Water recharge, hydrological processes, and surface water quality through Nature-Based Solutions (NBS) in streams of the Ilaló volcano.

David Carrera-Villacrés [a, b]*, Lizbeth Lima[a] and Wilter Montero[a]

Note:

[a] Universidad de las Fuerzas Armadas ESPE. Departamento de Ciencias de la Tierra y la Construcción. Carrera de Ingeniería Civil. Av. Gral. Rumiñahui S/N, Sangolquí, 17050, Ecuador

[b] Universidad Central del Ecuador. Facultad de Ingeniería en Geología, Minas, Petróleos y Ambiental (FIGEMPA). Carrera de Ingeniería Ambiental. Av. Universitaria, Quito, 170521, Ecuador

* Corresponding author. Email: dvcarrera@espe.edu.ec

Highlights:

1. Identification of water recharge through vertical electrical soundings in inter-Andean areas with water sources.

2. Visualization of soil stratigraphy through Bayesian Kriging in 3D with resistivity point interpolation.

3. Climography of meteorological variables and groundwater quality in soils from volcanic eruptions.

Abstract

In the Ilaló volcano, water supplied the Valle de los Chillos and Tumbaco to the south of the capital of Ecuador. Mamatena and Kanguil Uku are two water sources, and for approximately 40 years, there has been a pipeline for domestic and irrigation use. The main objectives were to identify the water recharge areas, characterize the groundwater flow lines, and determine the percentage of losses due to leaks in the existing conduction infrastructure. In addition, a Climography was prepared, and the quantity and quality of surface water were evaluated. Through vertical electrical soundings, geostatistics, and standardized laboratory methods, the physical and chemical parameters of the water are determined. Recharge was manifested to the southwest of the Ilaló at coordinates 787,348.39 and 9,970,679.33 at an altitude of 3170.95 masl with 20.5Ω.m resistivity, being the lowest and classified as saturated sand at depths of 3.25m to 8.67m. The Climography reported insufficient rainfall. The percentage of water leakage was 25.93% and the SbN showed that the soil is saturating with more water, preventing degradation and enhancing water storage.

Keywords: SbN, check dams, leakages, water recharge, soil.

1. Introduction

In the Ecuadorian highlands, soil erosion problems arise due to steep slopes and the soil's composition. The lack of productive land, water retention, and soil creates a need to identify recharge areas to rehabilitate and conserve affected zones (1). On the slopes of the Ilaló volcano, there is the highest rate of soil degradation in Ecuador, and the recovery of the cangahuas is needed to prevent further degradation and loss of soil (2,3)

The study of soil resistivity allows the analysis of hydrogeology at specific points and is done with the technique of vertical electrical sounding (VES). It identifies soil strata according to depth as: rocks, clays, gravels, and sands. The resistivity is expressed in Ohm-m of the soil; thus, it is possible to detect groundwater and flow lines. In geophysical studies, the resistivity value where groundwater is found is less than 20 Ω.m (4).

The study area is located on the Ilaló volcano, which last erupted 1.5 million years ago (5). In this volcano are the Mamatena and Urku Huayku streams. The source of water is called Kanguil Uku, from where a PVC and steel pipeline has been in operation for more than 40 years. This reaches the lower part of the volcano to a tank for domestic and irrigation use. In the context of water losses, the pipes are deteriorating due to climatic conditions, corrosion, geological settlements, among others. There are two detection methods: The direct method, which is visual, where the entire pipe is walked through, and the leak is located. The indirect method is done by acoustic means and is verified by a monitoring system (6).

Meteorological data collection is used to identify trends and behaviors of climatic variables. Climographs are graphical representations that show the evolution of temperature and precipitation in a region throughout the year (7). In Ilaló, the climate is temperate, the average monthly temperature is 15.7 °C, with rainfall ranging from 1000 - 2000 mm/year (8).

Groundwater access requires less treatment because it is less contaminated by the layers that cover it. The quality of the water is varied due to the geological origin of the sources, which may contain different minerals that are present due to the erosion of rocks and soils (9). Urku Huayku is a gorge smaller than 25 km^2 located on the slopes of the Ilaló volcano (5). This is the source of the Kanguil Uku spring, which is used by the ancestral Kitu Kara community of San Francisco de Baños.

In recent years, strategies using nature-based solutions (NbS) have been implemented for restoration, water resource protection, and prevention of soil erosion. The use of green infrastructures is designed to improve the sustainability of the environment (5). Check dams assist in watershed management by controlling sediment and alleviating soil loss (10).

The objectives of this research were to identify the water recharge zones, characterize the groundwater flow lines, determine the percentage of losses due to leaks in the conduction infrastructure, elaborate a detailed Climography based on meteorological variables, and evaluate the quantity and quality of surface water after the implementation of dams designed as a nature-based solution (NbS) in the Urku Huayku stream.

2. Materials and Methods

Location of study area

The study area corresponds to the Urku Huayku and Mama Tena ravine of the Ilaló volcano. It is located southeast of the city of Quito, in the parish of Pichincha, Ecuador, in South America, separating the valleys of Tumbaco and Los Chillos. It belongs to the Guayllabamba valley with an altitude of approximately 2400 masl, and its summit reaches 3185 masl (11). Figure 1 illustrates the study basin with the respective coordinates.

