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RECEIVED 20 May 2025

ACCEPTED 24 September 2025

PUBLISHED 21 October 2025

CORRECTED 14 November 2025

CITATION

Merchán-Sanmartín B, Arteaga-Bravo I,
Suárez-Zamora S, Velásquez-Molina A,
Rosales-Serrano P, Arias-Hidalgo M,
Jaya-Montalvo M, Aguilar-Aguilar M and
Carrión-Mero P (2025) Water availability in a
university campus: the role of an artificial lake
as a nature-based solution.
Front. Water 7:1631938.
doi: 10.3389/frwa.2025.1631938

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Carrión-Mero. This is an open-access article
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Water availability in a university campus: the role of an artificial lake as a nature-based solution

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Introduction: Escuela Superior Politécnica del Litoral (ESPOL) is a Higher Education Institution (HEI) located in a protected tropical dry forest that uses Nature-Based Solutions (NbS) (albarradas and artificial lakes) for water resource management and ecosystem conservation. This research aims to evaluate the water availability of an artificial lake at ESPOL through the water balance, focused on two consumption scenarios for the total or partial water provision to the campus community.

Methods: The study included: (i) water availability assessment; (ii) criteria operationalization using the Analytical Hierarchy Process (AHP) and the Likert scale for the location of the Drinking Water Treatment Plant (DWTP); and (iii) analysis of Strengths, Weaknesses, Opportunities, and Threats (SWOT) for sustainable management strategies.

Results: The lake can supply the ESPOL campus's water needs without a deficit until 2041. However, considering technical and environmental aspects, its use could be extended until 2055. Water quality tests indicate that ESPOL Lake represents an acceptable source for the proposed purposes, provided it receives adequate treatment. Furthermore, the campus has an elevated reservoir located in a high area, whose adjacent areas offer better conditions for implementing a drinking water treatment plant. Finally, the proposed strategies for the sustainable management of the lake focused on optimizing water use, enhancing water infrastructure, and promoting academic engagement.

Discussion: This research supports the concept of living and dynamic laboratories in higher education institutions through the application of NBS as necessary sustainable practices in response to global warming.

KEYWORDS

sustainable development, circular economy, water balance, artificial wetland, living labs

1 Introduction

Freshwater lakes are essential water collection sources that play a strategic role in providing ecosystem services such as climate regulation, flood and drought control, biodiverse habitats maintenance, and the development of anthropogenic activities (United Nations Environment Programme, 2022b). Their formation is associated with hydrogeological and climatic processes that, over time, form lake watersheds (Branstrator, 2015). However, lakes are also created artificially (reservoirs) through the construction of dams that allow water storage for various purposes (power generation, irrigation, or drinking water supply) (Ji et al., 2020).

Unfortunately, lakes constitute only 0.009% of the planet's available water (Shiklomanov, 1993; Musie and Gonfa, 2023). Furthermore, factors such as eutrophication, acidification, pollutants from productive and domestic sectors, saline intrusion, climate change, and overexploitation (closely linked to population growth) can compromise the long-term functionality and sustainability of these ecosystems (Han et al., 2020; Alifujiang et al., 2021).

Owing to these risks, the United Nations Environment Assembly adopted a resolution on the sustainable management of lakes, recognising their importance and emphasising the need for urgent action by member states to protect and restore them (United Nations Environment Programme, 2022a). Therefore, assessing the availability of water sources is essential for using them for the community's benefit without compromising the ecosystem integrity (Dolan et al., 2021).

The water balance is a quantitative analysis method based on mass conservation; that is, the amount of water that enters a system (hydrographic watershed, lake, or reservoir) must be equal to the amount that leaves. The method allows one to evaluate water resource availability and define conservation and sustainable use strategies (Dhote et al., 2021; Juma et al., 2022). Several studies have been based on water balance assessed the surface water availability in dams (Quinn et al., 2019), small reservoirs (Fowe et al., 2015) and underground sources (Rodríguez-Huerta et al., 2020).

In this context, the application of Nature-based Solutions (NbS) through "Water Sowing and Harvesting" techniques can improve aquifer recharge, promoting water system resilience through the efficient use of the vital resource (Albarracín et al., 2021). Integrating these practices allows for designing more sustainable and adaptive water management plans that consider the supply of population centres and ecosystem conservation (Jamion et al., 2023). In the field of urban planning, permeable pavements are considered NbS as they seek to mimic the behavior of natural soils that allow water infiltration for aquifer recharge, even generating capital savings of 5–10% compared to conventional paving techniques (Santhanam and Majumdar, 2020).

Global investment in NbS represents only 0.026% of global wealth (United Nations Environment Programme, 2021; Boston Consulting Group, 2025), which means that despite progress in the search for alternatives to water management, barriers related to financing still exist. Investments in the implementation of NbS should quadruple by 2050 if the goals of biodiversity, climate change, and land reduction are to be met (United Nations Environment Programme, 2021). To generate greater interest in financing these practices, Crockford's study (Crockford, 2022) recommends that greater efforts should be made to give real value to the impacts of natural processes on global society.

According to the United Nations (2024), by 2024, only 17% of the 135 targets set out in the Sustainable Development Goals (SDGs) are

on track to be achieved, another 17% are regressing, and the rest show marginal progress, mainly those associated with SDGs 1, 6, 8, 13, and 16. To successfully implement sustainable water management plans, a shift in education's focus toward sustainable development (ESD) and the achievement of the SDGs is important (Teh and Koh, 2020). Higher Education Institutions (HEIs) and their operations can serve as living laboratories by developing innovative solutions to real-world challenges, with the active participation of multiple stakeholders: students, teachers, researchers, administrative staff, civil society, the private sector, and local authorities (Leal Filho et al., 2019).

There are examples of several universities around the world that have documented in scientific publications and implemented practical solutions for water conservation and sustainable use on their campuses. For example, King Faisal University (Saudi Arabia) has implemented xeriscape, a technique focused on reducing or eliminating the need for additional irrigation while creating attractive and functional landscapes (Ismaeil and Sobaih, 2022). The American University in Cairo (Egypt) designed its campus to take advantage of sandy areas, allow infiltration and improved groundwater recharge, and implement drip irrigation systems (Amr et al., 2016). Another case is that of Duke University (United States), which in 2014 built a water reuse reservoir and a pond complex to capture urban stormwater and recycle it to provide cooling to the campus and reduce the nutrient and sediment load in Lake Jordan (Richardson and Flanagan, 2024).

The Escuela Superior Politécnica del Litoral (ESPOL) is a 658-hectare HEI located in Guayaquil, Ecuador. It is home to the Bosque Protector Prosperina (BPP), a tropical dry forest with various endemic species of flora and fauna. To support the conservation of the BPP, ESPOL has implemented NbS (Nature-based Solution) through artificial lakes and wetlands strategically distributed throughout its campus. These lakes provide water for local biodiversity and ecosystem services such as forest fire mitigation, flow management for flood control on campus and adjacent urban areas, timely irrigation of green areas, and experimental farm operations (Figure 1).

ESPOL has been developing various studies related to the optimisation of drinking water supply and rainwater drainage systems (Merchán-Sanmartín et al., 2023), as well as the wastewater reuse (Merchán-Sanmartín et al., 2022a). These studies are aligned with ESPOL's sustainability program, which considers operating the campus more efficiently in terms of water, energy, and waste (Sostenibilidad ESPOL, 2018). However, the lake's capacity as a source to fully or partially supply the campus's water demand has not been analyzed; therefore, the study poses the following research questions:

- i) Does the quantity and quality of water in the artificial lake in the HEI offer favourable conditions for use in different activities, including human consumption?
- ii) What would be the priority strategic factors for sustainable water resource management?

