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FIRST STEPS TO UNDERSTANDING INTRINSIC VULNERABILITY TO CONTAMINATION OF KARST AQUIFERS IN VARIOUS SOUTH AMERICAN AND CARIBBEAN COUNTRIES

PRVI KORAKI K RAZUMEVANJU NOTRANJE RANLJIVOSTI KRAŠKIH VODONOSNIKOV ZA ONESNAŽENJE V JUŽNOAMERIŠKIH IN KARIBSKIH DRŽAVAH

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Abstract UDC 502.1:504.5:556.33(8+729)

Rogério Tadeu de Souza, Luiz Eduardo Panisset Travassos, Olga Susana Heredia, Mariana Alicia Paparas, Silvia Alejandra Sicilia, Franco Urbani Patat, Rosa María Valcarce Ortega, Moraima Fernández Rodríguez, Francisco Bautista, Liane Gamboa Corrales, Nathalia Vanessa Uasapud Enríquez & Yameli Aguilar Duarte: First Steps to understanding Intrinsic Vulnerability to Contamination of Karst Aquifers in Various South American and Caribbean Countries

Protecting groundwater in karst aquifers is extremely important. Vulnerability maps can greatly help proper decision making based on physical environmental attributes that influence how easily a contaminant applied to the land surface can reach groundwater due to anthropogenic activities, and the properties of the contaminants. Methods for determining vulnerability based on the COST Action 620 Approach, when applied in the study area, may lead to contradictory results. The main purpose of this study is to provide an overview of academic research on intrinsic karst aquifer vulnerability methodologies applied in South American and Caribbean countries. Secondly, it describes studies related to karst aquifers that, in some cases, lack specific information on intrinsic vulnerability. The objective is to encourage and to help develop specific methods for determining karst vulnerability in these regions. To achieve these purposes, a systematic literature review was conducted including studies conducted at institutions such as universities, national water institutes, and by geological services. Several methods have been used in the region such as COP, DRASTIC, RISK, EPIK, PI, PaPRIka, and the Slovene Approach. And some attempts have been made to develop a specific methodology that best suits the specificities of the region's karst aquifers. South America and the Caribbean have almost 5 % of the world´s carbonate rocks. Some countries have large extensions of their territory covered by karst rocks, such as Peru, 15.4 %; Cuba, 67 %; and Mexico 25.29 %. Estimates indicate that more than 10 million people use water from karst systems in Mexico. In Cuba, 33 % of all available water volume originates from groundwater, and 91.51 % from karst aquifers. In Mexico, 13 studies have been conducted on the importance of karst aquifers, which mostly address the Yucatan Peninsula, followed by Brazil (9 studies), Cuba (5), Colombia (1) and Peru (1). Information about the theme is scarce in most of the other countries in the region. Some studies have incongruent results given the regional characteristics of tropical karst.

Keywords: South America, Caribbean, groundwater, intrinsic vulnerability, carbonate rocks.

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Rogério Tadeu de Souza, Luiz Eduardo Panisset Travassos, Olga Susana Heredia, Mariana Alicia Paparas, Silvia Alejandra Sicilia, Franco Urbani Patat, Rosa María Valcarce Ortega, Moraima Fernández Rodríguez, Francisco Bautista, Liane Gamboa Corrales, Nathalia Vanessa Uasapud Enríquez & Yameli Aguilar Duarte: Prvi koraki k razumevanju notranje ranljivosti kraških vodonosnikov za onesnaženje v južnoameriških in karibskih državah