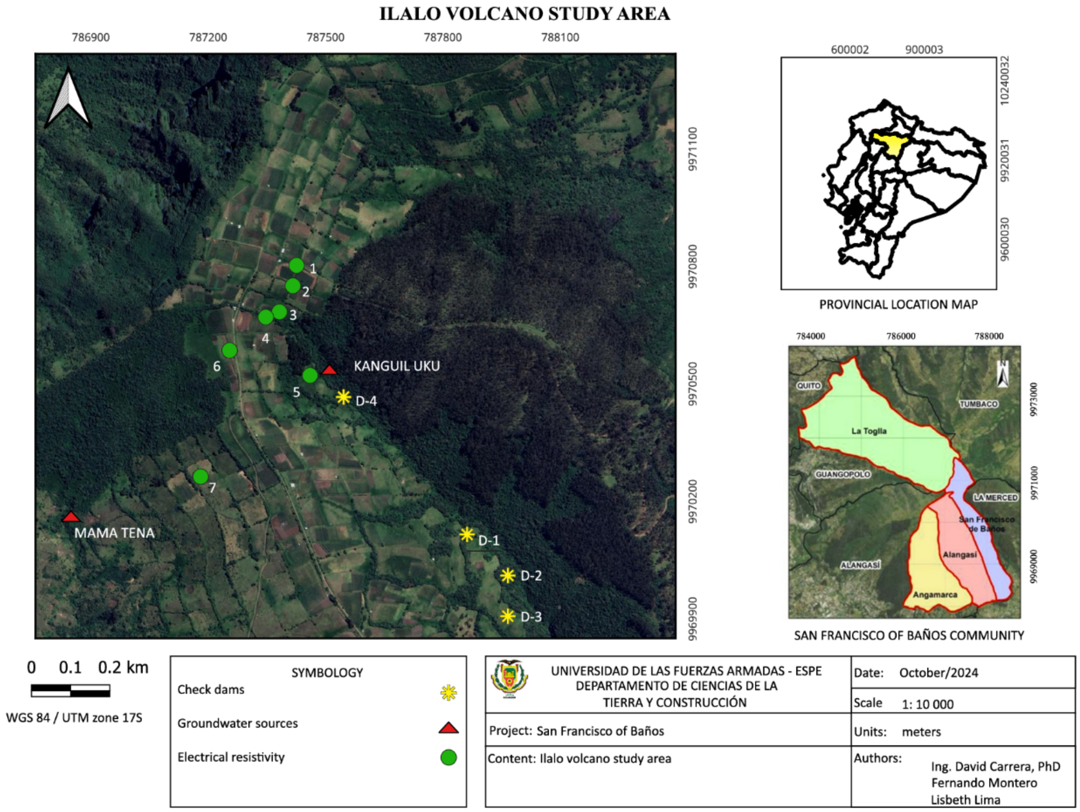


Figure 1: Study area of Ilaló volcano.

Vertical electrical sounding (VES) with the WDJD-4 equipment applying the Schlumberger array

The vertical electrical sounding (VES) determined the thickness of different strata and their resistivity. Current was injected into the ground by two electrodes, A and B, which are monitored by the potential difference between M and N. According to the Schlumberger arrangement, the distances must comply with AB/5 > MN > AB/20 (12). The equipment used is the WDJD-4, which is used for groundwater detection and hydrological prospecting (13). Figure 2 illustrates the equipment and the interpretation of the distances.

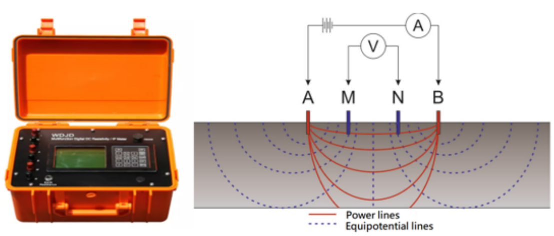


Figure 2: WDJD-4 equipment and Schlumberger array, retrieved from (13)**.**

The interpretation of results was made by means of curves with a logarithmic scale, on the abscissae, the distance AB/2, and on the ordinates, the apparent resistivity (14). It is common to perform the analysis for three layers (15). Based on the resistivity values, the soil type of the layer was assigned. It is essential to have prior knowledge of the geology of the study area to have equivalences between lithologies and resistivities (16). Table 1 shows the admissible values for resistivity based on the lithology of the Ilaló volcano.

Table 1: Electrical resistivity of the soil, retrieved from (16)**.**

Soil	Symbol	Resistivity (Ω.m)
Silty sand	SM	201 - 500
Clayed Sand	SC	51 - 200
Saturated sand	SM	0 - 50

Kriging Bayesiano for determining groundwater recharge zones and flow lines

The resistivity points were georeferenced in (x, y, z) to load them into the ArcGIS Pro software with an advanced license. Then, the base map was added to better recognize the study area. Consequently, the geostatistical prediction model was generated with the 3D Empirical Bayesian Kriging method using the interpolation of the points with the resistivity values, analyzing the soil profile in a three-dimensional map (17). Many studies demonstrate excellent results for determining groundwater flow lines (18,19).

Water leakage

Geophones detect leaks up to 6 meters deep in metal or PVC pipes; in fact, they are not calibrated, only maintained every year. Its parts are a telescopic rod that takes measurements on the surface, the isolating earphones that amplify the noise of the leak, and the control unit that reports the noise intensity values (20). Figure 3 shows the equipment and functionality.

