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ASSESSMENT OF DIFFUSIVE RECHARGE AT REGIONAL SCALE IN KARST SYSTEMS, AMAZON BASIN, ECUADOR

OCENA RAZPRŠENEGA NAPAJANJA NA REGIONALNI RAVNI V KRAŠKIH SISTEMIH, AMAZONSKO POREČJE, EKVADOR

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Abstract UDC 556.33:551.444(866)

Karla M. González, Yetzabbel G. Flores, Christian O. Camacho, Theofilos Toulkeridis, SanLinn I. Kaka & Péter Szűcs: Assessment of diffusive recharge at regional scale in karst systems, Amazon basin, Ecuador

Karst systems play a crucial role in drinking water supply and biodiversity. Therefore, their comprehensive characterization of their recharge mechanisms is essential for safeguard water resource quality and sustainable management. This study utilizes the open-access thematic cartography of Ecuador to analyze the lithological, geomorphological, and hydrographic boundaries of groundwater karst systems. Then, employing the APLIS method, the diffusive recharge for each system is calculated. As a result, five hydrogeological karst systems and twelve small isolated karst bodies were delineated within the Amazon Region of Ecuador, collectively occupying a total area of 11112 km^2. The effective infiltration of precipitation within these systems was found to vary between 11.11% and 77.11%, with a predominant low infiltration range (20%-40%) covering 48% of the karst area. One of the multiple parameters used in water balance calculations is defined by this research, serving as the initial step in creating conceptual models for evaluating karst aquifer systems in Ecuador from a hydrological perspective. The findings not only offer insights into the vulnerability and characteristics of these systems but also establish the foundation for informed decision-making in sustainable groundwater resource management and protection efforts.

Keywords: Ecuadorian karst, APLIS method, karst hydrology, groundwater management, Amazon region.

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Karla M. González, Yetzabbel G. Flores, Christian O. Camacho, Theofilos Toulkeridis, SanLinn I. Kaka & Péter Szűcs: Ocena razpršenega napajanja na regionalni ravni v kraških sistemih, Amazonsko porečje, Ekvador

Kraški sistemi imajo ključno vlogo pri preskrbi s pitno vodo in biotski raznovrstnosti. Zato je celovita opredelitev mehanizmov njihovega polnjenja poglavitna za zagotavljanje kakovosti vodnih virov in trajnostno upravljanje. V tej študiji je uporabljena odprtodostopna tematska kartografija Ekvadorja in z njo so analizirane litološke, geomorfološke in hidrografske meje kraških sistemov podzemne vode. Nato je bilo z metodo APLIS izračunano difuzijsko polnjenje za posamezni sistem. Tako je bilo v Amazoniji v Ekvadorju opredeljenih pet hidrogeoloških kraških sistemov in dvanajst manjših izoliranih kraških teles, ki skupaj zavzemajo 11.112 km^2 površine. Ugotovljeno je bilo, da se učinkovita infiltracija padavin v teh sistemih giblje med 11,11 % in 77,11 %, pri čemer prevladuje nizka infiltracija (20–40 %), ki zajema 48 % kraškega območja. V tej raziskavi je opredeljen eden od številnih parametrov, ki se uporabljajo pri izračunih vodnega ravnovesja, kar je začetni korak pri oblikovanju konceptualnih modelov za vrednotenje kraških vodonosnih sistemov v Ekvadorju s hidrološkega vidika. Ugotovitve omogočajo vpogled v ranljivost in značilnosti teh sistemov in tvorijo izhodišče za informirano odločanje pri trajnostnem upravljanju in varovanju virov podzemne vode.

Ključne besede: Ekvadorski kras, metoda APLIS, kraška hidrologija, upravljanje podzemne vode, Amazonija

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1. INTRODUCTION

The assessment and comprehension of recharge and discharge rates in karst groundwater systems become imperative given their susceptibility to contamination and degradation issues (Davis et al., 2002; Government of British Columbia, 2023). The contamination is attributed to a variety of factors including thin soil coverage, open recharge areas, and preferred flow paths in the epikarst and vadose zone (Naranjo et al., 2023). Therefore, the knowledge related to recharge mechanisms is essential for ensuring the sustainable utilization, management, and safeness of the groundwater resources (Day, 2023). It enables the assessment of the impacts that anthropogenic activities, enclosing agriculture, water supply, and anthropogenic contamination, have over the karst systems (Souza et al., 2023).

The natural recharge in karst groundwater systems exhibits a dual nature, comprising point and diffuse mechanisms (Espinoza et al., 2015). Point recharge involves the infiltration from shafts, sinholes, and conduits; whereas diffuse recharge encompasses infiltration through matrix, meso-pore, and macro-pore (Somaratne, 2014). A significant portion of the recharge volume arises from the infiltration of precipitation through the unsaturated zone until it reaches the water table (Anderson et al., 2015; Onac & Van Beynen, 2021), thereby contributing a significant volume of water to carbonate aquifers, frequently employed for water supply purposes (Johnson et al., 2011). This phenomenon is classified as a component of the diffusive recharge mechanisms, as outlined by Betancur-Vargas et al. (2020) and Farfán H. et al. (2010).

Numerous methods are employed to estimate groundwater recharge rates in karst systems (Hardyani et al., 2021; Haryono, 2023), among which the APLIS method holds prominence. Developed by Andreo et al. (2004) utilizing morphostructural analysis, this method leverages geographic information systems to spatially evaluate five fundamental variables: altitude (A), slope (P), lithology (L), preferential absorption-infiltration areas (I), and soil (S) (Andreo et al., 2004; Entezari et al., 2020; Errahmouni et al., 2022). Consequently, the multi-criteria analysis yields a spatial distribution map illustrating the effective potential infiltration within the karst groundwater system, facilitating the computation of yearly recharge expressed as the percentage of effective precipitation infiltration (Marina et al., 2014).

This approach provides valuable information, particularly in countries with limited detailed groundwater data. The APLIS method initially aimed at estimating recharge percentages in regional carbonate aquifers under Mediterranean climate conditions in Spain. Remarkably, it has been applied across various climatic conditions and working scales. Its application extends to diverse regions, including the tropical mountains of Viñales National Park in Cuba (Farfán et al., 2010), the 'La Florida' Catchment area in the Peruvian Andean Mountains (Espinoza et al., 2015), the arid region of North Khorasan in Iran (Alem et al., 2017), and the tropical karst area of Donorojo in Indonesia (Hardyani et al., 2021), among others.