Varovanje podzemne vode na kraških vodonosnikih je izjemno pomembno. V veliko pomoč pri pravilnem odločanju na podlagi dejanskih okoljskih značilnosti, ki vplivajo na to, kako zlahka lahko onesnaževalo, uporabljeno na površini tal, zaradi antropogenih dejavnosti in lastnosti onesnaževal doseže podzemno vodo, so lahko karte ranljivosti. Z metodami za opredelitev ranljivosti, ki temeljijo na pristopu COST Action 620, se lahko pri uporabi na proučevanem območju pridobijo nasprotujoči si rezultati. Glavni cilj te študije je zagotoviti pregled akademskih raziskav o metodologijah za ugotavljanje notranje ranljivosti kraških vodonosnikov, ki se uporabljajo v južnoameriških in karibskih državah. Poleg tega je podan opis študij, povezanih s kraškimi vodonosniki, pri čemer v nekaterih primerih ni specifičnih informacij o notranji ranljivosti. Cilj je spodbuditi in pomagati pri razvoju specifičnih metod za opredelitev kraške ranljivosti v teh regijah. Za dosego teh ciljev je bil opravljen sistematičen pregled literature, ki je vključeval študije, izvedene v institucijah, kot so univerze, nacionalni inštituti za vode in geološke službe. V regijah je bilo uporabljenih več metod, kot so COP, DRASTIC, RISK, EPIK, PI, PaPRIka in slovenski pristop. Poleg teh je bilo nekaj poskusov za pripravo specifične metodologije, ki bi najbolje ustrezala posebnostim kraških vodonosnikov v regijah. V Južni Ameriki in na Karibih je skoraj 5 % vseh karbonatnih kamnin na svetu. V nekaterih državah so veliki predeli prekriti s kraškimi kamninami, na primer v Peruju 15,4 %, na Kubi 67 % in v Mehiki 25,29 %. Po ocenah več kot 10 milijonov ljudi v Mehiki uporablja vodo iz kraških sistemov. Na Kubi 33 % vse razpoložljive količine vode izvira iz podzemne vode, 91,51 % pa s kraških vodonosnikov. V Mehiki je bilo opravljenih 13 študij o pomenu kraških vodonosnikov, s katerimi so obravnavali večinoma polotok Jukatan ter Brazilijo (9 študij), Kubo (5), Kolumbijo (1) in Peru (1). V večini drugih držav v regijah je informacij o tej temi malo. V nekaterih študijah so glede na regionalne značilnosti tropskega krasa rezultati neusklajeni.

Ključne besede: Južna Amerika, Karibi, podzemne vode, notranja ranljivost, karbonatne kamnine.

1. INTRODUCTION

1.1. BACKGROUND

Karst areas play an important role in society worldwide. They have great relevance in the supply of drinking water in various regions. For example, 50 % of the drinking water in Austria and Slovenia comes from a karst aquifer (Zwahlen, 2004).

Yet, karst areas are extremely sensitive to human pressures and karst aquifers present great complexity in how the recharge, storage and transmission of subterranean water (Gunn, 1985; Ford & Williams, 2007; Goldscheider & Drew, 2007), making them more vulnerable to potential contamination. Karst areas usually have thin pedological coverage (Zwahlen, 2004; Zhang et al., 2019; Jiang et al., 2019) and recharge is concentrated through sinks, which indicates the systems have high natural vulnerability and need special protection. Finally, in addition to their economic, historic and environmental importance, these regions often have incomparable scenic beauty.

In association with efforts to protect this important resource, in the late 1960s and early 1970s, in France, Albinet & Margat, 1970 described karst regions where water supplies suffer from contamination as vulnerable.

Definitions of vulnerability were proposed by the European Cooperation in Science and Technology organization through COST Action 620, according to Goldscheider et al., 2000. Intrinsic vulnerability is the term used to define the vulnerability of groundwater to contaminants generated by human activities and it considers the geological, hydrological and hydrogeological characteristics of a region. However, it does not consider the nature of the contaminant.

Several methods have been used to assess the intrinsic vulnerability of karstic aquifers and different methods when applied to the same area may yield different results (Gogu et al., 2003; Vías et al., 2005; Ravbar & Godscheider, 2009; Plan et al., 2009; Polemio et al., 2009; Doummar et al., 2012; Gustaldi et al., 2014). Iván and Mádl-Szonyi, 2017 present an overview and evolution of methods to determine karst vulnerability in which the EPIK (Döerfliger et al., 1999), PI (Goldscheider et al., 2000), COP (Vías et al., 2006) methods are the most used, having been created for application in temperate climate countries, and most existing methods used to evaluate aquifer vulnerability lack proper attention to the importance of a soil's physical and chemical properties (Heredia & Cirelli Fernandéz, 2008).

The physical, chemical, and biological processes that affect the properties of the contaminants require direct measurement of the attenuation capacity and protection of groundwater and, therefore, of how vulnerable an aquifer is to potential contaminants (Vías, 2005). Although many researchers have conducted case studies of natural attenuation in groundwater few studies have focused on soil, especially tropical clayey soil (Mulligan & Yong, 2004). It is important to emphasize that the composition of soil minerals plays an important role in the interaction between surface water and groundwater and on the geochemical characteristics of water sources, which primarily reflect their hydrological interrelationships (Gat, 1980). There is little research into the need for environmental protection from soil contamination in the tropics (Hartemink, 2002). Soil properties such as thickness, porosity, and permeability greatly affect the residence time of percolating water and/or contaminants (Ravbar & Golsdscheider, 2007). There are differences between European karst soils and tropical karst soil. Tropical soil is predominated by Oxisols with kaolinite clay mineral (Fassbender, 1994), and is very acid (Lal & Sanchéz, 1992) and deep (Souza, 2020). Durn, 2003 found that "Terra Rossa Soil" in the Mediterranean region has neutral pH, thick accumulation in the karst depressions, and is shallow outside of the depressions, with a predominance of clay minerals constituted by smectite vermiculite in the "Terra Rossa" soils originated by eolian dust from the Sahara as found in Morocco, Israel, Turkey, Spain, Greece, Portugal and Italy.