This research aims to assess the artificial lake water availability on a university campus through the water balance of its lake watershed, water quality analysis and supply/demand projection for sustainable water use. In addition, the expert-based multi-criteria analysis assesses the ideal location for the future Drinking Water Treatment Plant (DWTP) design to supply the university community. This study addresses the existing gap in research on water management as a sustainability indicator in HEIs,

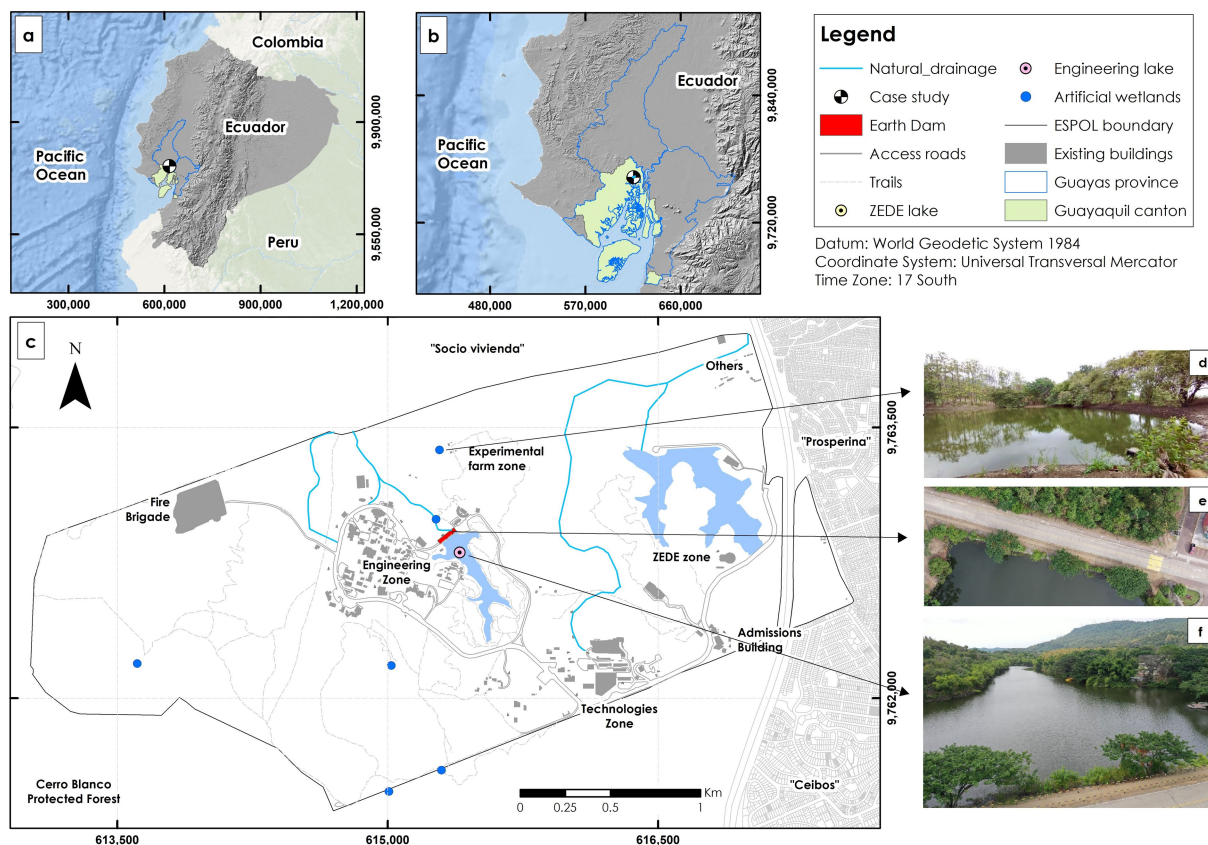


FIGURE 1

Case study location. (a) Geographic location of Ecuador, (b) guayaquil canton, (c) ESPOL property, (d) experimental farm artificial wetland, (e) engineering lake earth dam, (f) engineering lake.

proposing an NbS practical example using artificial lakes on a university campus as a water source for consumption.

2 Materials and methods

The methodology implemented in this study focused on a university campus with an artificial lake as a water management element for green areas irrigation, considering the climate seasonality, and as a regulatory entity against climate change because there are peri-urban areas with serious flooding risk and forest fires. The water availability from a protective forest source that could be used for human consumption was evaluated. The research was structured in three stages: (i) water availability assessment through water balance and resource quality analysis; (ii) operationalization criteria for DWTP implementation, through the integration of the Analysis Hierarchical Process (AHP) and Likert scale; (iii) analysis of Strengths, Weaknesses, Opportunities, and Threats (SWOT) for sustainable management strategies (Figure 2).

2.1 Stage I: Water availability assessment

2.1.1 Hydrological analysis

The ArcMap program (version 10.5) allowed watershed delimitation that feeds the ESPOL lake using a Digital Elevation

Model (DEM) obtained from the Alaska Satellite Facility online platform (NASA, 2011), which provides raster images with a resolution of 12.5 m. The lake's topography was obtained through studies conducted by Rosales Serrano and Velásquez Molina (2022) to estimate its dimensions and depth.

The annual precipitation data correspond to the period 1961–2019 (59 years), taken from the meteorological station M056 (Guayaquil Airport), located 8.5 km from ESPOL. The precipitation data were subjected to a goodness-of-fit test based on the Kolmogorov–Smirnov test (Δ_{K-S}), which is calculated as the absolute value of the difference between the probability of a theoretical distribution and the observed data empirical probability (Equation 1), to identify the theoretical distribution that best fits (Berger and Zhou, 2014).

$$\Delta_{K-S} = \max |F(x) - P(x)| \quad (1)$$

The study evaluated different distributions to analyse extreme events, such as Normal, Log-Normal, Pearson Type III, Log-Pearson III, Gumbel and Log-Gumbel. It employed the Weibull plotting position to determine the empirical probability of each observed data (Equation 2) (Villón Bejar, 2006). Subsequently, a critical value (Δ_o) was established that depends on the available data number and the desired significance level (for this case, a significance of 5% was considered), using Equation 3.

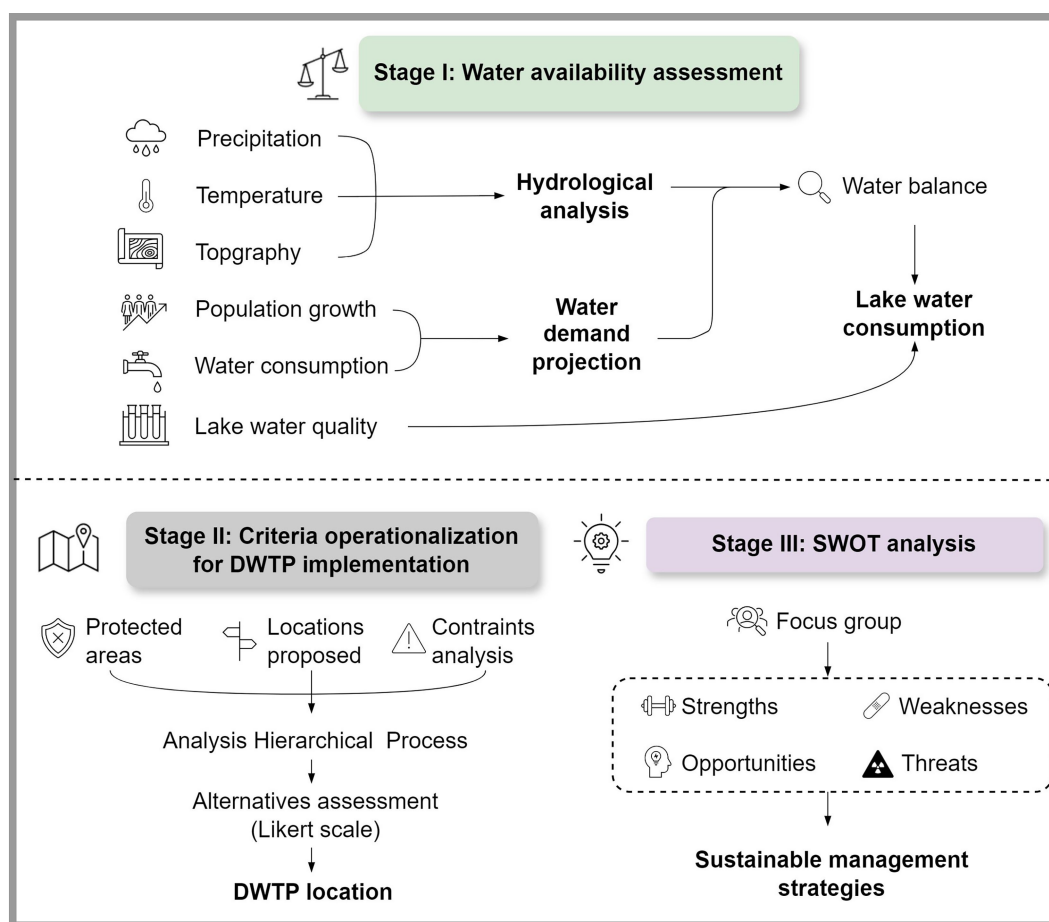


FIGURE 2
Stages applied to water availability assessment.

$$P(x) = \frac{m}{N+1} \quad (2)$$

$$\Delta_o = \frac{1.36}{\sqrt{N}} \quad (3)$$

Where:

$F(x)$: Theoretical distribution probability.