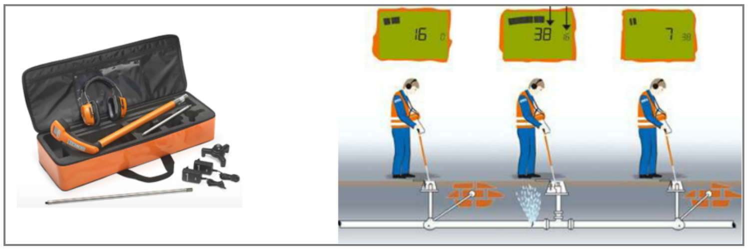


Figure 3: Sewerin Aquatest T10 geophone, retrieved from (21).

Climography

Precipitation is the main monitoring factor in the water balance of watersheds; it is measured in mm, allowing the prediction of atmospheric phenomena such as storms and droughts. The amount can vary according to the region and season of the year (22). According to INAMHI, the closest station to the Ilaló volcano is the La Tola station (M0002) with UTM-WGS84 coordinates of longitude 793.125 and latitude 9,974.612 (23). A Climography was used to analyze the variables of precipitation, evaporation, evapotranspiration, and temperature.

Water quantity and quality

In the Kanguil Uku spring with coordinates 787,479.01 and 9,970,578.98, located at the source of the Urku Huayku stream, the flow was measured using the volumetric method (24). Water is an indispensable resource for food security; therefore, it must comply with the necessary parameters to obtain good quality (3). Water samples were taken in 500 to 700-ml bottles and then taken to the laboratory according to the Standard (25).

The water quality methods of pH, electrical conductivity, total dissolved solids, evaporated dry residue, calcined dry residue, magnesium, potassium, sodium, calcium, carbonates, bicarbonates, chlorides, phosphates, sulfates, and fecal coliforms were made based on (5,26,27).

Nature-based solutions

Nature-based solutions (NbS) are alternatives to mitigate soil erosion. They focus on actions that sustainably protect natural ecosystems while providing for human well-being. They include practices that leverage to improve the challenges of water availability, soil, and reforestation. Traditional infrastructures are applied, providing environmental, social, and economic benefits (28,29). In the Urku Huayku stream, bamboo containment dikes were implemented as an alternative for hydrological recovery with excellent results (5).

3. Results

Recharge zone according to the electrical resistivity of the soil.

Around the entire Urku Huayku stream, which feeds the Kanguil Uku water source, seven resistivity lines of 200 m, that is, at a depth of analysis of 100 m each, were established. The results were obtained in October 2024. In the seven resistivity lines, the analyses were made according to (16), which resulted in soil types: silty sand (SM), clayey sand (CS), and saturated sand (SM). All curves were H-type, that is, three-layered. And it coincided with the geology of the Ilaló volcano, which is cangahua with proportions of silts, sands, and clays (30).

The point located at coordinates 787,348.39 and 9,970,679 at an altitude of 3170.95 masl, had a resistivity value of 20.50Ω.m, being the lowest of all seven tests, and it can be estimated that the water recharge is directed to this point. Figure 4 shows the resistivity curve in detail.

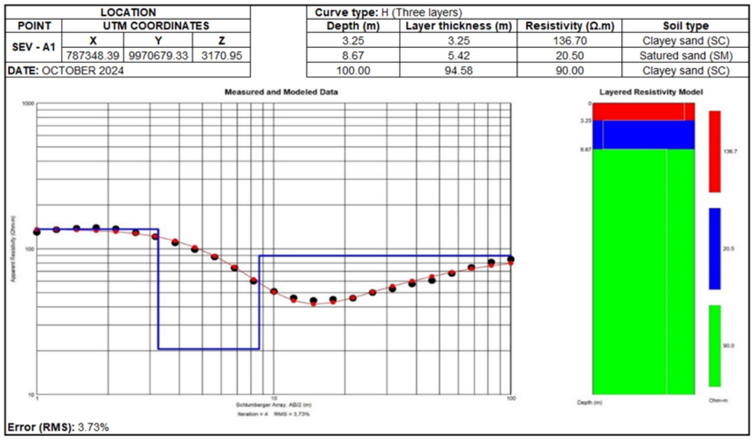


Figure 4: Resistivity curve extracted at 100 meters depth.

Flow lines

Interpolating all the resistivity results with the 3D Empirical Bayesian Kriging geostatistical method, the soil profile of the Ilaló volcano was obtained. The major recharge and flow lines are directed towards Kanguil Uku. Figure 5 shows the stratigraphy.

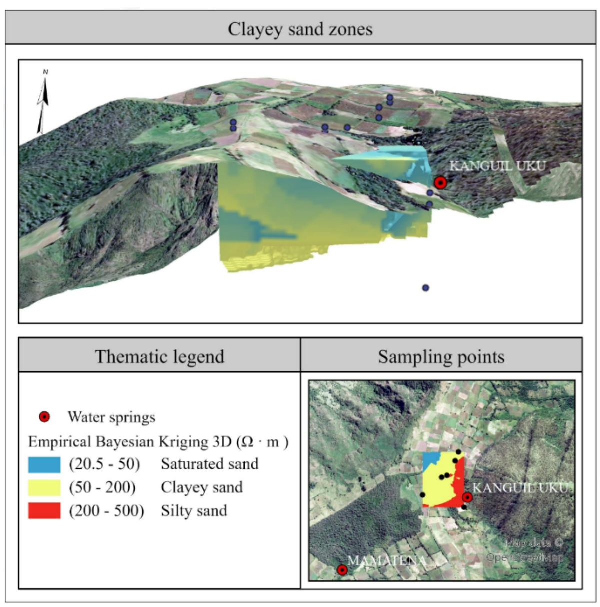


Figure 5: Water recharge profile and flow lines.