South America and the Caribbean have nearly 5 % of the world's carbonated rocks (Goldscheider et al., 2020), and some countries have large extensions of their territory covered by karst rocks, such as Cuba 67 % (Vázquez et al., 2019) and Mexico 25 % (Goldscheider et al., 2020). Information on the applicability of methods to determine karst vulnerability in Latin America and the Caribbean is extremely scarce, and the current state of studies in this field in these countries is unknown. To fill this gap, the purpose of this study is providing an overview of academic research on intrinsic vulnerability studies that have been conducted in the region, with the understanding that the development of a specific methodology to be applied in Latin America and the Caribbean depends primarily on such a survey. Secondly, in some cases, this paper describes studies related to karst aquifers, considering the lack of specific information on intrinsic vulnerability. Karst areas in various countries in South America and the Caribbean, including Brazil, Argentina, Venezuela, Colombia, Ecuador, Cuba, Mexico and Peru have been considered in this study, as a first step to understanding the theme in the region. For other countries, authors have no information about studies conducted, at times because the information is not public. The authors hope that researchers in the region will join the efforts of this group and contact them to support future efforts to understand this theme in the region. Several researchers from the continent participated in the survey, providing important information on the subject in their respective countries. It is noteworthy that this type of research about this theme is unprecedented in the continent.

It should be noted that methodologies based on COST Action 620, although it was developed especially for temperate climate countries, were the most applied until now in the region. Therefore, this reassessment is extremely important to allow developing an accurate scientific understanding of the application of this methodology in countries with predominantly tropical climates, considering that climate is an important factor in soil formation. These countries face the challenge of working to protect this important resource, particularly by increasing awareness of the importance of the protective layer in the vadose zone, the soil. Infiltration and propagation of pollutants into groundwater is very different in tropical than in temperate karst regions because of differences in thickness, mineralogy, and the predominance of clay minerals, leading to differences in the natural attenuation of pollutants (Souza, 2020). Methodologies that recognize the importance of soil characteristics for the protection of karst aquifers and the intrinsic vulnerability of karst aquifers is also presented by Aguilar et al., 2016b, Popescu et al., 2019 and Souza, 2020. Karst areas covered by a soil layer have significant differences (Gunn, 1985) in terms of protection, recharge and storage (Berthelin et al., 2020). A study conducted by Nguyet & Goldscheider, 2006 showed the importance of modifying methodologies for application in tropical karst regions and where data is scarce. The authors used less parameters in the methodology, it is necessary to emphasize that the quantity of parameters used in intrinsic vulnerability modeling methodologies are not the object of greater or lesser assertiveness of the results (Foster et al., 2013), but related of the quality of the geology, hydrogeology and hydrology data of the studied region.

1.2. STUDY AREA

This study examines South American and Caribbean countries covered by carbonate rocks (Figure 1). Figure 1 depicts carbonate continuous and discontinuous rocks, with first term used to describe small patches or thin strips of non-karst surfaces that are too small to be displayed on the generalized map, compared to original non-generalized ones. The lower threshold considered for classifying continuous carbonate rock observed was generally larger than 65 % among the polygons, while the term "discontinuous" was used where carbonate rock polygons contain many tiny, scattered or ramified polygons that cannot be displayed individually on the generalized map (Chen et al., 2017).