$P(x)$: Experimental or empirical probability.

m : Position occupied by the data when sorted in ascending order.

N : Available data number.

The theoretical distribution selected was the one with the minimum Δ_{K-S} ; as long as $\Delta_{K-S} < \Delta_o$ (Villón Bejar, 2006). According to the selected theoretical distribution, the study determined the probable maximum precipitation (P_r) for a 2-year return period (under the premise that the water contribution is minimal for this range). Equation 4 estimates the surface runoff (Q_{Rf}) (Fowe et al., 2015), based on micro watershed contributing area (A), precipitation (Pr), and the runoff coefficient (K), which depends on the terrain characteristics (Te Chow et al., 1993).

$$Q_{Rf} = K * P_r * A \quad (4)$$

The Thornthwaite method estimates evapotranspiration in a given area and uses air temperature and the study site's latitude as parameters (Equations 5–9) (Hendrayana et al., 2021). The study used mean monthly temperature values from the available historical record (1992–2013) to calculate annual evapotranspiration. The data obtained were analyzed similarly to precipitation data to determine evapotranspiration associated with a 2-year return period (Sánchez San Román, 2017).

$$i = \left(\frac{t}{5} \right)^{1.514} \quad (5)$$

$$ETP_{\text{uncorrected}} = 16 \left(\frac{10 * t}{I} \right)^a \quad (6)$$

$$a = 675 \times 10^{-9} \cdot I^3 - 771 \times 10^{-7} \cdot I^2 + 1792 \times 10^{-5} \cdot I + 0.49239 \quad (7)$$

$$I = \sum_{i=1}^{12} i \quad (8)$$

$$ETP = ETP_{\text{uncorrected}} \left(\frac{N \cdot d}{12 \cdot 30} \right) \quad (9)$$

Where:

t: Month temperature.

ETP: Corrected potential evapotranspiration.

N: Maximum number of sun hours, taken from Aparicio Mijares (1989).

d: Month days number.

i: Constant depending on the month temperature.

a, I: Coefficient as a function of i.

2.1.2 Water demand projection

This research used the results obtained from the study by Merchán-Sanmartín et al. (2022a), which projected the ESPOL population based on the historical record analysis from different university sectors, establishing six consumption categories: (i) Undergraduate students, (ii) ESPOL workers, (iii) high school students, (iv) high school workers, (v) graduate students, (vi) admissions students. Categories (iii) and (iv) correspond to the population of an educational institution located within the ESPOL premises in the Technologies zone.

The annual water consumption was determined based on three aspects: (i) water allocation, (ii) ESPOL academic period (261 days), and (iii) consumption hours of the previously established categories. The water allocation was taken from a previous study by Merchán-Sanmartín et al. (2022b), which set an initial value equal to 50 L/hab*day based on values proposed by the Ecuadorian Construction Standard (NEC, 2011) with an annual increase of 1.25% (Ecuadorian Standardization Institute, 1992).

The water volume for green area irrigation was projected to increase by 3% annually. Table 1 shows the water extractions from the lake used for green areas (currently 107,165.86 m³) and activities in the Experimental Agricultural Farm, provided by ESPOL's maintenance service.

2.1.3 Lake water quality

According to the protocols established in the Standard Methods for the Examination of Water and Wastewater (American Public Health Association, 2017), Physical, chemical, and microbiological analyses were performed on four water samples from the lake, integrating

parameters such as arsenic, total coliforms, fluoride, Chemical Oxygen Demand (COD₅), Biochemical Oxygen Demand (BOD₅), nitrate, pH, sulfate, temperature, turbidity, and Total Dissolved Solids (TDS). The results of the analyses were compared to the water quality standards established in the Unified Text of Secondary Legislation of the Ministry of the Environment of Ecuador (TULSMA) (Ministerio del Ambiente, Agua y Transición Ecológica, 2015).

2.1.4 Water balance

The study applied the water balance to assess the annual available volume of the lake from water inputs and outputs (Equation 10) (Ozturk and Dincer, 2018). The input conditions (Q_e) are based on the contribution due to precipitation (P_r) and surface runoff (Q_{RF}) on the watershed. In contrast, the output parameters focus on the existing conditions (Q_s) and the future ESPOL needs (Q_n). Existing conditions include the current ESPOL irrigation (V_I), water use for the Experimental Agricultural Farm (V_{EF}), and evapotranspiration of the lake (ET). Future needs included the drinking water supply for the university population (D_w) and the green areas not covered by the current irrigation (V_{IF}).

$$Q_e = Q_s + Q_n \rightarrow P_r + Q_{RF} = (V_I + V_{EF} + ET) + (D_w + V_{IF}) \quad (10)$$

Regarding underground runoff, Ecuador's hydrogeological map shows no evidence of aquifers in the area (Senagua-Empresa Pública Espol Tech, 2014). Additionally, according to data obtained from geoportals (Ministerio de Agricultura y Ganadería del Ecuador, 2020), the lithology of the study area consists of silty clay soils. Although these conditions suggest a scenario where the contribution of underground flow may be negligible, its contribution cannot be ruled out 100%, so its analysis is beyond the scope of this study.

The water balance application took 2022 as the starting point for the analysis, which made it possible to identify the year in which the deficit would be generated according to the estimates related to the increase in ESPOL's water consumption. The study analyzed two consumption scenarios:

- Scenario 1: Its objective is to cover the water needs of the campus population, thoroughly irrigate green areas, and operate operations in the experimental farm area. This scenario presents an unfavourable outlook for the lake's exploitation, as it addresses the maximum possible consumption.
- Scenario 2: The aim is to partially supply ESPOL, as the intake buildings were not shown due to their proximity to the main supply pipeline that connects to the public water service. This measure would reduce withdrawals from the lake, promoting its sustainability.

2.2 Stage II: Criteria operationalization for DWTP implementation

The study evaluated different alternatives for the possible DWTP location and identified the areas where intervention is not feasible for Protective Forest conservation reasons. The site selection process was based on the Likert scale, a scoring method that indicates a statement's acceptance or rejection level. The scale uses scores from

TABLE 1 Information on the lake uses for green areas irrigation and activities at the experimental farm.

Features		Green areas		Experimental farm	Units
Pump quantity		Pump 1	Pump 2	Pump 1	-
Flow rate		8.19	8.19	20.00	l/s
		29.48	29.48	72.00	m ³ /h
Irrigation days per week		4	3	2	days
Irrigation hours per week		6	6	18	hours
Station		Summer	Winter	For 8 months	-
Volume	Daily	176.90	176.90	1296.00	m ³
	Weekly	707.62	530.71	2592.00	m ³
	Annual	18,398	13,799	82.944	m ³

1 (very unfavourable condition) to 5 (very favourable condition) (Rokooei et al., 2022). Four evaluation criteria were proposed, broken down into sub-criteria, to select the alternative that obtained the highest score (Table 2).

However, weights were assigned to the evaluation criteria before scoring using Likert to reflect their relevance within the study context. The weights for the criteria were obtained based on an AHP, which consists of making pairwise comparisons between criteria based on their relative importance to the objective (Saaty, 1984). As described by different references (Saaty and Vargas, 2012; Prascevic and Prascevic, 2017), AHP method uses a standard scale between 1 and 9, where 1 indicates that criterion A is equally important as criterion B and progressively, 9 would indicate that criterion A has much greater relevance than criterion B. These scores are organized in a pairwise comparison matrix (M) that meets the following conditions:

- The matrix M is square, with dimensions $n \times n$, where n is the number of criteria to be evaluated.
- Being a_{ij} an element of M , such that $i, j = 0, 1, 2, \dots, n$. If $i = j$, then $a_{ij} = 1$.
- Being a_{ij} an element of M , such that $i, j = 0, 1, 2, \dots, n$, It's true that $a_{ji} = 1/a_{ij}$.