On another hand, recent studies in Ecuador have expanded the investigation of karst systems to include vulnerability analysis and hydrogeologic descriptions at local scales (Chamba Vásquez & Piispa, 2020; Jiménez-Iñiguez et al., 2022; Naranjo et al., 2023; Sánchez Cortez et al., 2022), departing from previous studies that predominantly focused on touristic, biological, and speleological aspects. This has shifted the focus of research from the initial tourist-oriented perspectives (Constantin et al., 2019; Sánchez Cortez, 2017) to a new level of complexity, involving multidisciplinary approaches. The current starting evolution represents a transformative advance in the understanding of karst systems, underscoring the significance boundary delineation of the systems on regional scales. Consequently, the evolving scientific context also generates interest for development of a recharge percentage map as a transcendental tool for the comprehensive analysis of karst systems.

This research aims to generate a spatial distribution map of diffuse recharge in the five primary karst systems within the Ecuadorian Amazon Region, area where the calcareous rocks undergo karstification processes (CISPDR, 2016a, 2016c, 2016d; Constantin et al., 2019), leading to the development of secondary porosity that constitutes the primary component of effective porosity in the hydrogeological systems, where gravity forces primarily drive the flow within these systems (Tóth, 2009). The proposed methodology employs spatial constraints that enable a detailed examination of the five crucial parameters for calculating diffuse recharge percentages using the APLIS method. Thus, the present study contributes a versatile tool applicable to local-scale investigations. This includes long-term water balance assessments, analysis of geochemical parameters, tracer testing, monitoring station location, and comprehensive mapping of soils, vegetation, depressions, and geological structures.

1.1. REGIONAL GEOLOGY AND TECTONICS

The study area is focused on the geographical expanse of the Amazon Basin in Ecuador, spanning approximately 112,000 km² andlocated between the eastern flank of the Andean Mountain Range and the national border with the Republic of Peru. This region lies in the northwest region of the South American continent (as illustrated in Figure 1), and showcases a diverse and ecologically significant landscape.

The geological characteristics of Ecuador have evolved in response to tectonic provinces aligned in a north-south direction, paralleling regional tectonic displacements (Jackson et al., 2019). Notably, during the Early Cretaceous to Eocene period, oceanic terrains accreted to the Amazonian craton, signaling the initiation of the orogenic processes that led to the uplift of the Andes. The investigation area represents the outer-frontal segment of the fold-thrust belt and the associated flexion foreland basin (Hungerbühler et al., 2002). Characterized by a predominantly horizontal sedimentary succession from the Cretaceous to the Cenozoic, this landscape undergoes local deformations towards the west while remaining unchanged towards the east.

The Cretaceous basin fill, sourced from the craton, comprises sandstones, siltstones, organic-rich slates, and subordinate limestones. In contrast, the Cenozoic sequence is composed of sandstones, siltstones, and conglomerates originating from Andean sources. These sequences overlay the Jurassic magmatic arc exposed in the Sub-Andean Zone, characterized by non-metamorphic granites, monzonites, and granodiorites (Aspden & McCourt, 2002; Egüez et al., 2019; Gutiérrez et al., 2019). To the south, the investigation area includes the Loja terrains, encompassing Palaeozoic schists and gneisses, Triassic granites, and anatexites. Additionally, the Alao insular arc is composed of Jurassic metabasalts and andesites. These sublinear metamorphic belts consist of deformed igneous and volcanic sedimentary rocks spanning the Upper Paleozoic to the Lower Cretaceous (Jackson et al., 2019; Litherland et al., 1994).

1.2. KARST GEOLOGY IN THE ECUADORIAN AMAZON BASIN

In the context of this investigation, two geological periods within the sedimentary record of the Ecuadorian Amazon Basin (refer to Figure 2) merit specific attention due to the deposition of karst deposits including limestone and dolomite (Pulido-Boch, 2021).

Firstly, the Upper Triassic-Lower Jurassic period holds significance due to distinctive sedimentary formations. Sedimentation during this interval commenced with a pronounced marine transgression, resulting in the deposition of organic-rich marine sediments in the Lower Santiago member. Subsequently, volcanic sediments from the Upper Santiago member were submerged, accompanied by terrestrial volcanic tholeiitic events. The initial appearance of marine calcareous rocks from this period is evident in the lower-middle section of the Santiago Formation, exposed in the Cutucú Range with skarn alterations. In the southern region of the Ecuadorian Amazon Basin, these rocks exhibit increased thickness and are influenced by tectonic activity, primarily

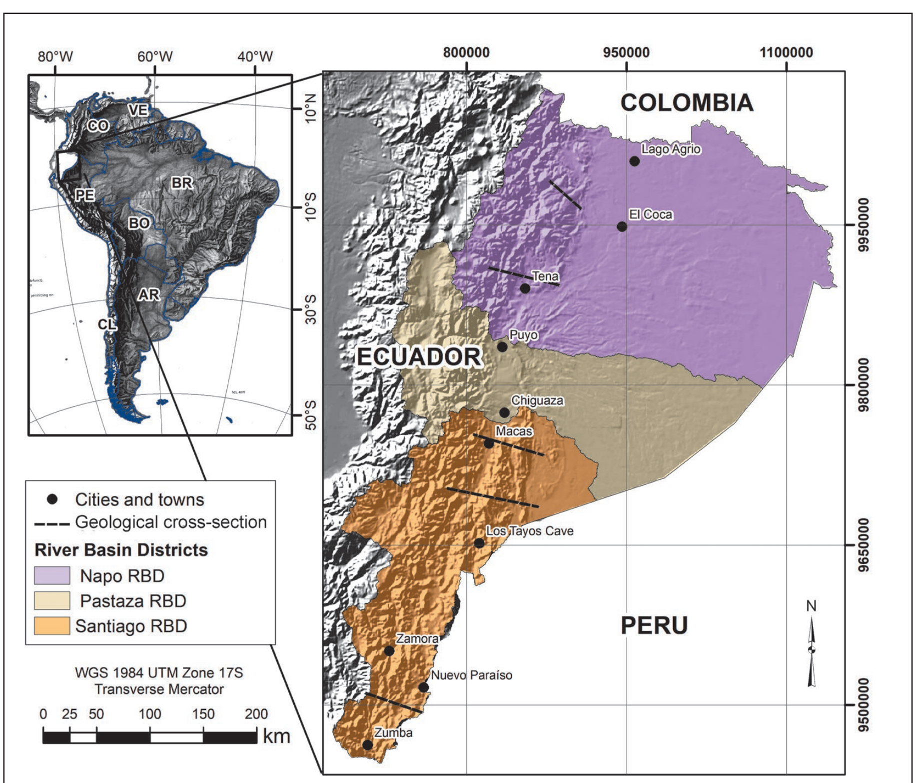

Fig. 1: Location map of the study area. Ecuadorian Amazon Basin and its three river basin districts (RBD). They were delineated according to the Ecuadorian Water Development Plan.