Most of the study area is characterized by karst partially covered by a thick soil mantle and significant

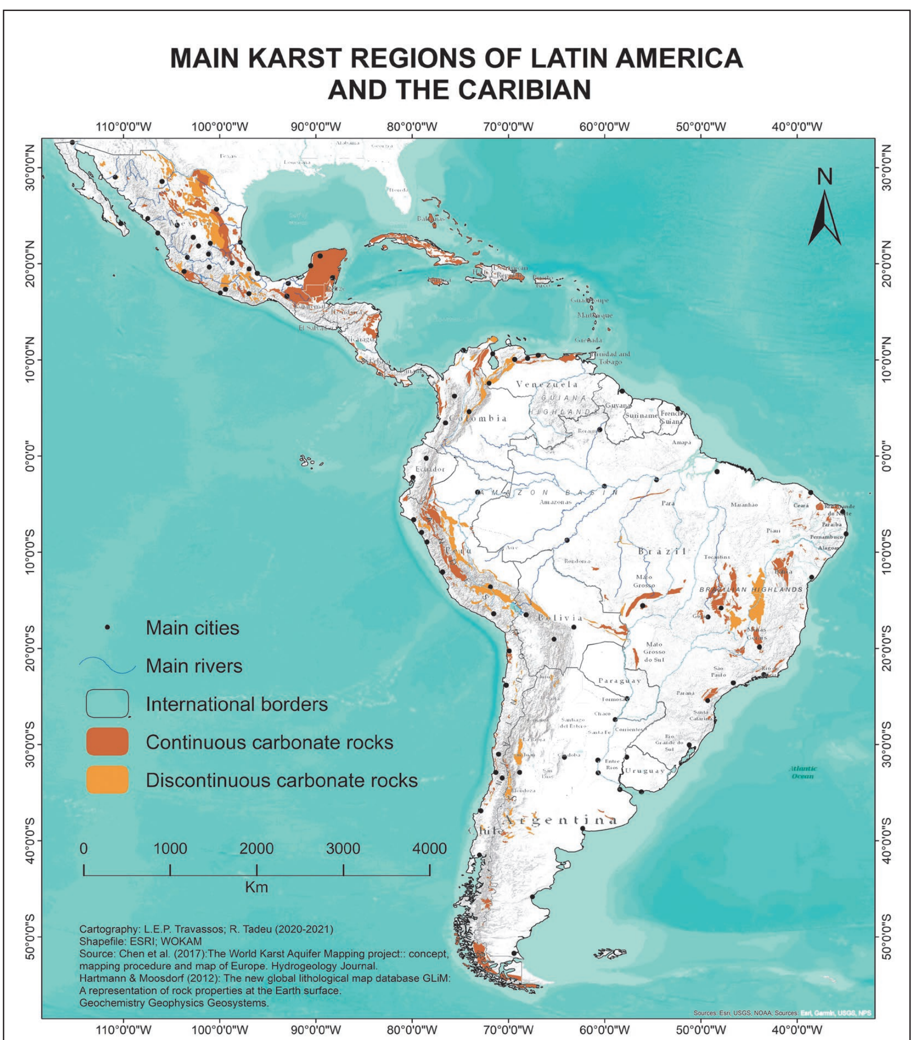

Figure 1: Main karst regions of South America and the Caribbean.

limestone outcrops. This study sought to understand and explore the level of knowledge, previous studies and the methodologies they used, and their applicability in different countries and karst environments in South America and the Caribbean to analyze the intrinsic vulnerability of karst aquifers in carbonate rocks.

2. METHODS

To achieve the proposed objective, a systematic literature review of the available information was conducted; including studies done at institutions such as universities, national water institutes and geological services, among others in the countries that are the object of the research, to identify and list potential researchers working with the theme and the quantity of studies in the object area. In addition, researchers who are references in their countries for karst and hydrogeological studies were consulted.

The methodology proposed for the data analysis comprises a sequence (see Figure 2) that allowed the analysis to be carried out.

The maps were created based on shape files from the WOKAM project (Chen et al., 2017; Goldscheider et al., 2020) and the sites where vulnerability assessment were conducted are depicted in the maps with local information for each country studied. Territories with karst areas from Venezuela, Colombia and Ecuador were measured using polygon tools in Arc GIS® Desktop by ESR (version 10.8.2) and Global Map (version 23.1).

3. FIRST STEPS TO UNDERSTAND INTRINSIC VULNERABILITY TO CONTAMINATION OF KARST AQUIFERS IN SOUTH AMERICAN AND CARIBBEAN COUNTRIES

3.1. BRAZIL

The Brazilian National Water Agency (Oliveira et al., 2010) reported that 39 % of Brazilian municipalities are supplied exclusively by groundwater, while 14 % use surface and underground water sources. The remaining 47 % depend on surface sources alone and estimated groundwater usage is around 17.7 % (Hirata et al., 2019).