The following steps are then followed, where the weights of the established criteria are established, and if the matrix M is consistent:

- A new matrix N is generated from M by dividing each element $a_{ji} \in M$ by the sum elements of the corresponding column j .
- The matrix N allows to calculate the priority vector $\bar{X}$ by averaging the values of each row of the matrix N .
- The product between the matrix M and the priority vector $\bar{X}$, divided for each element of $\bar{X}$, results in the vector $\bar{e}$, from which the maximum value $\bar{e}_{\max}$ is extracted to obtain the consistency index (CI) by means of Equation 11.

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (11)$$

- The random consistency index (RI) is selected depending on the size of the matrix M (Chaiyaphan and Ransikarbum, 2020).
- Finally, the consistency ratio (CR) is determined with Equation 12, where if $CR \leq 0.1$, then M is consistent and the values of $\bar{X}$ are reliable.

$$CR = \frac{CI}{RI} \quad (12)$$

Below are the mathematical expressions used to obtain the weighting of criteria from the pairwise comparison matrix (M)

$$M = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix} \rightarrow N = \begin{bmatrix} b_{11} & b_{12} & \dots & b_{1n} \\ b_{21} & b_{22} & \dots & b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ b_{n1} & b_{n2} & \dots & b_{nn} \end{bmatrix} \rightarrow \bar{x} =$$

$$\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}; W = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix}; \lambda = \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \vdots \\ \lambda_n \end{bmatrix} \rightarrow \lambda_{\max} = \frac{\sum_{i=0}^n \lambda_i}{n}$$

Where:

$$b_{ij} = \frac{a_{ij}}{\sum_{i=1}^n a_{ij}}; x_i = \frac{\sum_{j=1}^n b_{ij}}{n}; w_i = N * \bar{x}; \lambda_i = \frac{x_i}{w_i};$$

$$\text{For } i, j = 1, 2, 3, \dots, n$$

TABLE 2 Evaluation criteria for site selection.

Criteria	Sub-criteria
Technical (TEC)	(1) Proximity to the lake.
	(2) Site accessibility.
	(3) Topography.
	(4) Proximity to demand areas.
Economic (ECO)	(5) Capital Expenditure (CAPEX).
	(6) Operational Expenditure (OPEX).
Environmental (ENV)	(7) Proximity to high biodiversity areas or protected areas.
	(8) Energy used in operation.
	(9) Potential alteration of habitats in the Prosperina Protective Forest.
Socials (SOC)	(10) Community acceptance.
	(11) Potential impact on current space uses.
	(12) Potential to serve as an educational model for sustainability.

The M matrix was constructed by consensus among the authors of the study (with expertise in geology, hydrogeology, hydraulics, sanitation, and the environment), while the scores shown in the Likert evaluation were determined with the participation of experts linked to ESPOL's sustainability and physical infrastructure departments, as well as professors of subjects related to water management and student representatives.

2.3 Stage III: SWOT analysis

The analysis considered the focus group participation made up of eight professionals related to five areas of management and education at ESPOL: (i) Physical Infrastructure Management (GIF); (ii) Sustainability Department; (iii) student chapter representative and teacher of the Civil Engineering program, (iv) ESPOL student federation president, (v) Earth Sciences department student association president. In the first stage of the focus group, the feasibility of implementing a DWTP on campus was introduced.

Subsequently, participants completed a survey based on a questionnaire with open questions focused on stakeholders' opinions regarding the lake's use and the DWTP implementation (Supplementary material). The survey was conducted anonymously online through the Google Forms platform (Hasan and Hameed, 2022). Finally, a SWOT analysis was carried out regarding the lake's use as a supply source for ESPOL to establish strategies that guarantee water availability and ecosystem conservation. The SWOT analysis is a practical tool that allows one to organize several factors in a systematic way that are relevant to an objective and establish clear conclusions (Büyüközkan and Ilıcak, 2019; Phadermrod et al., 2019).

3 Results

3.1 Lake water availability

3.1.1 Delineation of hydrographic watersheds and reservoir modeling

The Micro-Watershed (MW) around the lake in the engineering area contributes 90.13 ha (Figure 3a). According to the topographic and bathymetric data, the lake has a volume of 380,000 m³, an area of 57,304.30 m², and a maximum depth of 12.80 m (Figure 3b). The dam is part of the ESPOL main road, whose surface course is 80.29 meters above sea level (m.a.s.l.), while the lake's maximum level is generally 78 m.a.s.l. The structure has an internal impermeable clay core with a maximum depth of 19.35 m on a porous rock stratum with sandstones, micro breccias, and shales with fractures. The material surrounding the clay core comprises silt and clayey sand, with a covering layer of large rocks to mitigate erosion (Supplementary Figure S1).

3.1.2 Climatic conditions and hydrological analysis

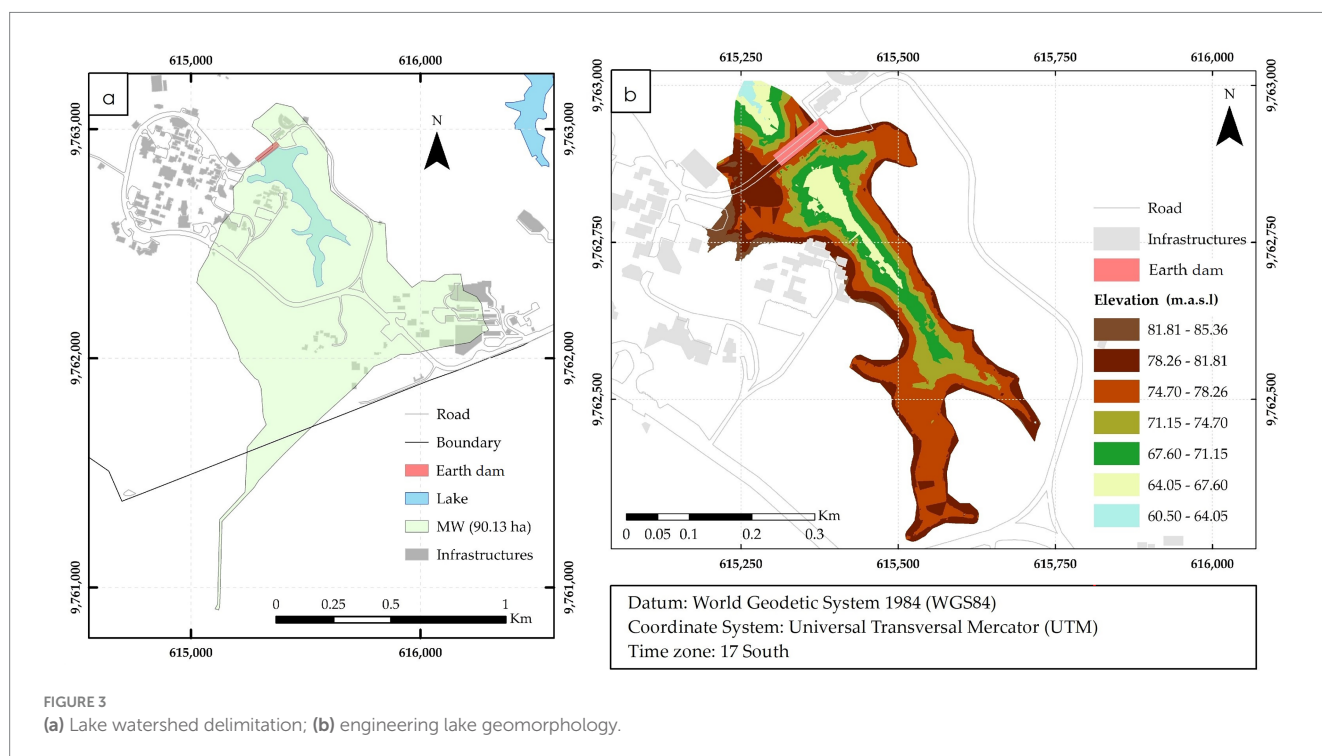
In Guayaquil, the first months of the year are characterized by intense rains, while the dry season begins in June. Between 1961 and 2019, 8% of the annual accumulated precipitation data is less than 500 mm, while 19% is above 1,500 mm. The years 1983 and 1998 recorded peaks of 4,231 and 3,442 mm, respectively, due to the “El Niño” phenomenon. The K-S method indicated that the precipitation dataset best fits a Log-Pearson III distribution, which obtained a minimum test statistic 0.05 compared to the other distributions. This implies that for a return period of 2 years, the contribution volume due to precipitation is 58,619 mm, while the runoff volume would be 302,175.65 m³/year (Figure 4).