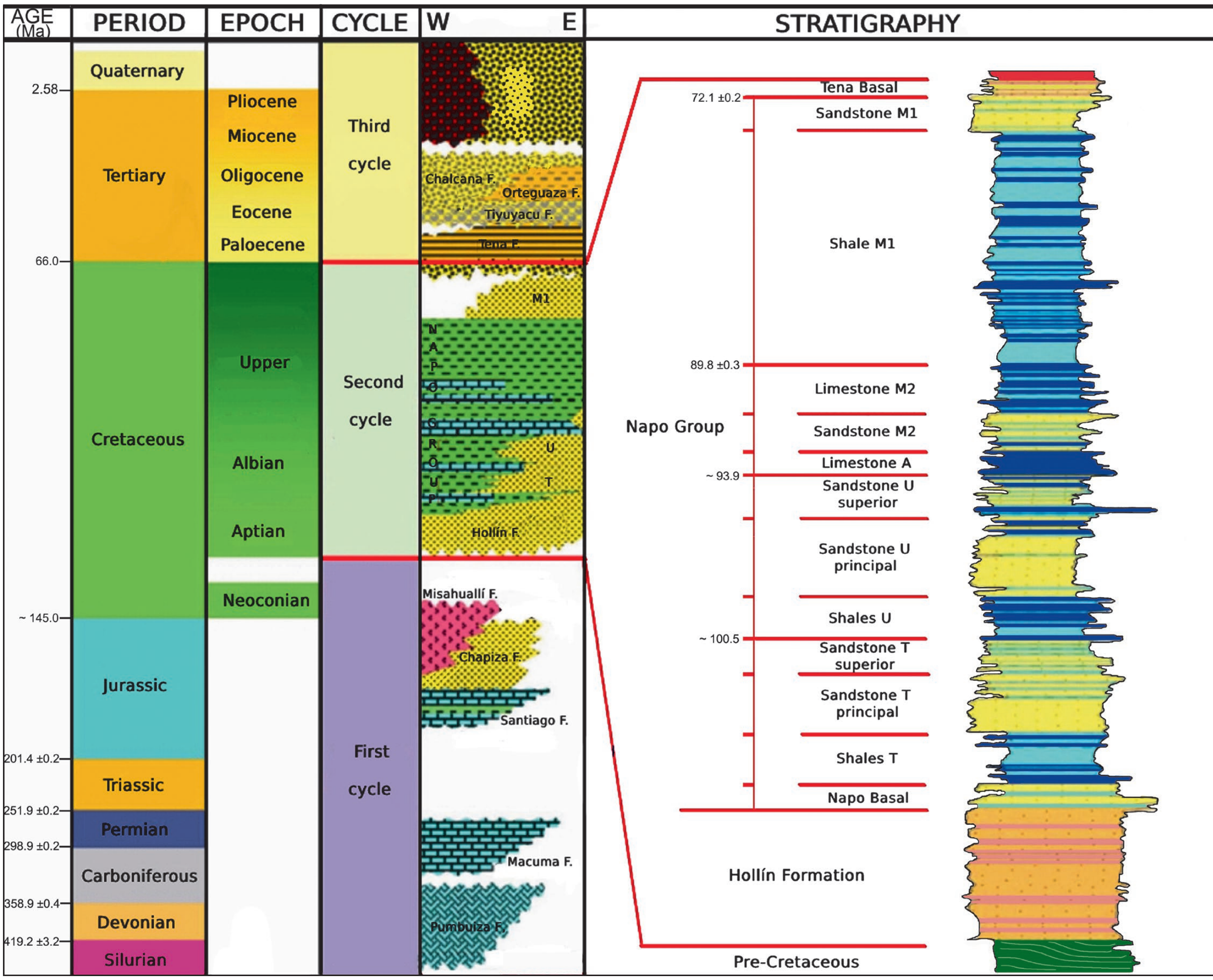

Fig. 2: Sedimentary cycles of the Cretaceous sediments of the Ecuadorian Amazon Basin. Adapted from Barragán et al. (2004), and Estupiñan et al. (2010).

normal faults. Conversely, in the northern region, the Sacha Formation serves as the lateral equivalent, characterized by shallow marine rocks and breccias.

Secondly, the Cretaceous period encompasses the stratigraphic sequence of the Hollín, Napo, and Tena formations. Within this period, the clastic sections of these formations reflect variations in eustatic levels during the Aptian and Maastrichtian epochs, suggesting a facies transition from east to west. The sedimentary environments range from continental fluvial settings to estuaries and shallow marine platforms. Of particular interest within the Cretaceous stratigraphy (see Figure 2) are the Napo limestones distinguished as A and M2 as described by Barragán et al. (2004), as shown in Figure 2. These limestones, deposited in a marine environment, are bounded by the Napo Medio shales and Napo Superior shales.

2. MATERIALS AND METHODS

2.1. REGIONAL DELINEATION OF THE KARST SYSTEMS

The regional delineation of karst systems initially involves conducting a qualitative analysis of multiple cartographic maps, including Geomorphology Maps, Geologic Maps, Digital Elevation Models, Drainage Maps, and Karst bodies maps (Constantin et al., 2019; Instituto Geográfico Militar, 2014). The aim was to spatially define the karst areas boundaries. Subsequently, this analysis was integrated with theoretical concepts of the unit