It is estimated that 3.7 % of Brazilian territory is covered by karst (Goldscheider et al., 2020). Therefore, the importance of karst aquifers is undeniable (Travassos, 2019). Regarding Brazilian carbonate terrains, Sallun Filho & Karmann, 2012 emphasize that although it is possible to find caves in siliciclastic rocks and Precambrian iron formations, known generically as Banded Iron Formation-BIF, most of the karst and the largest caves are in carbonates. Also, for these authors, the deposition of carbonate rocks in the country occurred in the Proterozoic, predominantly in the Neoproterozoic period, and were consolidated in cratonic areas and associated folding bands, mentioned by Travassos (2019). The carbonate Brazilian karst areas and studies developed are depicted in Figure 3.

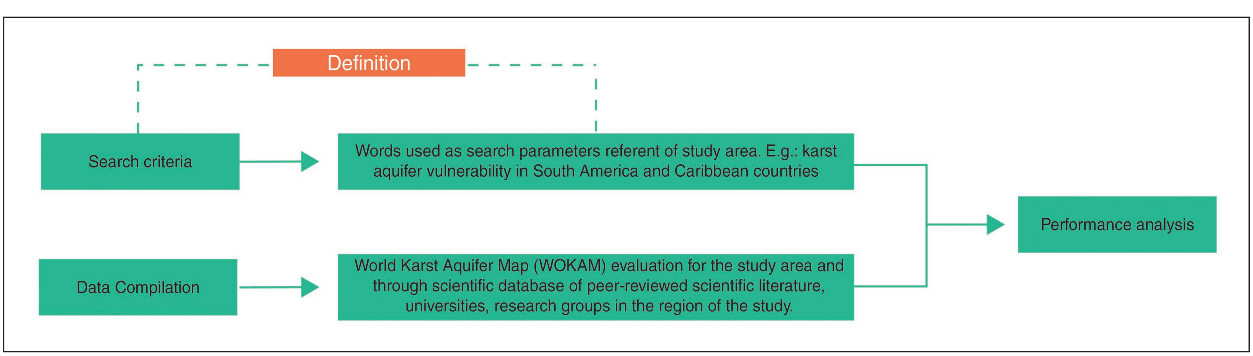

Figure 2: Scheme of the methodology applied in this study.

Among the Brazilian karst areas, the Lagoa Santa region, located approximately 35 km north of the city of Belo Horizonte in Minas Gerais state, is one of the most important in Brazil and one of the most studied (Auler & Pessoa, 2020; Meneses, 2003; Berbet-Born, 2002).

Brazilian tropical karst has significant differences from Mediterranean European karst (Souza, 2020). Travassos (2019) highlights that, in a tropical climate, the genesis of karst features of silicate karst are influenced by organic matter, such as guano, hummus, and animal remain that increase the acidity of rainwater. Furthermore, alkaline water (pH>10) is quite aggressive to silicates. It is noteworthy that alkaline conditions are more common in deep waters, which would form hypogenic karst. However, current methodologies created by the COST Action 620 approach do not always apply well to regional characteristics and parameter adaption are necessary (Moreno Gómez et al., 2018). Studies conducted by various authors (Souza, 2020; Valcarce et al., 2020; Moreno Gómez et al., 2019; Gainza et al., 2019; Moreno Gómez et al., 2018; Aguilar et al., 2016) in South American and Caribbean countries demonstrate the need to adapt methodologies that are based on European conditions.

Until now, in Brazil, the COP and EPIK methodologies have been the most applied. Nossa, 2011 carried out the first application of the COP methodology in the country. This author applied the original methodology to assess the vulnerability of the Salitre karst aquifer, which is located in the north-central region of the state of Bahia, in the municipalities of Irecê and Lapão. In the same karst aquifer, Gasser, 2017 applied the same original methodology but in the municipality of Cafarnaum, Bahia. Finally, Lima, 2019 applied the COP and PI in the same Salitre aquifer but in the Una-Utinga Basin. It is noteworthy that hydrochemical analyses accompanied all the works conducted in the Salitre aquifer.

Tayer (2016) carried out another application of the original COP methodology in the Karst Environmental Protection Area of Lagoa Santa (EPA Lagoa Santa Karst), Minas Gerais, and made a small modification to account for the vegetation parameter. This author applied the methodology used by Leyland, 2008 by modifying the indices that gave rise to the final vulnerability map, without modifying the final assessment.