Leaking water in the existing pipeline

A geophonic survey was carried out along the entire length of the Urku Huayku stream, which is used to support agricultural and domestic needs, resulting in 4 water leaks shown in red on the isohyet map, as shown in Figure 6.

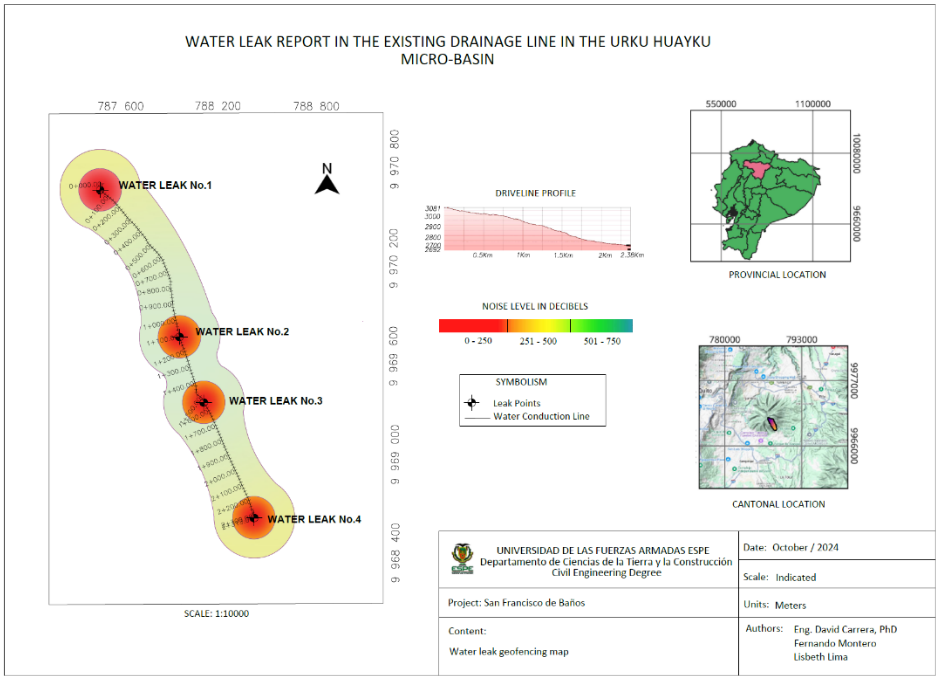
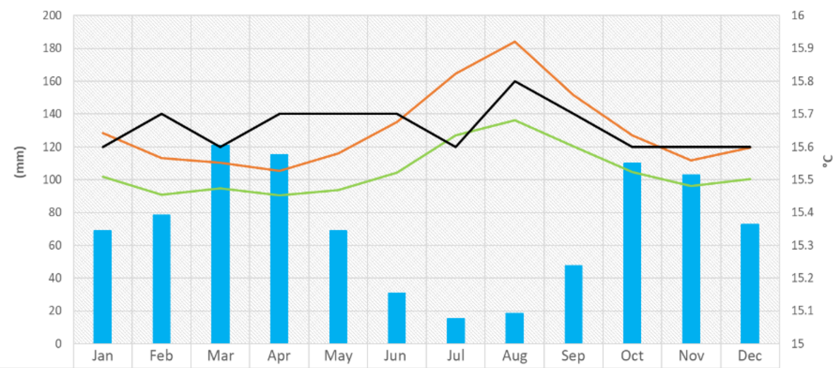


Figure 6: Water leakage reporting map.

The volumetric flow measurement method was applied. In this method, the initial flow of the pipeline, which is in the Kanguil Uku source, is equivalent to 100% water. The final flow in the pipeline was measured, and the difference between the initial and final flow is equivalent to the percentage of water leakage. Therefore, the result was 25.93%.

Climographya del volcán Ilaló

The average precipitation and average evaporation in each month of the La Tola M0002 station from 1987 to 2022 were plotted. It was observed that March and April presented higher precipitation and exceeded evaporation, which implies a gain of water for the recharge of the aquifer, while the other months are below evaporation, generating a water deficit, especially in June, July, and August. Figure 7 shows the absence of precipitation in a climograph. Several studies have shown that climograms provide excellent results for visualizing water surplus and deficit in a study area (27,31,32).



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Precipitation	68.9	78.4	120.8	115.2	68.9	30.9	15.4	18.4	47.5	109.8	102.8	72.9
Evaporation	128.3	113.1	110.2	105.4	115.9	135.3	164.6	184.1	151.4	126.9	111.7	119.7
ET	102.00	91.00	94.60	90.60	93.60	104.40	127.10	136.10	120.30	104.80	96.00	100.40
Temperature	15.6	15.7	15.6	15.7	15.7	15.7	15.6	15.8	15.7	15.6	15.6	15.6

Figure 7: Climography based on station La Tola M0002.

The construction of check dams as an NbS among its main purposes is to regulate the extreme climatic variability in the Ilaló volcano, among other things. This facilitates the inhabitants of this sector with better water management for agricultural use or human consumption (33).

Water quantity and quality

The amount of water from the Kanguil Uku spring was obtained by the volumetric method, which resulted in an average of 0.267 l/s in the 12 weeks of analysis from September to December 2024. However, it has remained consistently active despite the low water levels.