According to the meteorological records obtained from the M056 station, the annual temperature in the study area varies from 27.5 to 24.9 °C. The annual accumulated evapotranspiration peaked at 1264.5 mm in 1997, while in 2001, a minimum value of 881 mm was recorded, leading to an average evapotranspiration of 1073.1 mm during this period. Through distribution analysis, it was estimated that for a return period of 2 years, the evapotranspiration would be 1,212.6 mm, equivalent to a volume of 69,486.9 m³/year as output to the lake (Figure 5).

3.1.3 Population analysis, water demand projection and water quality

According to the consumption categories, the “undergraduate students” population represents about 53% of the total ESPOL population. In 2022, ESPOL registered 20,096 inhabitants, which, according to the population projection, will increase to 30,011 inhabitants by 2050, representing an increase of 49% (Figure 6).

For the year 2022, the water allocation resulted in 51.26 L/hab*day, which was distributed proportionally to each category's



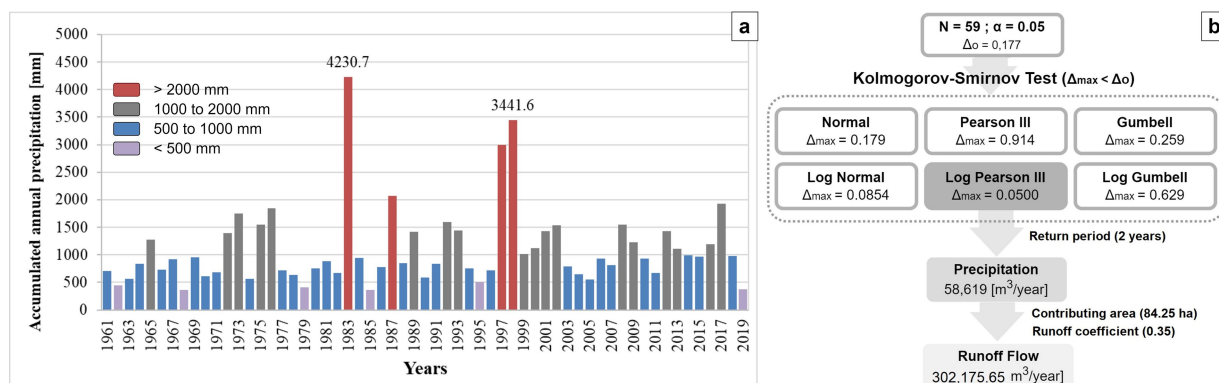


FIGURE 4

(a) Historical rainfall record; (b) precipitation and runoff flow for a 2-year return period.

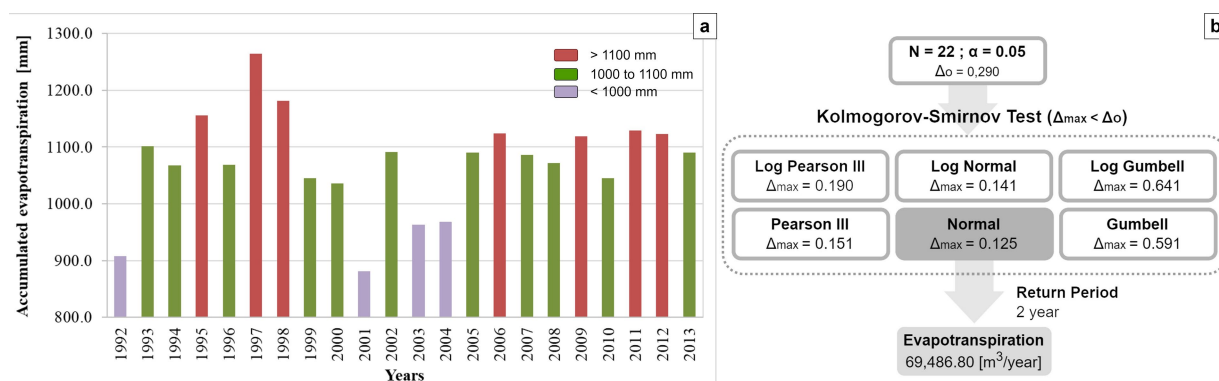


FIGURE 5

(a) Annual evapotranspiration from monthly historical temperature records; (b) evapotranspiration for a 2-year return period.

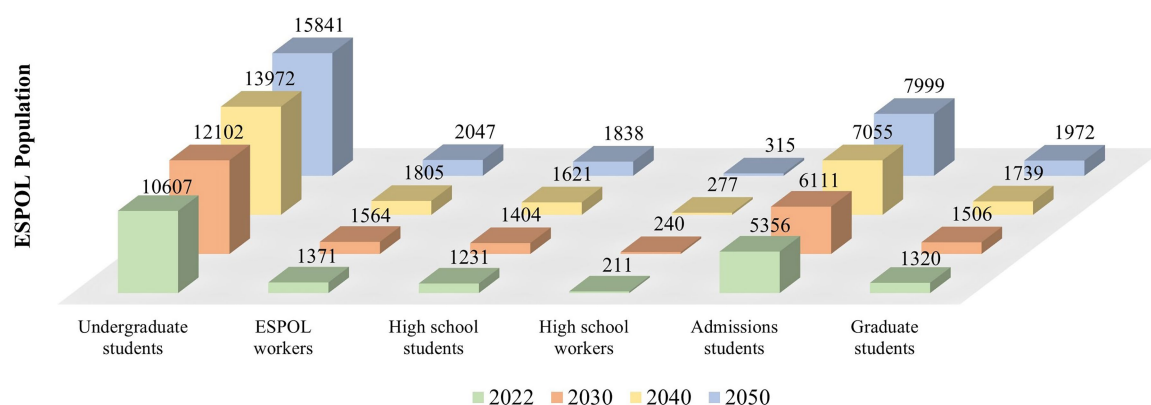


FIGURE 6

ESPOL population project.

consumption hours. Considering the university activities period (261 days), ESPOL's annual water consumption (Q_c) in 2022 was 104,974.06 m³/year. In this context, the undergraduate students category represents about 70% of ESPOL's water consumption (Supplementary Table S1). Consumption increases as the

population increases, so by 2055, it will increase by 83% in 33 years (Figure 7).

The total ESPOL's green areas are 123,370.80 m²; however, only 87% are irrigated with water from the lake (107,165.86 m²); therefore, 16,205 m² would need to be covered. Based on the data provided by

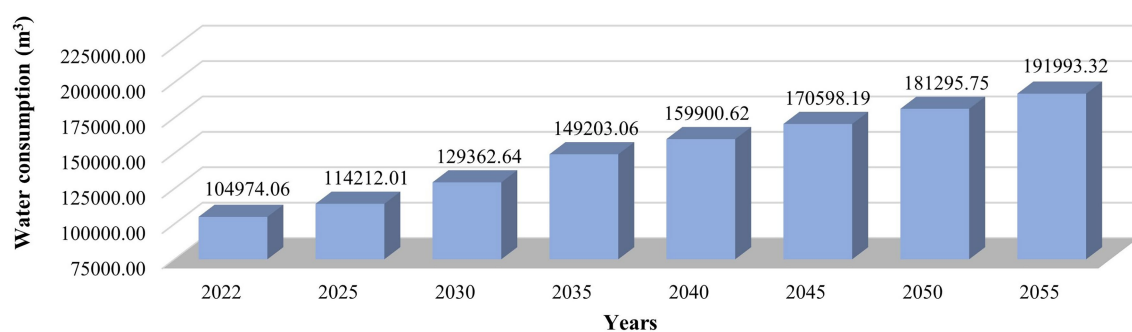


FIGURE 7
Water demand projection of the ESPOL population.

TABLE 3 Water samples analysis from different points of the engineering lake.

Parameter	Unit	Samples				MPL	
		(1)	(2)	(3)	(4)		
Arsenic	mg/l	0	0	-	-	0.05	
Total coliforms	NMP/100 mL	1.88	1.69	2.18	1.37	3,000	
Fluoride	mg/l	0.236	0.263	0.239	0.223	1.5	
COD ₅	mg/l	17	-	18	25	<4	
BOD ₅	mg/l	4.55	6.29	10.97	5.69	<2	
Nitrate	mg/l	8.317	2.179	0.744	0.061	10	
Nitrite	mg/l	BDL	BDL	BDL	BDL	1	
pH		6.44	6.66	6.57	6.48	6.0–9.0	
Sulfate	mg/l	8.12	8.32	7.74	6.76	400	
Temperature	°C	23	23.3	23.7	23.7	-	
Turbidity	NTU	14.3	15.7	16	13.2	100	
TDS	mg/l	146.9	148.6	147.3	147.6	1,000	

Maximum permissible limit (MPL) according to local regulations. Below Detection Limit (BDL).