The first study carried out in South America and the Caribbean to apply the COP methodology with the necessary adjustments to account for the protective

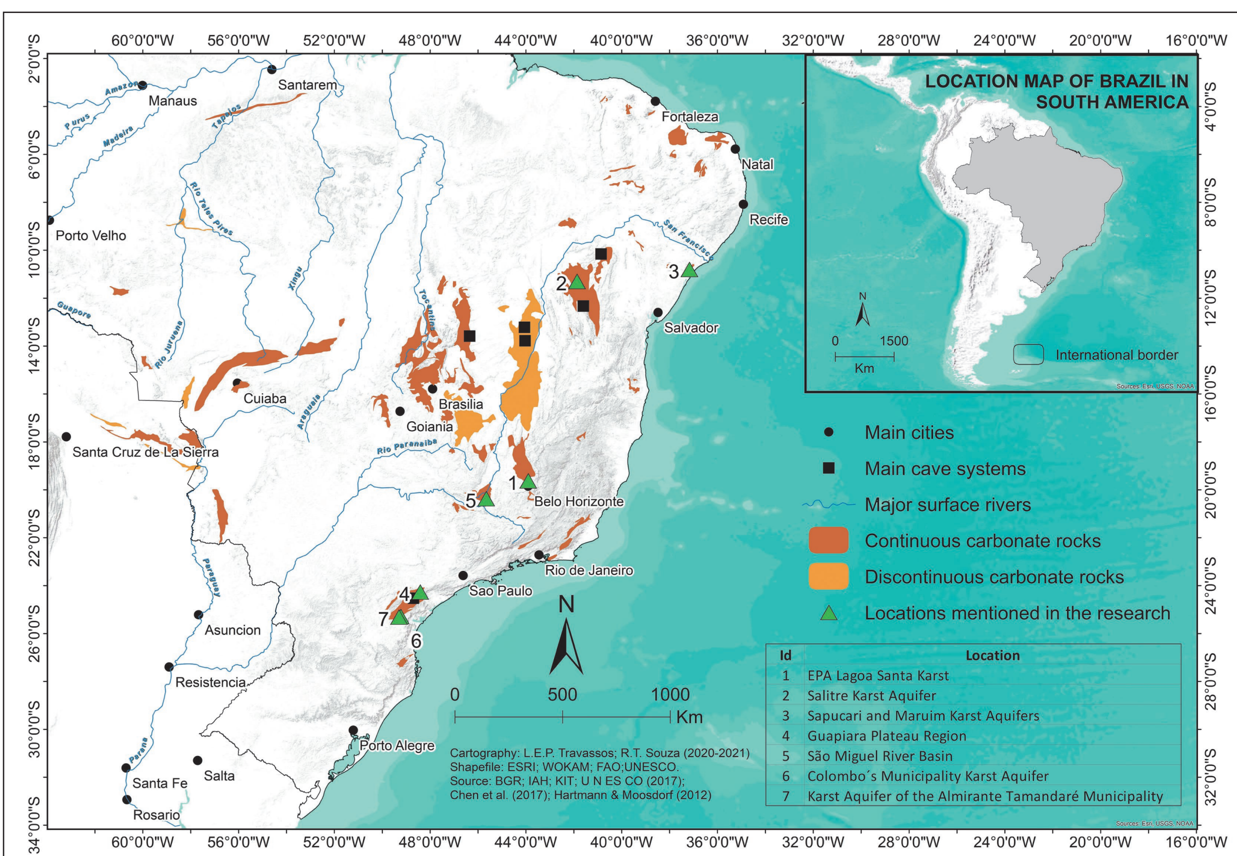

Figure 3: Location of the main Brazilian karst areas and sites where intrinsic vulnerability methods were developed.

layer of the aquifer in a humid tropical region, specifically, soils, was developed by Souza (2020) in the karst region of Lagoa Santa. Souza modified this method to consider the specificities of this layer that naturally attenuate potential surface contamination. The main reason for the adaption was that the soil thickness layer at the site is rarely less than 1 m with a clayey texture, providing high protection to the aquifer according to the O_s subfactor presented in the COP method, in addition the O_L subfactor is not relevant. Souza also modified the scales of the final vulnerability indices considering the characteristics of the two different karsts in relation to the original and modified methodology (suitable to tropical humid karst conditions) for comparison purposes. The outcomes displayed no congruence when applied to the original and modified COP method with regional humid tropical karst characteristics. In the original method, a very low vulnerability classification was found for 64.88 % of the region, a low classification in 28.55 %, moderate in 6.11 %, high in 0.42 % and very high for 0.04 %. Meanwhile, in the modified method a very low vulnerability class was found in 0.29 %, a low classification in 38.19 %, moderate in 44.29 %, high in 11.3 % and very high in 5.93 %. The high and very high classes are related to point infiltration catchments, especially in limestone outcrop areas, indicating the most vulnerable areas in comparison with those with diffuse infiltration.