The water quality is presented in Table 2. Depending on the result, it can be used for different domestic uses after disinfection and irrigation.

Table 2: Water results from the Kanguil Uku spring.

Parameters	Units	Result

pH	-	6.2
Electrical Conductivity (EC)	(µS/cm)	138.07
Total Dissolved Solids (TDS)	(ppm)	118.5
Evaporated Dry Residue (DRR)	(%)	0.0122
Calcined Dry Residue (CDR)	(%)	0.0085
Magnesium (Mg^{2+})	(mg/l)	1.62
Potassium (K^{+})	(mg/l)	4.17
Sodium (Na^{+})	(mg/l)	0.17
Calcium (Ca^{2+})	(mg/l)	3.23
Carbonates (CO_3^{2-})	(mg/l)	0
Bicarbonates (HCO_3^{-})	(mg/l)	135.42
Chlorides (Cl^{-})	(mg/l)	0.15
Phosphates (PO_4^{3-})	(mg/l)	0.79
Sulfates (SO_4^{2-})	(mg/l)	3.9
Fecal Coliforms	NMP/100ml	380

Check dams with an approach to nature-based solutions

Downstream of the Urku Huayku stream, four permeable check dams made of biodegradable materials were designed and installed to increase the residence time of the water in the stream and also to generate infiltration pools and allow sediments to accumulate and compact (5). Figure 8 shows the constructed dikes.

Check dams 1

Check dams 2

Check dams 3

Check dams 4

Figure 8. Dikes built in the Urku Huayku creek of the Ilaló volcano.

4. Discussion

Groundwater recharge in the Urku Huayku stream influences the aquifer cycle. However, the flow line was directed towards the Kanguil Uku source. According to (34), resistivity values of 20 to 80Ω.m are classified as sand or clay type soils and are associated with high water saturation. In this research, a saturated sand-type soil with 20.5Ω.m was measured (35).

The cangahua, being a subsoil of volcanic origin, is sensitive to erosion, and water retention is low because infiltration is rapid at the surface in shallow layers. Electrical resistivity is frequently used for water location and deep well drilling for different uses (36). In case of exploration at a depth of 150m, the vertical electrical sounding should start with an electrode opening of AB/2 = 2m and end at AB/2=300m, making at least 5 to 20 measurements for greater reliability(37).

It is estimated that about 45 million cubic meters of water are wasted daily in the distribution networks of developing countries, due to leaks and abuses. This represents an expenditure of approximately 260,000 million. Breaks or poor connections in water pipes easily allow the entry of viruses and contaminants that can cause diseases such as gastrointestinal infections (38). Water is a resource that is increasingly diminishing due to incorrect management, which must be solved (39). In another study conducted at the Universidad de las Fuerzas Armadas – ESPE of Ecuador, it was concluded that losses are due to the lack of maintenance of pipes (40).

Climographs help in planning with respect to water availability, in the management of water resources, in mitigating the effects of droughts, and generally in studies of long-term climate change. In the Ilaló volcano, there is a decrease in rainfall, which generates water stress and soil degradation. Therefore, the Climography has limitations since it does not specify specific storms or droughts, such as the days that the event occurred, and its accuracy depends on the amount of data collected (41).

Water quantity and quality are essential for any hydraulic project. The Kanguil Uku source was analyzed. However, it would be ready to be evaluated for different uses as long as the limits of current regulations are compared. The analyses are essential to guarantee access to clean and sufficient water for present and future generations (42).

Potassium from the Ilaló volcano water source is high. The maximum limit for agricultural use is 2mg/l, but it resulted in a value of 4.17 mg/l. Volcanic activity generates substances in the particulate ash material that alter water quality and influence high potassium concentrations (43). They oscillate in (32.8±0.93 mg/l)

(44). The high level of potassium does not interfere with plant growth and can be considered up to 10 mg/l; otherwise, the water would already be in the presence of fertilizers (45).

In watershed restoration in rural areas, dams with bamboo are environmentally friendly as they have a focus on nature-based solutions (NbS). In Ecuador, they have developed the initiative of projects with bamboo to protect riverbanks, to control erosion, and to build fog collector systems(46). On the other hand, the flow lines where the infiltration water runs through were in the saturated sand layer reaching depths up to 8.67 m, feeding the Kanguil Uku recharge zone (47,48).

5. Conclusions

The water recharge zone was directed towards the Urku Huayku stream, feeding the Kanguil Uku spring. Three flow lines were characterized: saturated sand, silty sand, and clayey sand. The saturated sand layer, which reaches a depth of 8.67 m, is predicted to carry all the infiltration water. The percentage of water leakage in the existing pipeline was 25.93% which was due to poor connections between fittings. Based on the Climography, the low water level in the Ilaló volcano was determined from June to September. The flow provided by the Kanguil Uku source was 0.267 l/s, which remained stable from September to December 2024. On the other hand, the quality parameters were: pH of 6.2, electrical conductivity of 138.07µS/cm, total dissolved solids of 118.5 ppm, inorganic matter of 0.0085%, magnesium of 1. 62mg/l, sodium of 0.17mg/l, calcium of 3.23mg/l, bicarbonates of 0.5mg/l, chlorides of 0.15mg/l, phosphates of 0.79mg/l, sulfates of 3.9 mg/l and fecal coliforms of 380NMP/100ml. It should be noted that potassium was elevated at 4.17mg/l and is due to the geological past with volcanic ashes containing mineral-rich compounds. The containment dikes in the Urku Huayku stream channel helped regulate water flow, controlling erosion by capturing sediments upstream. This method generates greater nutrient richness and enhances water recharge in the soil.