ESPOL's maintenance service, with an annual irrigation volume of 32,197 m³ and considering an irrigation frequency of 3.5 days per week (182.7 days per year), the irrigation coverage was estimated at 1.65 L/m²*day. Under the same irrigation frequency, the missing area would consume 4,868.55 m³ of water per year.

The quality water results indicate that the lake has problems associated with the Chemical Oxygen Demand (COD₅) and Biochemical Oxygen Demand (BOD₅), as they are above the quality standards established in TULSMA (Table 3).

3.1.4 Water balance

Under current conditions, where the water from the engineering lake is used for specific activities, extractions can continue without generating a deficit. However, under consumption scenario 1, a deficit would be generated in 2042 due to the added population demand, representing 49% of consumption. This is followed by extractions for agricultural farms (26%), evapotranspiration (21%), and green areas (15%). The water balance results under consumption scenario 2 (more conservative) show that it is possible to take advantage of the lake's use until 2055; after this year, the outputs

exceed the inputs, causing a deficit (Table 4). It is important to mention that the buildings in the admissions area currently do not have an elevated reservoir for water distribution. Instead, they are supplied from a pumping system, which could damage pipes and sanitary appliances.

3.2 Drinking water treatment plant location

ESPOL's protected areas comprise the buffer zone, nucleus 1, nucleus 2 and permanent protection zone, which total 332.30 ha, equivalent to 49% of ESPOL's total land area, therefore, the expansion of impermeable surfaces or concrete areas is restricted. The Special Economic Development Zone (ZEDE zone in Figure 1) is a space intended to house industries focused on export and import activities of raw materials. In addition, ESPOL has a site that connects with Guyaquil's public water service, where five ground-level reservoirs of 200 m³ each are supplied. Drinking water is transported from a pumping station to ESPOL's elevated reservoir, with a capacity of 1,000 m³, through the supply pipeline. The admissions buildings are

TABLE 4 Lake water availability under current conditions and consumption scenarios.

Year	Input			Output				Availability
	P	Q_{RF}	Total	V_I	V_{EF}	ET	Total	
Water balance results: currently conditions								
2022	58,619	302,175.66	360,794.65	32,196.53	82,944	69,486.80	184,627.33	176167.3 (S)
2030	58,619	302,175.66	360,794.65	32,977.41	84,955.68	69,486.80	187,419.89	173374.76 (S)
2040	58,619	302,175.66	360,794.65	33,980.19	87,539.00	69,486.80	191,006.03	169788.62 (S)
2050	58,619	302,175.66	360,794.65	35,013.47	90,200.95	69,486.80	194,701.22	166093.43 (S)

Year	Total input	Total output	ESPOL need			Output + Need	Availability
			V_{IF}	D_W	Total		
Water balance results: consumption scenario 1							
2022	360,794.65	184,627.33	4,868.55	104,974.06	109,842.62	294,469.94	66324.71 (S)
2030	360,794.65	187,419.89	4,986.60	129,362.64	134,349.27	321,769.17	39025.49 (S)
2040	360,794.65	191,006.03	5,138.30	159,900.62	165,038.89	356,044.92	4749.73 (S)
2042	360,794.65	191,736.24	5,169.10	164,179.65	169,348.79	361,085.03	−290.38 (D)

Year	Total input	Output			ESPOL need		Output + Nedd	Availability
		V_I	V_{EF}	ET	V_{IF}	D_W		
Water balance results: Consumption scenario 2								
2022	360,794.65	32,196.53	82,944	69,486.80	4,869.60	83,801.06	276,296.94	84497.71 (S)
2030	360,794.65	32,977.41	84,955.68	69,486.80	4,986.60	107,032.18	299,438.71	61355.94 (S)
2040	360,794.65	33,980.19	87,539.04	69,486.80	5,138.30	132,279.33	328,423.63	32371.02 (S)
2050	360,794.65	35,013.47	90,200.95	69,486.80	5,294.50	149,978.66	349,974.39	10820.26 (S)
2056	360,794.65	35.648,46	91.836,79	69.486,80	5,390.50	160,598.25	362,960.83	−2166.18 (D)

Values shown are in units of m³/years. Surplus (S) and Deficit (D).

supplied from the supply pipeline, while the elevated tank supplies the other areas of ESPOL through the distribution network (Figure 8).

According to the focus group results in the AHP matrix, the technical criterion has the greatest weight (44%), followed by the environmental (25%), economic (25%), and social (7%) criteria. The CR coefficient was equal to 0.02, which is less than 0.10; therefore, the AHP matrix is consistent (Table 5).

According to the scores established in each alternative using Likert and considering the weights obtained from the AHP, alternative 4 received the highest score (14.1), so it was selected for the DWTP location. This alternative is located in a high area of ESPOL and close to the existing elevated tank, allowing a better water resource distribution by gravity (Table 6).

3.3 Strategies for the sustainable lake use

The main weaknesses and threats identified correspond to financial limitations, climate variability, increased water consumption, and resource availability and quality. On the contrary, one of ESPOL's main strengths is the availability of technical and scientific knowledge to develop innovative solutions for managing water resources (Table 7).

The study proposed 19 strategies that promote the academy's active participation (students, teachers, and ESPOL authorities) in developing comprehensive solutions for water resource management.

In addition, it highlights the importance of cooperation between the academy and the productive sectors, both public and private, as well as the support of non-profit organizations (Table 8).

4 Discussion

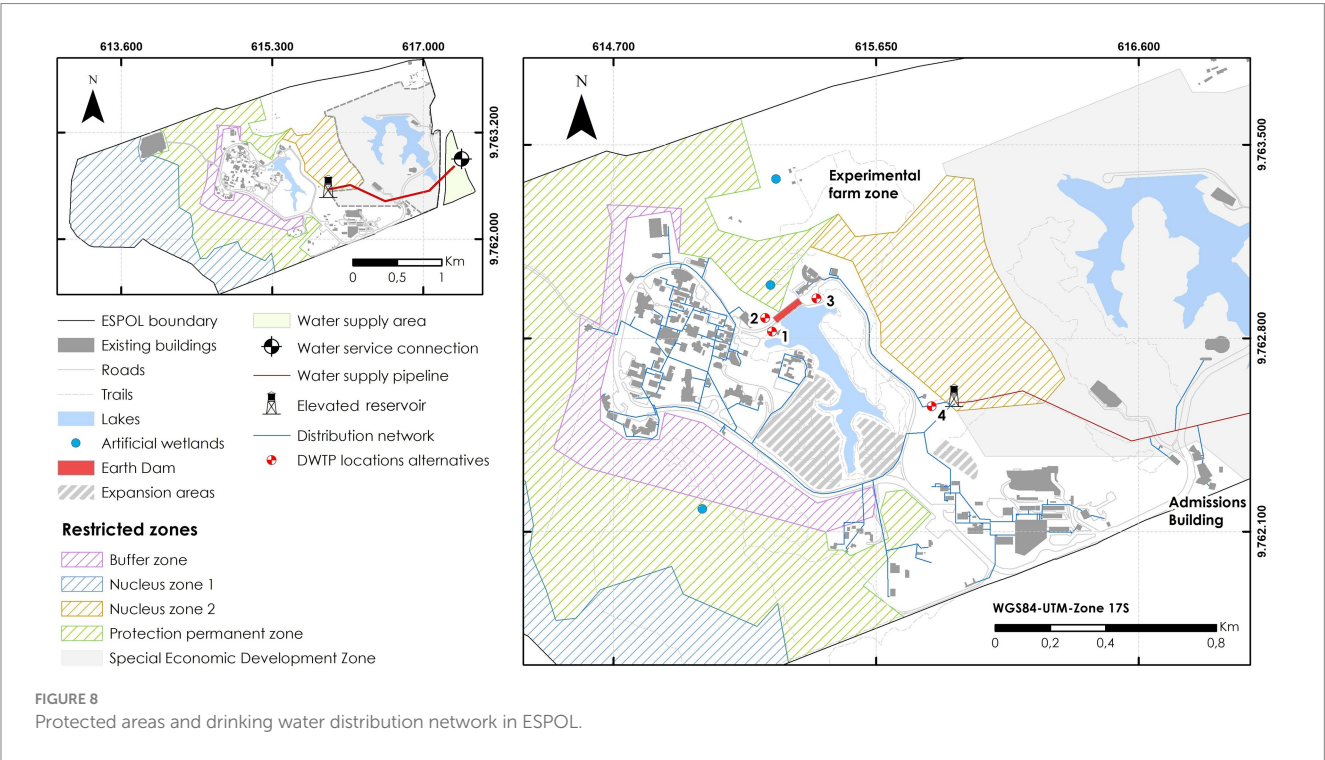
The methodological approach applied to this research promotes sustainable water resource management and ecosystem conservation in accordance with SDGs 6, 11, and 15. The lake has an estimated storage capacity of 380,000 m³, and the water balance results show that resource availability for human consumption in scenario 1 is 17 years. Scenario 2 results are more conservative than Scenario 1 since it allows its exploitation capacity to be extended up to 31 years without registering a deficit.