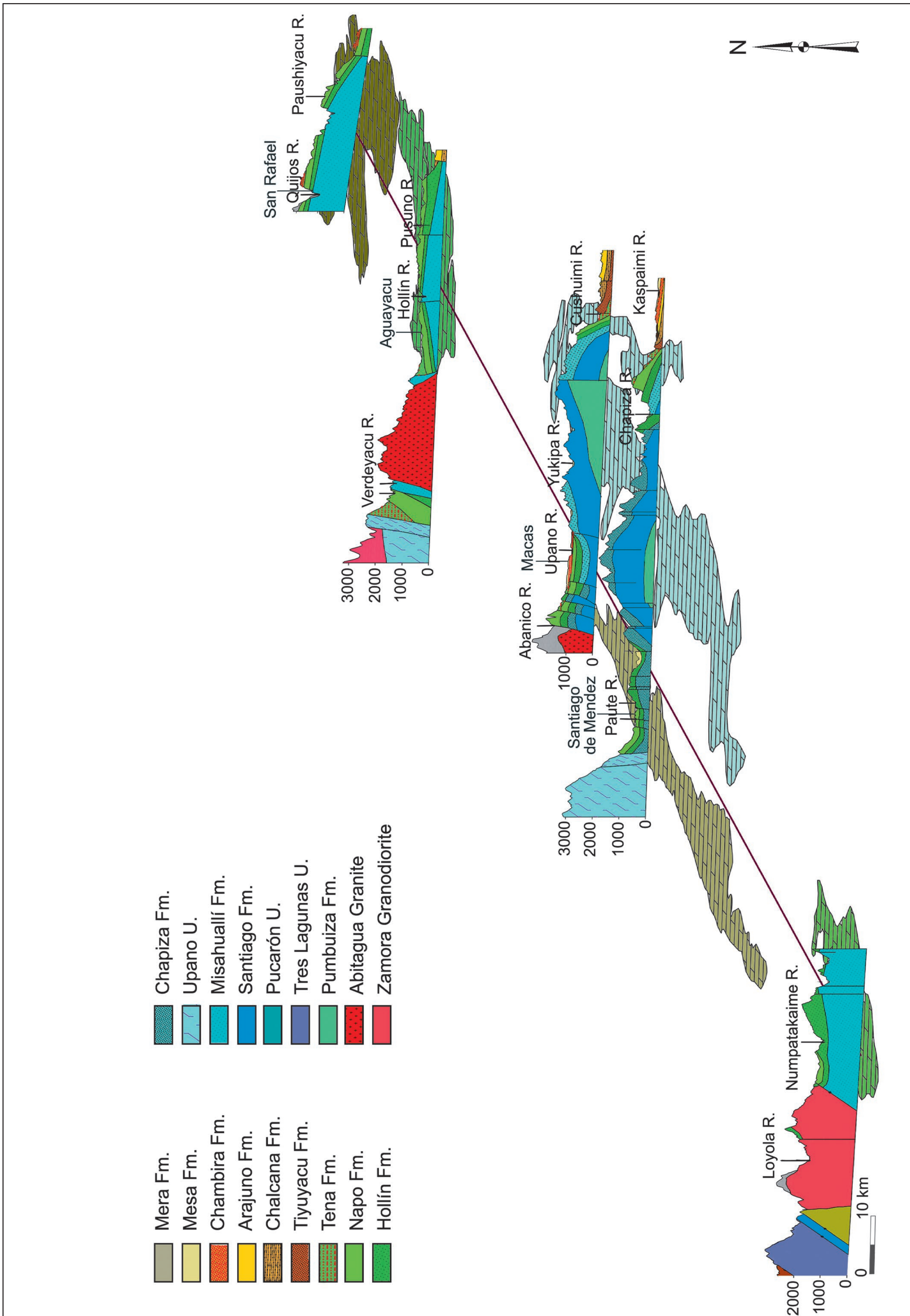

Fig. 3: Regional cross-sections over the five major karst systems in the investigation area. The major rivers and settlements are pointed out in the cross-sections. Their geographic location is included in Figure 1. Notice the vertical axis has been magnified five times with respect to the horizontal axis.

basin of gravitational groundwater flow systems (Flores et al., 2020; Kresic, 2006; Miklós et al., 2020; Onac & Van Beynen, 2021; Tóth, 2009) to establish the hydraulic boundaries of the karst aquifer systems in the Ecuadorian Amazon Basin using Geographic Information Systems (GIS).

The delineation process of the karst areas involves considering overlapping parameters within the same geographic location. This includes assessing the occurrence of calcareous lithology using geological maps at various scales (e.g., 1:1,000,000, 1:500,000, 1:50,000) (Instituto Geográfico Militar, 2014), identifying the location of karst structures and sedimentary geo-forms using the National Geomorphological Map (Instituto Geográfico Militar, 2014) and the National Landscape Map (Winckell et al., 1997), incorporating information regarding karst or fractured aquifer systems from the National Hydrogeologic Map of Ecuador (Pierre et al., 1982); and finally comparing the defined polygons with the existing information about karst bodies from the research conducted by the Instituto Geográfico Militar (2014), Constantin et al. (2019), Sánchez Cortez (2017) and Sánchez Cortez et al. (2022).

The hydrogeological relationships between the identified karst areas are analyzed through cross-sections (see Figures 1 and 3), outlining the spatial and structural relationships between the polygons. This analysis supplies the geological framework, which plays a key role in defining aquifer system geometry (Tóth, 2009). For this purpose, the ASTER Digital Elevation Model (DEM) with a cell size of 30 meters, obtained from Global Mapper, was used to interpolate profiles of chosen cross-section lines and assign corresponding elevation (Z) values. The geologic and structural features represented in the cross-sections were a combination of information sourced from cross-sections printed the geologic maps (Instituto Geográfico Militar, 2014), concepts derived from stratigraphy and structural geology, and relevant bibliographic references like Estupiñan et al. (2010); Gutiérrez et al. (2019), Hungerbühler et al. (2002), and Steinmann et al. (1999).

2.2. ESTIMATION OF DIFFUSIVE GROUNDWATER RECHARGE

The APLIS method operates under the assumption that the mean annual recharge available for the aquifer consistently maintains a proportional relationship with precipitation. This approach utilizes geological and geomorphological features to elucidate the spatiotemporal distribution of karst recharging, including Altitude (A), Slope (P), Lithology (L), Infiltration (I), and Soil (S), as established by Andreo et al. (2004). The acronym APLIS represents these variables.

2.2.1. Datasets

The information layers for each variable characterization are derived from open-source datasets, including the ASTER Digital Elevation Model (DEM) with a 30-meter cell size obtained from Global Mapper, the geological map of the Republic of Ecuador at a scale of 1:1000000, provide by Institute of Geology, Mining, and Metallurgy (Egüez et al., 2019). The geomorphological map is acquired from the interactive map of the Ministry of Water, Environment, and Ecological Transition (Ministerio de Ambiente, Agua y Transición Ecológica, 2024). Finally, the soil map, infiltration velocity, and coverage and soil use data are collected from the information system portal of the Ministry of Agriculture (Ministerio de Agricultura y Ganadería, 2024).

All layers are georeferenced in UTM coordinates and employing the WGS-84 17S datum. The information is undergoing processing using ArcGIS 10.3.7, employing the approach outlined by Andreo et al. (2004), , and Martos et al. (2015).

2.2.2. Characterization of the variables

The calculation of recharge rate values, which can be compared to those obtained through conventional techniques (refer to Table 6 in Andreo et al., 2004), is performed according to the following equation:

$$R = \frac{A + P + 3L + 2I + S}{0.9} \quad (1)$$

Where A represents altitude, P signifies slope, L denotes lithology, I stands for infiltration, and S represents soil ordinal values, and where the lithology (L) and infiltration (I) parameters are three and two times more significant than the other factors.

The altitude (A) and slope (S) maps are prepared using the 30 m DEM in the GIS environment. The altitude map is done at intervals of 300 m, and categorized into ten classes, following the distribution proposed by Andreo et al. (2004). Subsequently, the slope map (P) is categorized into 10 classes, as outlined in Table 1. Areas with gentle to flat slopes typically exhibit larger infiltration zones compared to steep, hilly areas. Therefore, in this aspect, areas with slopes below 3% are assigned the highest score, while areas with slopes above 100% receive the lowest scores (Entezari et al., 2020).