References

1. Palacios Orejuela I, Ushiña D, Carrera Villacrés D. Técnicas SIG para recuperación de suelos cangahuosos, con fines de agricultura comunitaria en el Ilalo. Argentina). 2020;38(2):295–309.

2. Manciati Carla. Etude de l'intéraction surface-souterrain du système aquifère Tumbaco-Cumbaya en Equateur, avec une approche hydrodynamique et géochimique [Internet] [sein de l'école doctorale]. [Montpellier]: UNIVERSITE MONTPELLIER 2; 2014 [cited 2025 Sep 21]. Available from: https://horizon.documentation.ird.fr/exl-doc/pleins_textes/divers16-09/010063373.pdf

3. Carrera-Villacrés D. Ciencia del Suelo. Caracterización y Conservación en el Ecuador [Internet]. 1st ed. EDIESPE, editor. Vol. 1. Sangolquí: ESPE; 2022 [cited 2025 Sep 16]. 1–197 p. Available from: https://repositorio.espe.edu.ec/items/8600b9cf-6502-4492-8c33-56c38eb5b98d

4. Adagunodo TA, Akinloye MK, Sunmonu LA, Aizebeokhai AP, Oyeyemi KD, Abodunrin FO. Groundwater Exploration in Aaba Residential Area of Akure, Nigeria. Front Earth Sci (Lausanne) [Internet]. 2018 Jun 6;6(1):1–12. Available from: https://www.frontiersin.org/article/10.3389/feart.2018.00066/full

5. Carrera-Villacrés D, Gavilanes P, Brito MJ, Criollo A, Chico A, Carrera-Villacrés F. Water and Sediment Quantity and Quality Generated in Check Dams as a Nature-Based Solutions (NbS). Water (Basel) [Internet]. 2025 Mar 12;17(810):1–15. Available from: https://www.mdpi.com/2073-4441/17/6/810

6. Farah E, Shahrour I. Water Leak Detection: A Comprehensive Review of Methods, Challenges, and Future Directions. Water (Basel). 2024 Oct 18;16(2975):1–26.

7. Kāne HL, Mair A, Johnson AG, Rotzoll K, Mifflin J, Oki DS. Estimated groundwater recharge for mid-century and end-of-century climate projections, Kaua'i, O'ahu, Moloka'i, Lāna'i, Maui, and the Island of Hawai'i [Internet]. Reston; 2024 Dec [cited 2025 Sep 21]. Available from: https://pubs.usgs.gov/sir/2023/5130/sir20235130.pdf

8. Carrera-Villacrés D V, Quinteros-Carabalí JA, Gómez AJ, Solano EM, Llumiquinga GE, Burgos CA. Dynamic model for the management of water resource and water aptitude for irrigation of the Togllahuayco gorge in the Guangopolo micro-basin. IOP Conf Ser Earth Environ Sci [Internet]. 2019 Oct 1;344(012029):1–8. Available from: https://iopscience.iop.org/article/10.1088/1755-1315/344/1/012029

9. Ayers RS, Westcot DW. Water quality for agriculture [Internet]. Food, of the United Nations AO, editors. 1994. p. 1–80. Available from: https://www.fao.org/4/T0234E/T0234E00.htm#TOC

10. Sun P, Wu Y. Dynamic Modeling Framework of Sediment Trapped by Check-Dam Networks: A Case Study of a Typical Watershed on the Chinese Loess Plateau. Engineering [Internet]. 2023 Aug;27:209–21. Available from: https://linkinghub.elsevier.com/retrieve/pii/S2095809922000741

11. Curipoma Heredia S. Evaluación de la diversidad florística de la quebrada Shullum, bosque protecor Ilaló, Ecuador. AXIOMA [Internet]. 2021 Jun 24;1(24):57–63. Available from: http://axioma.pucesi.edu.ec/index.php/axioma/article/view/631

12. Febriani Y, Rohman RA, Asra A, Apriniyadi M, Wardani DNW. Determination of Groundwater Using Geoelectric Methods: Schlumberger Configuration in Rokan Hulu Regency. Jurnal Ilmiah Pendidikan Fisika Al-Biruni. 2019 Oct 30;8(2):141–52.

13. GEOEQUIP. WDJD-4 Medidor de resistividad de CC digital multifunción / medidor de IP Fabricantes y proveedores - Precio barato WDJD-4 Medidor de resistividad de CC digital multifunción / IP - Chongqing Gold [Internet]. 2025. p. 1–5. Available from: http://www.cqgeoequip.com/geophysical-equipment/resistivity-meter-and-induced-polarization/wdjd-4-multi-function-digital-dc-resistivity.html

14. Fajana AO. Groundwater aquifer potential using electrical resistivity method and porosity calculation: a case study. NRIAG Journal of Astronomy and Geophysics. 2020 Jan 1;9(1):168–75.

15. Azizan FA, Aznan AA, Ruslan R, Nazari M, Jaafar MN. Groundwater Assessment Using Geophysical Survey at Insat, Perlis, Malaysia. IOP Conf Ser Mater Sci Eng. 2018 Nov 9;429(012026):1–6.