According to a previous study, between 2017 and 2019, an average of 296,629.33 m³ of water was consumed, which resulted in an approximate annual expenditure of \$210,639 for water services (\$ 0.71/m³) (Merchán-Sanmartín et al., 2022a). Under the conditions of Scenario 1, where 100% of the population is supplied, savings of \$252,830.51 are expected by 2040; while, in the same year, Scenario 2 (partial supply) would generate savings of \$233,216.40. This is a reference analysis based on ideal conditions, since consumption dynamics may vary over time, and it does not include the investment costs for the implementation of the proposed DWTP, or the operation and maintenance costs; therefore, a more comprehensive financial analysis is recommended.

TABLE 5 Comparative criteria matrix: weights obtained from the AHP.

AHP	TEC	ECO	AMB	SOC	$\bar{\lambda}$	λ_i	CI	RI	CR
TEC	1 (0.455)	2 (0.471)	2 (0.471)	5 (0.357)	43.82%	4.043	0.01	0.9	0.02
ECO	1/2 (0.227)	1 (0.235)	1 (0.235)	4 (0.286)	24.59%	4.030			
AMB	1/2 (0.227)	1 (0.235)	1 (0.235)	4 (0.286)	24.59%	4.030			
SOC	1/5 (0.091)	1/4 (0.059)	1/4 (0.059)	1 (0.071)	7.00%	4.009			
Total	2.20 (1.00)	4.25 (1.00)	4.25 (1.00)	14.0 (1.00)	100%	4.043			

Normalized values are shown in parentheses. The values in bold represent the weights of the criteria.



Factors such as the sedimentation rate in lakes due to natural or anthropogenic factors could compromise their storage capacity over time and quality resources. According to [Baud et al. \(2021\)](#), the sediment accumulation in these water bodies is 3–4 times faster than 150 years ago, mainly due to human presence in watersheds. However, as other studies suggest, the sedimentation rate in a water body is reduced when the forest cover has not been disturbed for anthropogenic purposes ([Zhao et al., 2019](#); [Sadeghi et al., 2022](#)), and NbS can store significant sediment amounts ([Robotham et al., 2023](#)). In this context, the existing artificial wetlands (albarradas in Spanish) in strategic ESPOL areas play an essential role in conserving the lake and providing ecosystem services.

Water quality tests at the lake’s physical, chemical and microbiological levels showed favourable conditions for its use since most of the parameters analyzed comply with the quality standards for raw water sources according to national regulations ([Ministerio del Ambiente, Agua y Transición Ecológica, 2015](#)). Although the analyses show concentrations of BOD₅ and COD₅ above the limits established by local environmental regulations, this can be contrasted with other regulatory texts ([Consejo de las Comunidades Europeas,](#)

[1975](#); [Conagua, 2016](#); [Ministerio de Ambiente de Perú, 2017](#)) that indicate Lake ESPOL represents an acceptable source for the proposed purposes, provided it receives adequate treatment. It should be noted that the presence of these pollutants may be due to stagnation, which favors the accumulation of organic matter, as well as possible diffuse contributions of wastewater from adjacent buildings. Therefore, to make the lake water suitable for human consumption, the design of a conventional DWTP is required, which involves collection, coagulation, flocculation, and filtration processes. Similarly, the city of Guayaquil captures raw water from the Daule River in the “Puente Lucia” sector (11 km north of the city), whose quality parameters exceed the standards established in the regulations ([Huayamave Navarrete, 2013](#)). The city uses a conventional DWTP to convert the raw water into a safe source for the population’s consumption, in compliance with current INEN 1108 standards ([Interagua, 2015](#)).

In addition to the water quality analyses, the study proposed an implementation area for a DWTP near the existing elevated tank (alternative 4). This allows for the direct inflow of treated water to the elevated tank, avoiding the risk of recontamination. The operational area becomes more efficient in monitoring and maintenance, and the

TABLE 6 Likert evaluation results.

Criteria		DWTP location alternatives							
		(1)		(2)		(3)		(4)	
TEC (43.8%)	(1) Proximity to the lake	5	2.19	4	1,75	5	2,19	3	1.31
	(2) Site accessibility	4	1.75	4	1,75	4	1,75	5	2.19
	(3) Topography	3	1.31	3	1,31	3	1,31	5	2.19
	(4) Proximity to demand areas	3	1.31	3	1,31	4	1,75	5	2.19
ECO (24.6%)	(5) Capital expenditure (CAPEX)	4	0.98	4	0,98	3	0,74	4	0.98
	(6) Operational Expenditure (OPEX)	3	0.74	3	0,74	3	0,74	4	0.98
ENV (24.6%)	(7) Proximity to high biodiversity areas or protected areas	5	1.23	5	1,23	5	0,98	4	0.98
	(8) Energy used in operation	3	0.74	3	0,74	3	0,74	5	1.23
	(9) Potential alteration of habitats in the Prosperina Protective Forest	5	1.23	5	1,23	3	0,74	5	1.23
SOC (7%)	(10) Community acceptance	4	0.28	4	0,28	3	0,21	5	0.35
	(11) Potential impact on current space uses	5	0.35	5	0,35	3	0,21	4	0.28
	(12) Potential to serve as an educational model for sustainability	4	0.28	4	0,28	5	0,35	3	0.21
Total			12.40		11.96		11.72		14.14

The values in bold represent the weights of the criteria.

costs associated with pumping treated water may be higher than those required for pumping raw water.

The lake use is part of the ESPOL's sustainability plan, which seeks to create circular economy criteria, strengthen a responsible consumption culture within the university community, and serve as a replicable model for other institutions and urban areas. Self-supply of water in an academic and protected forest environment is an alternative to mitigate the dependence on external water sources that may be compromised by climate change and human activity. This approach would reduce the demand on the public network, creating an opportunity to supply other city sectors with more significant needs.

Future studies could analyse the contributions generated by underground runoff through the implementation of piezometers to adjust water balance estimates (Norton et al., 2019). The contribution of groundwater to the water balance of lakes varies significantly in terms of gains and losses. According to Rosenberry et al. (2015), in 65 cases analysed, the gain in water balance due to groundwater contribution to a lake varied between 0.01 and 94.4%, with an average value of 25%. In contrast, in terms of loss (flow from a lake to groundwater), 44 cases reported a range of 0.1 to 91%, with an average value of 34.5%.

Other approaches can be taken to generate greater long-term sustainability without compromising resource availability. In this context, previous studies show that ESPOL has the necessary infrastructure for wastewater treatment so it can be used to supply the green areas irrigation and activities on the experimental farm, reducing extractions from the lake (Merchán-Sanmartín et al., 2022a). This area of knowledge has been addressed by other universities, such as the Technical University of Panama (Geraldine et al., 2022) and Emory University in the United States (Emory University, 2020), reuse wastewater for non-potable purposes. Additionally, studies such as that by Santhanam and Majumdar (2022), offer a method for

assessing the state of lake environments and the impact of urbanisation using four metrics (green-blue ratio, blue/built ratio, percentage of impervious surface, and rate of urbanisation), which may be helpful in ecological conservation areas.