The lithology map (L) is categorized in five classes based on the geological maps of the study site, and considering its specific characteristics (refers to Table 1). The Misahuallí, Pumbiza, Llanganates series, and Cuyuja formations, composed of granite, shales, silts, and clays, have been assigned a value of 1. The Tena Formation, Chalcana, Chapiza Unit, and volcanic deposits of Sangay, consisting of shales, conglomerates, sandstones, breccias, basalts, plutonic, and metamorphic rocks, have been assigned a value of 2. Santiago, Quillollaco, Mesa, and Mera Fm., formed by alluvial fan deposits and conglomerates, are assigned a value of 3. The Tiyuyacu, Hollín, and Arajuno formations, consisting of alluvial terraces, conglomerates, and sandstones, are categorized with a value of 4. Lastly, the Macuma, Napo, and Santiago Formations, predominantly composed of limestone affected by karstification processes and fissures, are assigned a value of 7.

The infiltration map (I) is categorized in three zones including scarce, moderate, and abundant infiltration landforms (refers to Table 1), with rating of 1, 5, and 10 respectively. These designations are made based on geomorphology, lineaments density, infiltration velocity, and rock type. It is based on the knowledge that surface hydrology and groundwater are linked by intensive infiltration through joints, cracks, and sinkholes. Then, that in current assessment is considered the lineaments density obtained through image geoprocessing of the hillshade produced at a regional scale from the 30 m DEM (Abdullah, A et al. 2010).

For the soil map (S), one of the key elements to consider in this procedure is the type and thickness of the soil. For the research area, there were no soil maps based on the FAO categorization, which is often utilized with the APLIS approach (Farfán et al. 2010). The USDA Soil Taxonomy categories (2006) were used to assign the parameter values based on a site soil map, as indicated by the Ministry of Agriculture of Ecuador. Therefore, the standardization process was carried out under the bibliographic review of the database of the Ministry of Agriculture and the World Reference Base of the Soil resource (FAO, 2008), which provides a conceptual framework for the qualification, correlation, and international communication following the requirements of the APLIS method. In this context, vertisols, alfisols, ferralsols, nitisols, and andosols soils were assigned a weighting of 1, histosols and mollisoles a value of 4 (Espinoza et al, 2015), inceptisols and cambisols a value of 6, and entisols and regosols a value of 7.

After producing the required five parameter maps, the final APLIS model is prepared according to Equation 1. The average annual recharge rate is subsequently

Tab. 1: Weight of the five variables of the APLIS method adjusted to local conditions.

(A) Altitude (m)		(P) Slope %		(L) Lithology		(I) Infiltration landform		(S) Soil		(R) Recharge %	
Range	Rating	Range	Rating	Range	Rating	Range	Rating	Range	Rating	Class	Range
< 300	1	> 100	1	Shale, slate, siltstone, clay	1	Scarce infiltration landform	1	vertisols, alfisols, ferralsols, nitisols, andosols	1	Very low	< 20
300 - 600	2	100 - 76	2	Plutonic and metamorphic rocks	2	Moderate infiltration landform	5	histosols, mollisoles	4	Low	20-40
600 - 900	3	76 – 46	3	Alluvial sediments and conglomerates	3	Abundant infiltration landform	10	inceptisols cambisols	6	Moderate	40-60
900 - 1200	4	46 - 31	4	Gravel, sand, and colluvium	4			entisols, regosols	7	High	60-80
1200 - 1500	5	31 - 21	5	Fractured limestone, slightly karstified limestone	7					Very high	> 80
1500 - 1800	6	21- 16	7								
1800 - 2100	7	16 - 8	8								
2100 - 2400	8	8 – 3	9								
2400 - 2700	9	< 3	10								
> 2700	10										

categorized into five distinct intervals (refers to Table 1), with each interval assigned a corresponding category. For each parameter, there are ten ratings ranging from 1 (the lowest level of influence) to 10 (the highest level of impact) for various parameter sections, proportionate to their impact on the aquifer filling, and adapted to the conditions of the study area. This allows for the estimation of the refill coefficient (R) of the aquifer, also known as recharge rate for aquifers, which will be the result of this study.

3. RESULTS AND DISCUSSION

3.1. REGIONAL KARST BODIES

The assessment encompasses an extensive outcrop of calcareous rock blocks, spanning a vast surface area of 11112 km^2 and exhibiting an elongated NE-SW axis. The geometric arrangement of the hydrogeological systems corresponds with the geological evolution of the tectonic terrains, forming elongated belts of calcareous rocks oriented in an NE-SW direction.

From the analysis of the five regional cross-sections presented in Figure 3, two distinct hydrogeological units emerge as karst formations: (1) the limestone layers of the Medium Member of Napo Formation (KN) exposed on the uplifted blocks of the eastern side of the Ecuadorian Andean Mountain Range, and partially confined by the sandstones of the Hollín Formation (KH) and the shales of the Lower Member of Napo Formation (KN), and (2) the calcareous rocks of the Santiago Formation (JS), which are exposed in the Cutucú and Cóndor Ranges.

In the northern part of the study area, the Napo North System (1610 km^2) and the Napo South System (1361 km^2) are positioned around the Sumaco volcano, within the Napo RBD (CISPDR, 2016a) and the corresponding water basin. Currently, the Napo South System stands out as a particularly well-documented region compared to the other systems, primarily due to its significant tourism potential. In recent years, a geopark project has been in progress to showcase the distinctive geological environment of the area, encompassing both karst aquifer systems in Napo County (Jiménez-Iñiguez et al., 2022; Sánchez Cortez, 2017; Sánchez Cortez et al., 2022).

In the central part of the study area, two hydrogeological units are identified: the Upano System (1814 km^2) and the Los Tayos System (3952 km^2). The Upano System is situated within the Santiago River Basin District (RBD) (CISPDR, 2016c) and spans across the valley between the Eastern and Cutucú Mountain Ranges. It encompasses the Santiago River basin, covering areas in the counties of Morona Santiago and Zamora Chinchipe. On the other hand, the Los Tayos System is located within both the Santiago and Pastaza RBDs (CISPDR, 2016c, 2016b) and extends into Peru. This system forms an elongated body that runs parallel to the Upano System and stretches from the Cutucú Range into the Amazon Basin. It belongs to the Santiago and Morona River basins.

In the southern part, the Numpatakaime System (968 km^2) is located into the Santiago River Basin, within Zamora Chinchipe County, and extends into Peru (CISPDR, 2016c). While a comprehensive documented description of the area is currently unavailable, it is widely recognized as a popular tourist destination. The region's popularity is attributed not only to its rich biodiversity but also to its remarkable karst geological features.

The twelve isolated karst bodies, covering a total area of 1407 km^2, consist of individual elongated blocks of calcareous rocks scattered along the Eastern Mountain Range. These bodies, distinguished by their size and spatial arrangement, function as independent hydrological entities, displaying distinct hydraulic behavior. Consequently, they contribute to the development of unique areas with high recharge within diverse and complex aquifer systems.