16. Waspodo RSB, Asra A, Dewi VAK. Determination of aquifer distribution using resistivity method in South Tangerang, Banten Province. IOP Conf Ser Earth Environ Sci. 2020 Jul 1;542(012054):1–9.

17. Castillo B. Aplicación de métodos geoestadísticos en el modelado espacio-temporal de los niveles de agua subterránea del acuífero Valle de Sébaco, Nicaragua. Revista de Ciencias Ambientales [Internet]. 2022 Jul 1 [cited 2025 Sep 21];56(2):194–210. Available from: https://www.scielo.sa.cr/pdf/rca/v56n2/2215-3896-rca-56-02-194.pdf

18. Adhikary PP, Dash ChJ. Comparison of deterministic and stochastic methods to predict spatial variation of groundwater depth. Appl Water Sci [Internet]. 2017 Mar 16;7(1):339–48. Available from: http://link.springer.com/10.1007/s13201-014-0249-8

19. Romero J, Castaño D. Modelado espacial hidrogeológico para determinar índices de calidad y vulnerabilidad de las aguas subterráneas en la zona centro de Boyacá [Internet] [Tesis]. [Bogotá]: Universidad Distrital Francisco José de Caldas; 2021. Available from: http://hdl.handle.net/11349/29264

20. Nati M, Despina-Stoian C, Nastasiu D, Stanescu D, Digulescu A, Ioana C, et al. Non-Intrusive Continuous Monitoring of Leaks for an In-Service Penstock. Sensors [Internet]. 2024 Aug 11 [cited 2025 Sep 22];24(5182):1–13. Available from: https://www.mdpi.com/1424-8220/24/16/5182

21. SEWERIN. SEWERIN. 2025. p. 1–3 AquaTest T10 | Sewerin. Available from: https://www.sewerin.com/es/productos/agua/deteccion-acustica-de-fugas-de-agua/aquatest-t10/

22. Vittecoq B, Reninger PA, Lacquement F, Martelet G, Violette S. Hydrogeological conceptual model of andesitic watersheds revealed by high-resolution heliborne geophysics. Hydrol Earth Syst Sci. 2019 May 14;23(5):2321–38.

23. INAMHI. INAMHI. 2025. Anuarios Metereologicos. Available from: https://servicios.inamhi.gob.ec/anuarios-metereologicos/

24. FAO. FAO. 2025. p. 1–5 Estimations du débit d´eau. Available from: https://www.fao.org/fishery/static/FAO_Training/FAO_Training/General/x6705f/x6705f03.htm

25. INEN 1108. NTE INEN 1108: Agua potable. Requisitos [Internet]. NTE INEN, NTE INEN Ecuador: INEN ; Jan 23, 2014 p. 1–10. Available from: https://www.grupoquimicomarcos.com/wp-content/Links/INEN%201108-2020.pdf

26. Carrera-Villacrés D, Chicaiza MM, Choloquinga CA, Ramos SM, Unda LJ, Carrera-Villacrés F. Water Quality and Dynamic Time Series Based on Meteorological Variables at the Muisne Station Located in the Bunche Enclosure, Esmeraldas, Ecuador. In: Botto-Tobar M, Zambrano Vizuete M, Montes León S, Torres-Carrión P, Durakovic B, editors. Communications in Computer and Information Science [Internet]. SPRINGER. 2023 [cited 2025 Sep 22]. p. 243–57. Available from: https://link.springer.com/chapter/10.1007/978-3-031-24971-6_18

27. Carrera-Villacrés D, Guevara-García P, Maya-Carrillo M, Crisanto-Perrazo T. Variations of Species Concentration in Inorganic Water Dam “Purpose Multiple Chone”, Ecuador Based on Precipitation, Evaporation and Evapotranspiration. Procedia Earth and Planetary Science [Internet]. 2015;15:641–6. Available from: https://linkinghub.elsevier.com/retrieve/pii/S1878522015003859

28. Marino M, Nasca S, Alkharoubi AI, Cavallaro L, Foti E, Musumeci RE. Efficacy of Nature-based Solutions for coastal protection under a changing climate: A modelling approach. Coastal Engineering [Internet]. 2025 May;198:104700. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0378383925000055

29. Webber MK, Mei L, Samaras C. Bridging the gap: riverine nature-based solutions for climate resilient transportation infrastructure in the United States. npj Urban Sustainability [Internet]. 2025 May 21;5(28):1–7. Available from: https://www.nature.com/articles/s42949-025-00215-x

30. Wang C, Bao F, Lu Y. Study on the resistivity characteristics and mechanism of silt clay under different initial conditions. Nartowska, E, editor. PLoS One [Internet]. 2025 Apr 2;20(4):1–18. Available from: https://dx.plos.org/10.1371/journal.pone.0319072

31. Carrera D, Crisanto T, Guevara P, Maya M. Relación entre la composición química inorgánica del agua, la precipitación y la evaporación en la cuenca de Río Grande, Chone, Ecuador. Enfoque UTE. 2015 Mar 31;6(1):25–34.