Through SWOT analysis, the focus group defined a set of preventive, corrective and predictive strategies for sustainable lake use based on three main approaches:

- Implementation and adaptation of artificial wetlands as NbS for conservation measures for the ecosystem of the BPP and the engineering lake, as well as a potential source of rainwater for irrigation of green areas, activities in the experimental farm and cleaning. This strategy is aligned with the case study developed at Duke University in the United States, which successfully implemented a wetland system that not only provided water sustainability for the campus through rainwater use but also improved the resource quality downstream and served as a habitat for plant species around the wetlands (Amr et al., 2016; Richardson and Flanagan, 2024).
- Strengthening strategic alliances with public, private companies, or non-profit organizations to generate innovation through research (Lundberg and Andresen, 2012; Shvetsova and Lee, 2021). Promoting living labs offers an attractive scenario for different actors to use joint resources to search for innovative knowledge (van Geenhuizen, 2018). It is recommended that living lab managers handle their projects adaptively to avoid disagreements between stakeholders (Schuurman and Tönurist, 2017).
- Development of competencies and skills for conservation and knowledge transfer in "living labs and sustainable water management" that are aligned with UNESCO priority areas (UNESCO, 2024).

TABLE 7 SWOT analysis.

Strengths	Weaknesses
(1) Lakes and artificial wetlands as NbS for flood control and ecosystem services. (2) Water management that strengthens the conservation objectives of the BPP. (3) Institutional support for sustainable projects on campus. (4) Academic and scientific prestige. (5) Strategic location to function as a living lab for research, outreach, academia and tourism.	(1) Limited budget. (2) Fractures at the dam's base (rock mass) that cause leaks and water volume decrease. (3) Earth dam weakening. (4) Lack of studies related to the lake's recharge by groundwater. (5) Leaks in the water distribution network. (6) Difficulty in the decision-making process due to changes in personnel in administrative areas.
Opportunities	Threats
(a) Scientific tourism and ecotourism. (b) Circular economy in ESPOL. (c) DWTP implementation. (d) Green areas irrigation with water from lakes and embankments. (e) Treated wastewater use. (f) Early warning system. (g) Recognition of a demonstration site for ecohydrology.	(a) Climate variability. (b) Country seismic situation. (c) Increased consumption of water resources. (d) Reduction in storage capacity due to sediment accumulation. (e) Proliferation of mosquitoes in stagnant areas of the lake.

TABLE 8 Strategies to the sustainable water resources management.

Strengths + Opportunities	Weaknesses + Opportunities
(1.c) Technical and academic support for DWTP design and implementation studies. (3.4.e) Conduct studies on using treated wastewater to irrigate green areas and crops at the experimental farm. (1.b) Implement NbS that collect and store rainwater for irrigation and cleaning activities. (1.4.d) Migrate to more efficient irrigation systems with less water waste. (3.4.b) Encourage the active participation of the university community in sustainable water management. (4.5.a.g) Promote scientific tourism and ecotourism to promote the lake's importance in conserving the BBB.	(1.b-g) Establish strategic alliances with public, private institutions or non-profit organizations for ESPOL water management. (3.b) Conduct studies to identify and measure filtration flows through the dam. (4.f) Piezometer installation and geophysical studies to identify underground flows. (5.f) Implement a sensor network in the water distribution network for early detection of leaks.
Strengths + Threats	Weaknesses + Threats
(3.4.a) Monitor the impacts of climate change on water availability and lake ecosystems. (3.4.a) Establish a water use plan that considers the seasons of the year. (3.4.c) Conduct environmental impact studies to assess the lake's ecosystem services alteration due to intensive water use. (3.4.d) Erosion control plan in watershed vulnerable areas. (3.4.d) Maintenance of existing artificial wetlands to prevent the transport of sediments and nutrients into the lake.	(2.3.b) Conduct fracture characterization studies to assess the dam's structural performance. (6.c) Conduct a distribution system audit to identify and correct leakage problems in the network. (7.a-d) Restructure process manuals to adapt management to institutional needs, prioritizing operational continuity. (3.e) Implement a comprehensive pest control plan to mitigate vector proliferation.

In line with other studies that have applied different water management approaches on university campuses (Amr et al., 2016; Ismaeil and Sobaih, 2022; Richardson and Flanagan, 2024), this study presents an artificial lake as an NbS for the conservation of a protected dry forest and flood control in the surrounding urban areas. This study seeks to explore the use of greywater for the sustainable supply of water resources on a university campus. Considering that universities are spaces with operational dynamics similar to micro-cities, where the impacts associated with resource use can be significant (Ai et al., 2019; Nyborg et al., 2023), this type of study contributes to the need to seek sustainable water management models in which the concepts of urbanisation, water, nature, and circularity overlap (Katsou et al., 2020; Langergraber et al., 2021).

This research offers an approach based on ecohydrology because the study area involves the interaction of water systems, ecosystems and human activities, where the living lab concept takes on importance by fulfilling the five pillars proposed by Ståhlbröst (2012): (i) value, the case study is developed in a sensitive ecosystem in a protection state; (ii) sustainability, it seeks self-sufficiency of the water resource without affecting its availability, (iii) influence, it offers a replicable model to similar case studies, (iv) realism, since it addresses a fundamental human need (water supply) and (v) openness, because it involves multiple actors in the evaluation process that enrich the project with a holistic approach. The case study opens the possibility of connecting and applying the NbS concept to address the water sustainability challenges of HEIs; however, further analysis of

critical factors related to climate variability and consumer culture is required.

5 Conclusion

The study evaluated the water availability from an artificial lake to meet the consumption needs of the ESPOL population, which in 2022 was 104,974.06 m³. Under the proposed consumption scenarios, the lake use could be feasible until 2054, benefiting approximately 30,000 users, according to the projections. Even so, using rainwater and treated wastewater for specific activities could extend the use time much longer.

The water quality results confirm that ESPOL's lake represents a safe source of water for the university population. The lake's physical, chemical, and microbiological conditions favour a less rigorous treatment, which could lead to lower investment, operation, and maintenance costs. However, monitoring must be carried out to assess the quality and availability of the resource.

The SWOT analysis allowed defining a set of strategies for sustainable management, reducing dependence on conventional water sources. The focus group contribution was essential to minimize some bias. Specifically, the strategies proposed for water sustainability on the university campus are summarized in three axes: (a) water management optimization and responsible resource use, (b) monitoring, maintenance and improvement of water infrastructure, and (c) academic participation, financing and sustainability.

Future studies could address water balance adjustment through the possible contribution of groundwater, changes in ESPOL's water demand, and the impact of extreme weather events, such as the El Niño phenomenon, which would influence water supply. On the other hand, it is also essential to consider sediment accumulation and its long-term effects on the lake's storage capacity.

Finally, some measures that would reduce lake extractions are wastewater reuse in non-potable activities, irrigation system optimization, and loss control in the distribution network. The participation of academia in developing these studies promotes the Living Labs concept within the ecohydrology framework, which is essential to address the challenges posed by a changing environment due to global warming.

Data availability statement

The original contributions presented in the study are included in the article/[Supplementary material](#), further inquiries can be directed to the corresponding author.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the (patients/participants or patients/participants legal guardian/next of kin) was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

BM-S: Conceptualization, Formal analysis, Methodology, Supervision, Validation, Writing – review & editing. IA-B: Conceptualization, Writing – original draft. SS-Z: Conceptualization, Data curation, Methodology, Writing – original draft, Writing – review & editing. AV-M: Conceptualization, Data curation, Writing – original draft. PR-S: Conceptualization, Data curation, Writing – original draft. MA-H: Conceptualization, Formal analysis, Supervision, Validation, Writing – review & editing. MJ-M: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. MA-A: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. PC-M: Conceptualization, Formal analysis, Methodology, Supervision, Validation, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This research was funded by Enfoque Participativo de la Gestión del Agua, Alcantarillado Sanitario, Desechos y Aprovechamiento para el Desarrollo Sostenible, code FICT-20-2022.

Acknowledgments

We would like to thank the ESPOL Maintenance Department for providing the data for this research, as well as the Sustainability Department, Physical Infrastructure Management, and representatives of the ESPOL student sector for their participation in developing the survey for the third phase of the study. Additionally, the work presented is part of the existing cooperation framework between the Centro de Investigación y Proyectos Aplicados a las Ciencias de la Tierra (CIPAT) of ESPOL and the Programa Iberoamericano de Ciencia y Tecnología para el Desarrollo (CYTED), through the network titled Red SbN-GIA - Soluciones basadas en la Naturaleza para la Gestión Integral del Agua, en comunidades vulnerables, with code 625RT0176.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Correction note

A correction has been made to this article. Details can be found at: [10.3389/frwa.2025.1737015](https://doi.org/10.3389/frwa.2025.1737015).

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Supplementary material

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