Ribeiro et al. (2016) applied the EPIK methodology to the Sapucari and Maruim karstic aquifers, which are important underground water reserves that supply the municipalities with the same names and the large city of Aracaju in Sergipe. Lenhare & Sallun Filho (2019) applied EPIK in the south of São Paulo state, in the Guapiara plateau region, where the authors identified vulnerability with a low association with the high population, and in the Serra of Paranapiacaba where vulnerability was high but associated with low population. Pereira et al., 2018, presented a validation of the intrinsic vulnerability map of the São Miguel River Basin (MG), elaborated using the EPIK methodology. These authors mentioned that they adapted the parameters to account for particularities of the basin studied, but do not indicate what modifications were made. The authors emphasize that some researchers do not accept the methodology used for validation (hydrological modelling) and others support its verification and even validation by statistical techniques. It is noteworthy that the COST Action 620 approach does not include recommended methodologies for validating intrinsic vulnerability maps to contamination of this type of methodology.

Other studies such as those carried out by Schleder et al. (2017), evaluated vulnerability to nitrate, coliforms and atrazine in a karst aquifer in the city of Colombo in Paraná state (in the Curitiba metropolitan region in Southern Brazil), but did not apply any specific methodology to determine the intrinsic vulnerability to contamination in this assessment. Duarte & Weber, 2019 applied the DRASTIC methodology (Aller et al., 1987) in a region close to the Karst Environmental Protection Area of Lagoa Santa (EPA Lagoa Santa Karst), in a karst aquifer in the metropolitan region of the municipality of Vespasiano, MG in Southeast Brazil. Rosa Filho et al., 2002 conducted a vulnerability and risk assessment in a karst aquifer in two areas in the city of Almirante Tamandaré, PR. One in an urban portion of the Curitiba metropolitan region and the other in a rural area called Botiatuva, approximately 32.5 km from Curitiba. In the urban region the study was performed by applying tracers in karst sinks. In the rural area the hydrogeological conditioning of the aquifer was evaluated. However, no specific method for determining intrinsic vulnerability was applied for preparing the vulnerability maps.

3.2. ARGENTINA

Argentina has about 45,000 km^2 of carbonate rocks (Goldscheider et al., 2020) and little is known about the intrinsic vulnerability of the karst aquifer in the country (Figure 4).

In Argentina, no specific records were found regarding the vulnerability of karstic aquifers. Nevertheless, more advanced hydrogeological and hydrogeochemical studies were found in clastic and fissured-clastic aquifers, especially because these kinds of aquifers are responsible for drinking water supplies. According to data from the Argentine Government (Nucleo Socio-Productivo Estratégico-Recursos Hídricos, 2012) the percentage of groundwater usage is estimated at 30 %. In addition, some approaches to vulnerability analysis were found that tried to adapt the assessment methods used in European countries to the climatic, geological, demographic and other variable conditions typical of Argentina.

The case of aquifers in fissured rocks may be similar since they combine the variable of water flow dynamics through fractures to the hydrodynamic behavior of karst systems. However, there are few studies carried out of these cases.

The only ones found included an isotopic and hydrochemical study of karst conducted in the Tapalqué aquifer in Buenos Aires province. However, it did not focus on vulnerability (Glok-Galli et al., 2020). The other was a vulnerability study in the fissured zone of the Guaraní Aquifer System, where the fracture density was calculated by interpreting satellite images, but a vulnerability index was not generated (Rodríguez et al., 2006).