The two identified hydrogeological units, Napo Medium Member and Santiago Formation, are integral components of five distinct regional karst systems and several isolated bodies (refer to Figure 4), situated within three of the ten River Basin Districts (RBD) delineated in the Ecuadorian National Plan of Integrated and Integral Management of Hydric Resources and Hydrographic Basin and Micro Basins. The relatively low thickness compared with areal extension, and transverse flow pathways, contribute to the hydrogeological behavior of the karst systems in the study area, featuring shallow hydrostatic levels and short transit times of water before discharging to the surface, thereby contributing to the development of superficial drainage systems as had been also pointed by Constantin et al. (2019).

The geo-tectonic evolution, explained by Barragán et al. (2004), and karstification processes have led to the division of the outcropping calcareous rocks into five major hydraulic systems and 12 isolated small individual blocks, all contributing to diverse and complex aquifer systems (see Figure 4). In this research, the major hydraulic systems were named based on their geographic and river basin locations. Starting from the north and progressing southward in the study area, the following systems are identified: Napo North, Napo South, Upano, Los Tayos, and Numpatakaime Karst System. Both, Los Tayos and Numpatakaime Aquifer Systems extend beyond the national borders of Ecuador, making them transboundary aquifer systems shared with Peru. Therefore, their management should be conducted through bilateral policies and agreements between the two countries.

3.2. SPATIAL DISTRIBUTION OF THE APLIS METHOD CHARACTERISTICS

The spatial distribution within the defined karst bodies of the characteristics of each variable used in the APLIS method involved mapping, analyzing patterns, and adapting weighting for the study site. Each map produced for the different variables is illustrated in Figure 5, constructed based on the range and rating summarized in Table 1. The area total was 11130 km^2, but the diffusive recharge was calculated for 92% of the total area (10285.4 km^2) of the Karst Aquifer Systems due to missing data in

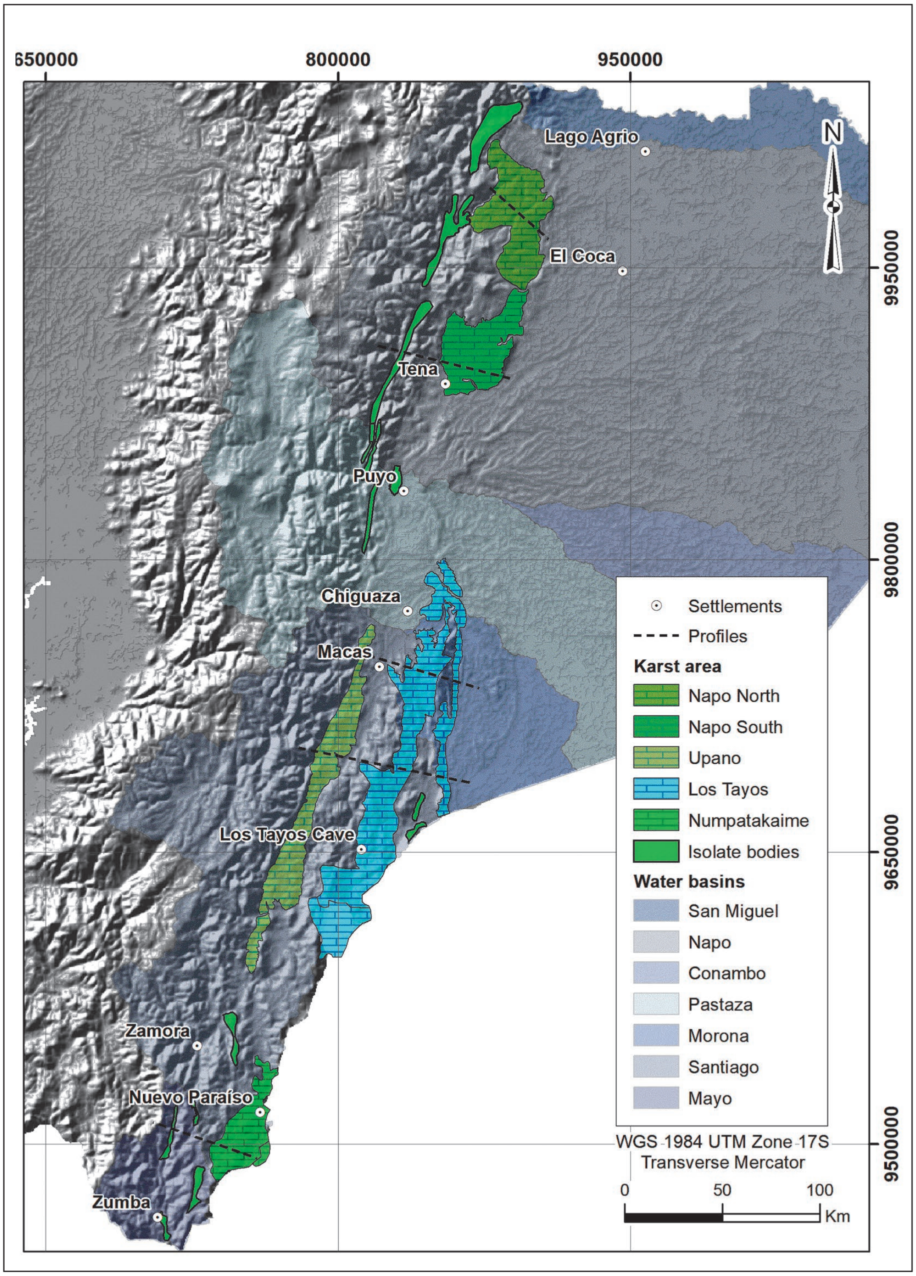

Fig. 4: Karst aquifer systems in the Amazon Region of Ecuador. Overview of the 11112 km^2 of karst bodies areas within the three RBD and their water basins.

the lithology, infiltration, and soil intrinsic variables of the method, as visible in Figure 5.

The altitude map of the study area shows that the maximum height is 5357 m above sea level (a.s.l.) while the minimum is 512 m a.s.l. Four altitude ranges, ranked as 3,4,5, and 6, collectively encompassed 81.29% of the study area (see Figure 6), distributed evenly from north to south (see Figure 5). Conversely, the remaining six altitude ranges covered the 18.81%, with the highest elevation situated in the northern region and the lowest located in the central region. The slope map (P) outlines slopes ranging from 2% to 97%. Five slope ranges, ranked as 3,4,5, 6, and 7, collectively encompass 80.03% of the study area. Conversely, the remaining five slope ranges cover the 19.97%, with the steeped slope found at north and the gentle slopes in the central area (see Figures 5 and 6).

