634*, 131074. [CrossRef]