32. Radwan N, Halder B, Ahmed MF, Refadah SS, Khan MYA, Scholz M, et al. Seasonal Precipitation and Anomaly Analysis in Middle East Asian Countries Using Google Earth Engine. Water (Basel) [Internet]. 2025 May 14;17(10):1–27. Available from: https://www.mdpi.com/2073-4441/17/10/1475

33. Matovelle C, Mudarra M, Andreo B. Efficiency analysis of irrigation ditches over different land uses in the Andean region of Ecuador: implication for nature-based water management strategies. Environ Earth Sci [Internet]. 2025 Feb 7;84(4):107. Available from: https://link.springer.com/10.1007/s12665-024-12070-7

34. Ayolabi EA, Enoh IJE, Folorunso AF. Engineering Site Characterisation Using 2-D and 3-D Electrical Resistivity Tomography. Earth Science Research [Internet]. 2012 Oct 9;2(1). Available from: http://www.ccsenet.org/journal/index.php/esr/article/view/21238

35. Emeka AL, Samuel YM. Estimation of aquifer hydraulic parameters using electrical resistivity method: A case study for Damaturu, Northeast Nigeria. Dutse Journal of Pure and Applied Sciences. 2023 Jul 14;9(2a):191–202.

36. Alogla SM, Alawad OM, Elragi AF, Elkholy S, Al-Saadi GA, Arif M. Comparison between Electrical Resistivity Tomography and Geotechnical Field Data for Characterizing Soil Profiles. The Open Civil Engineering Journal [Internet]. 2022 Aug 24;16(1):1–9. Available from: https://opencivilengineeringjournal.com/VOLUME/16/ELOCATOR/e187414952206271/

37. Solís B. Groundwater in Latin America and the Caribbean: Policies and Experiences for Managing and Preserving Aquifers [Internet]. BID. Vol. 1. Inter-American Development Bank; 2023. 1–98 p. Available from: https://publications.iadb.org/en/groundwater-latin-america-and-caribbean-policies-and-experiences-managing-and-preserving-aquifers

38. Romero-Ben L, Alves D, Blesa J, Cembrano G, Puig V, Duviella E. Leak detection and localization in water distribution networks: Review and perspective. Annu Rev Control [Internet]. 2023;55:392–419. Available from: https://linkinghub.elsevier.com/retrieve/pii/S1367578823000160

39. Maldonado Santana C, Franco-Billini C, Jáuregui-Haza UJ. Gestión integrada de las cuencas hidrográficas: hacia un nuevo paradigma en la gobernanza del agua. Ciencia, Ambiente y Clima [Internet]. 2023 Dec 29;6(2):67–101. Available from: https://revistas.intec.edu.do/index.php/cienacli/article/view/2951

40. Carrera D, Martínez-Molina CA, Montero-Yancha WF. Fugas de agua no visibles en los sistemas de abastecimiento hídrico de la Universidad de las Fuerzas Armadas (ESPE). European Public & Social Innovation Review [Internet]. 2024 Sep 3;9:1–20. Available from: https://epsir.net/index.php/epsir/article/view/326

41. Obradovich N, Lawrance EL, Minor K. Our current climate already merits serious research and policy attention. Proceedings of the National Academy of Sciences [Internet]. 2025 Aug 19;122(33):1–4. Available from: https://pnas.org/doi/10.1073/pnas.2503892122

42. Venegas-Quiñones HL, Thomasson M, Garcia-Chevesich PA. Trend Analysis of Precipitation, Groundwater Level and Flow Rate Data by using Mann-Kendall and Sen's Slope Estimator Statistical Tests in the Petorca Communer. Am J Environ Sci. 2019 Jun 1;15(6):180–7.

43. Rey-Romero DC, Domínguez I, Oviedo-Ocaña ER. Effect of agricultural activities on surface water quality from páramo ecosystems. Environmental Science and Pollution Research [Internet]. 2022 Nov 28;29(55):83169–90. Available from: https://link.springer.com/10.1007/s11356-022-21709-6

44. Padrón L, Paz S, Gutiérrez Á, Rubio C, González D, Hardisson de la Torre A. Contenido de metales y elementos traza en aguas subterráneas de abastecimiento de la isla de El Hierro (islas Canarias, España). Rev Esp Salud Publica [Internet]. 2020 Oct 15 [cited 2025 Jan 23];94:e202010119. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC11582777/

45. Aranguren-Díaz Y, Galán-Freyle NJ, Guerra A, Manares-Romero A, Pacheco-Londoño LC, Romero-Coronado A, et al. Aquifers and Groundwater: Challenges and Opportunities in Water Resource Management in Colombia. Water (Basel) [Internet]. 2024 Feb 26;16(5):1–26. Available from: https://www.mdpi.com/2073-4441/16/5/685

46. Carrera-Villacrés DV, Gallegos Rios DF, Chiliquinga López YA, Córdova Córdova JJ, Arroba Giraldo AM. The Implementation of IoT Sensors in Fog Collector Towers and Flowmeters for the Control of Water Collection and Distribution. Applied Sciences [Internet]. 2024 Sep 16;14(18):1–13. Available from: https://www.mdpi.com/2076-3417/14/18/8334

47. Masitoh F, Taryana D, Wijaya AA, Arysandi SA, Rusydi AN. Promoting Bamboo as Water Resources Conservation Plant in Jedong Community. IOP Conf Ser Earth Environ Sci [Internet]. 2022 Sep 1;1039(1):012059. Available from: https://iopscience.iop.org/article/10.1088/1755-1315/1039/1/012059

48. Zheng D, Bezuijen A, Thewes M. An experimental study on foam infiltration into saturated sand and its consequence for EPB shield tunneling. Tunnelling and Underground Space Technology [Internet]. 2021 May;111(103878):1–15. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0886779821000699