The lithology (L) characteristic encompasses a variety of geological materials, as illustrated in Figures 5 and 6. These included granite, shales, silts, and clays, assigned a ranking of 1, and covering 16% of the area. Additionally, shales, conglomerates, sandstones, breccias, basalts, plutonic, and metamorphic rocks, that were assigned a ranking of 2, covered 18% of the area. The subsequent range combined alluvial fan deposits and conglomerates, assigned with a ranking of 3, occupy 20% of the area. Alluvial terraces, conglomerates, and sandstones, catego-

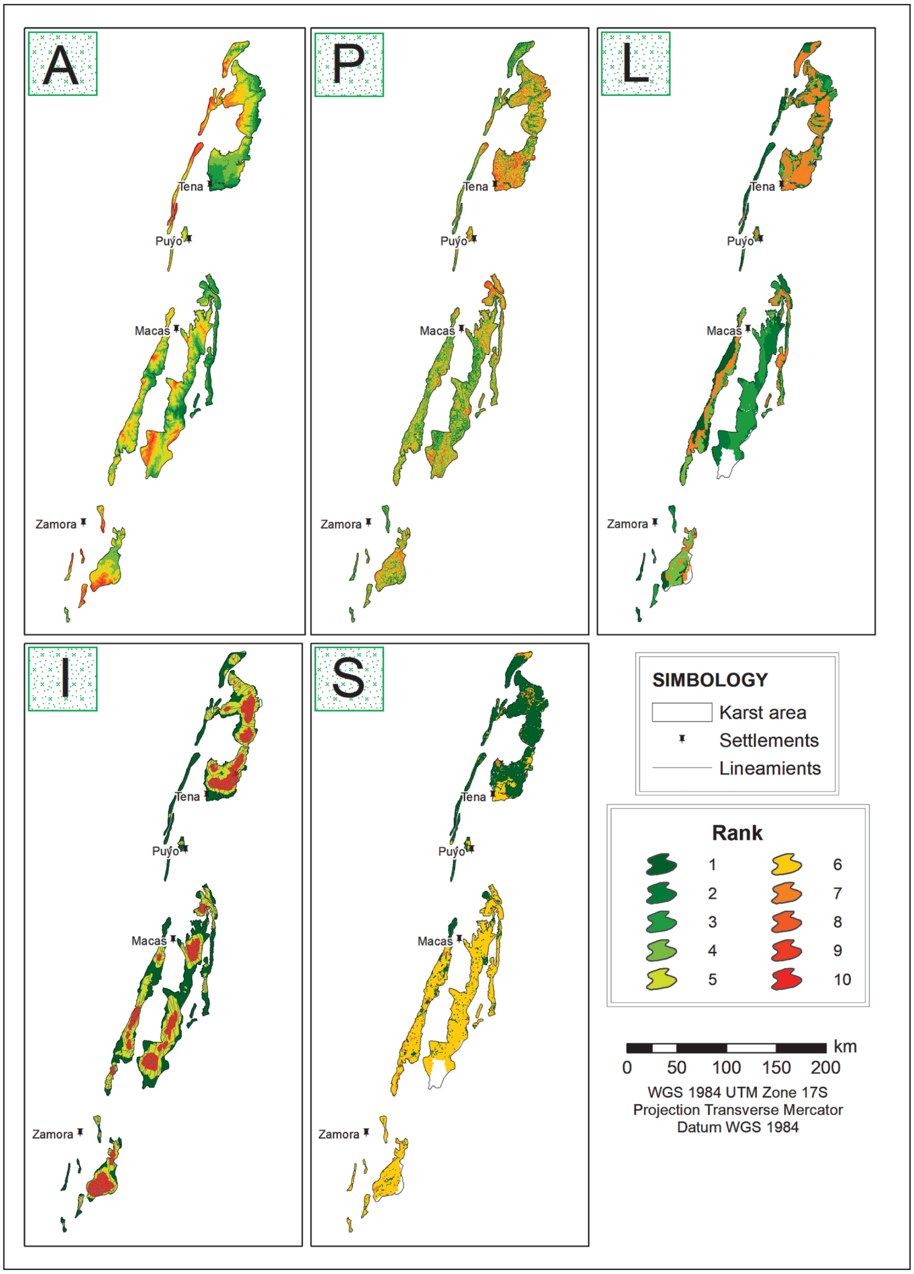

Fig. 5: Spatial distribution of the five intrinsic variables of the APLIS method within the regional karst bodies in the Amazon Region of Ecuador.

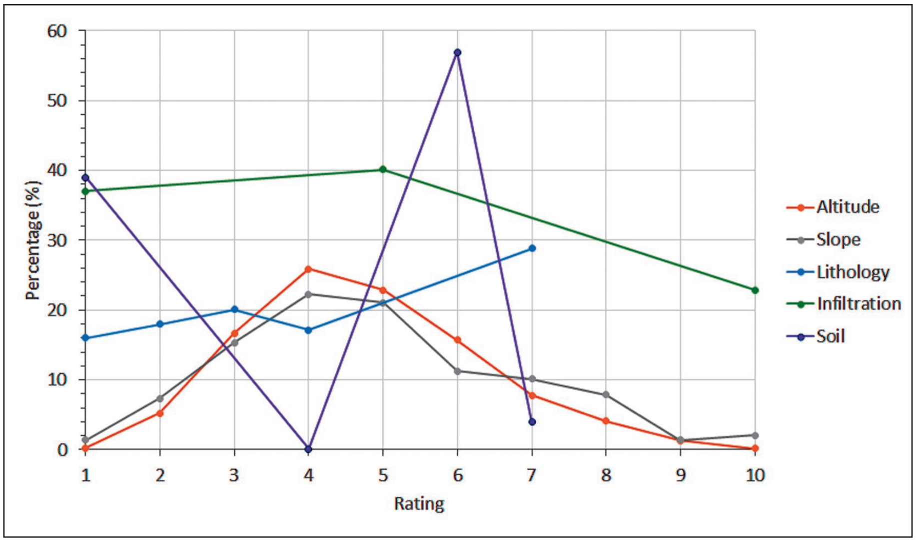

Fig. 6: Percentage of covered area by rank in each one of the intrinsic characteristics of the APLIS method.

rized with a ranking of 4, covered 17%. Finally, 23% of the area falls within the rank 7, predominantly composed of limestone affected by karstification.

The infiltration (I), classified into three ranges, delineates the area as follow: 37.06 % of scarce infiltration, 40.09% of moderate infiltration, and 22.83% by abundant infiltration landforms (see Figures 5 and 6), with corresponding ranking values of 1, 5, and 10. Finally, among the four ranks of soil (S) variables, two stand out as predominant in the area. Rank 1 soil types largely occupy the northern region, constituting 38.99% of the study area. Additionally, rank 6 predominantly covered from central to southern region, encompassing 56.94% of the study area.

Recharge rate that receives rainfall on the surface of karst areas ranging from a minimum of 11.11% to a high of 71.11%. The results of the analysis of groundwater recharge rates show that there are 4 levels of groundwater recharge in the area of study, namely very low, low, moderate, and high as shown in Table 2, and spatially distributes as illustrated in Figure 7. The summary statistics table (Table 2) shows that the low recharge class (20 to 40%) dominates over the other classes, occurring in 48% of the Karst Systems area. This class is associated with the presence of impermeable volcanic rocks, shales, silts, and clays, meanwhile, the moderate recharge class (40 to 60%) is characterized by the presence of semi-permeable materials, such as limestone, breccias or conglomerates, moderate slopes, and sparse edaphic cover, occupied 37%. Conversely, the very low class (< 20%) occurs only in 5% of the study area, mainly in locations dominated by river beds composed of clayed materials, and usually consider as discharge areas of the hydrogeological systems.

In areas characterized by a high recharge class (60 to 80%), the dominant features are higher altitudes, gentle slopes, and the presence of limestone rock. These areas exhibit forms of preferential infiltration, where karstification or fissuring of the rock is commonly observed due to its chemical characteristics and the high precipitation in the region. However, such high recharge areas are limited, covering only 2% of the total area with a maximum value of 71.11% of diffusive recharge. Notably, the very high recharge rate does not occur anywhere within the study area.

Tab. 2: Diffusive recharge summary for each class.

Diffusive recharge		**Summary Statistics**				**Covered area**	
Class	(%)	Min	Max	Mean	Std. d.	(km²)	(%)
Very low	< 20	11.11	20	17.94	1.74	539.01	5
Low	20-40	21.11	40	31.44	5.56	5364.91	48
Moderate	40-60	41.1	60	48.57	5.30	4072.22	37
High	60-80	61.1	71.1	63.28	1.81	309.23	2
Very high	> 80	--	--	--	--	--	--
					Total calculated area	**10285.4**	**92**

Appropriate management actions can be planned in the context of conservation and control of water resource use by taking into consideration the recharge rate in the Ecuadorian Karst Systems, Amazon Basin. This means that the rate at which precipitation recharges will strictly regulate how much water is used in the area; this is especially true when the rate of recharge is low.

4. CONCLUSIONS

This study delves into the intricate dynamics of karst aquifer systems within the Ecuadorian Amazon Region for the first time, by calculating diffusive recharge rates through the APLIS method. The spatial distribution map generated describes varying recharge percentages across different Amazon areas, shedding light on the hydrogeological nuances of the region. This provides a foundational understanding of the geological and hydrological features governing the karst systems by identifying distinct hydrogeological units, such as the limestone layers

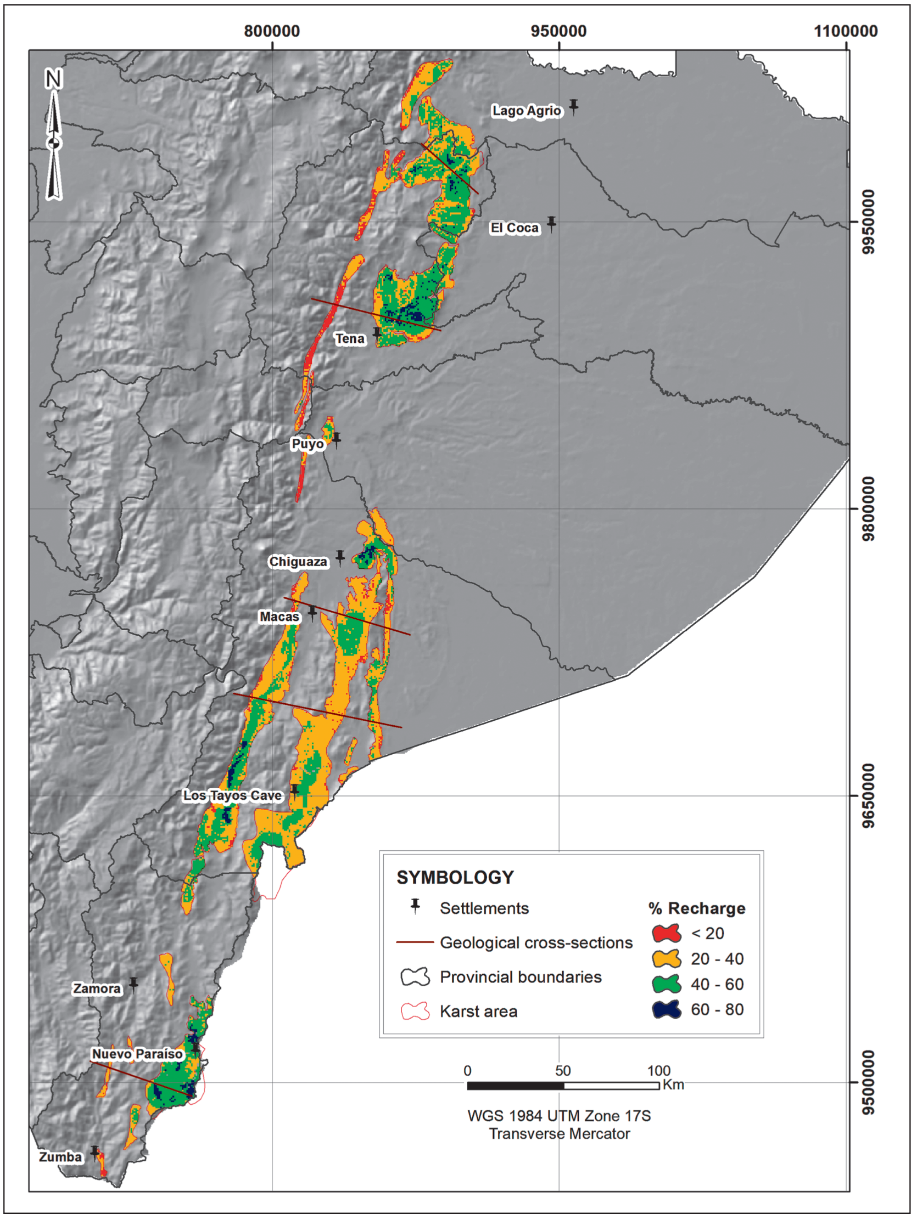

Fig. 7: Diffusive recharge spatial distribution map.

of the Medium Member of the Napo Formation, and the calcareous rocks of the Santiago Formation.

The generated data provides a hydrogeological perspective aimed at delineating the geometric boundaries of karst systems on a regional scale and calculating the percentage of diffusive recharge. This approach yields insights into the hydrological dynamics of the karst systems within the Ecuadorian Amazon region, particularly regarding their potential as sources of drinking water.

The local hydraulic delineation of the karst aquifer system can significantly contribute to environmental conservation plans for the delicate biological environments that develop within them. It serves as a complement to speleological investigations and aids in emphasizing the importance of establishing and maintaining protection zones, such as natural parks and reserves, to safeguard these unique and valuable ecosystems. In addition, as a starting point for future research, it serves as a tool to identify connections with possible aquifer zones, where quality and quantity can be maintained within the aims Ecuadorian Water Development Plan and its River Basin Districts.

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