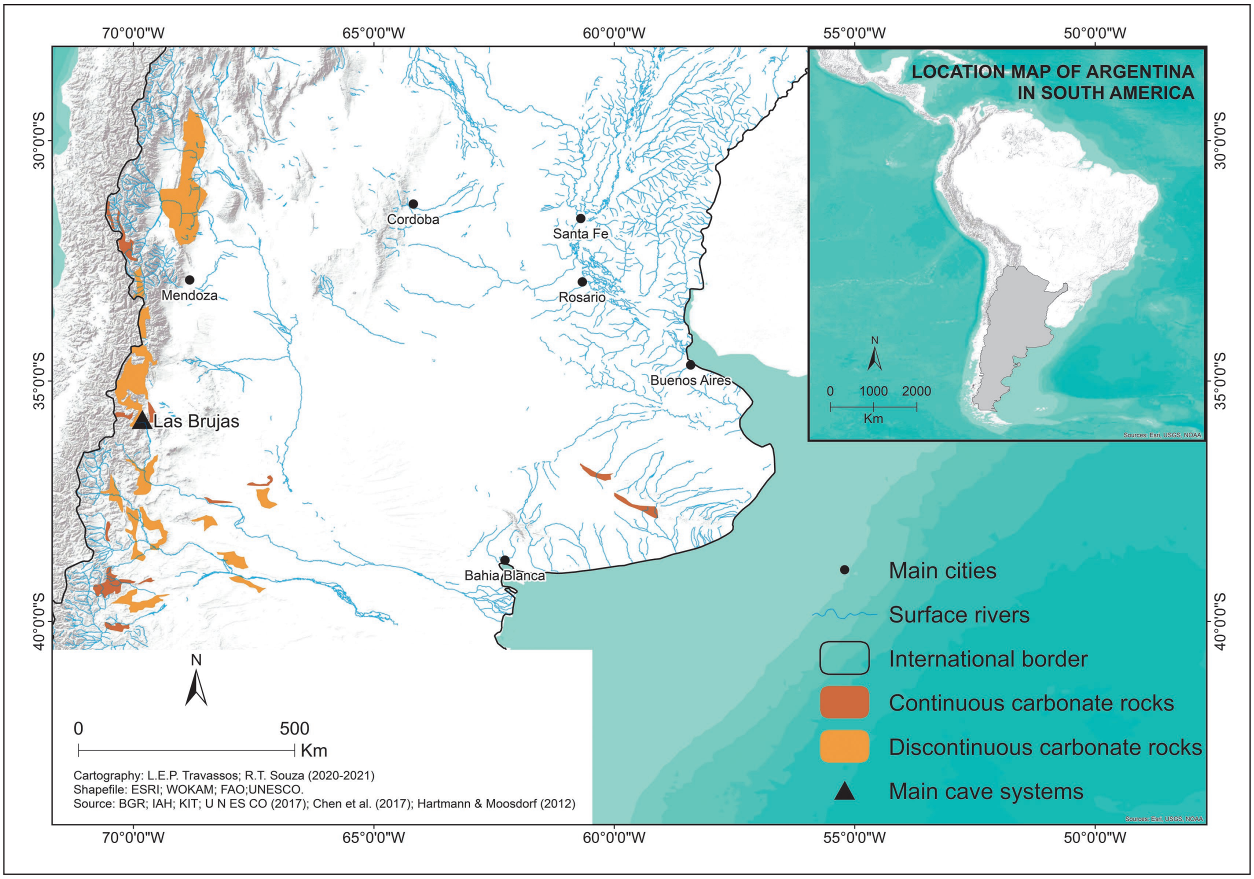

Figure 4: Main karst provinces of Argentina.

3.3. VENEZUELA

No study on vulnerability to contamination of karst aquifers in Venezuela has been published in recent decades. However, it is noteworthy that little water from karst systems is used in the country, except in the Northern half of the state of Falcon and other small towns. Figure 6 presents the karst areas in Venezuela.

Galán & Herrera (2015) affirmed that the theme is an unfamiliar topic, since it does not refer to the hydrographic network of surface but to groundwater contained in aquifers in karstic areas of Venezuela. According to the authors, karst covers 20 % of Venezuela's territory, divided into numerous independent hydrogeological units and practically all compact limestone outcrops are karstified and possess cave systems. Around 40 % of water usage comes from groundwater (Martínez et al., 2013). The most significant karst area is located in the north of the country and is distributed among a number of states.

The authors consider, based on field observations and more than 50 years of studies, that the aquifers most vulnerable to contamination are in the northern half of the Sierra de Perijá, and especially the entire watershed of the Guasare and Socuy rivers and in La Sierra de San Luis.

Differences are seen between the data presented in the shape files of the WOKAM project and the data presented by Galán & Herrera (2015). While the former found that 6.48 % of the country is composed of a karst surface, the latter found 20 %.

3.4. COLOMBIA

Karst terrains in Colombia cover about 9.83 % of the territory. The karst of the Department of Antioquia is located on the eastern flank of the Cordillera Central in the Magdalena Medio Antioqueño region. It is formed by marbles and quartzites that are part of the metamorphic basement of the Cordillera Central. For this system, at least 65 significant underground cavities have been reported, many of which are active (e.g., caves containing a running stream or caves where speleothems are growing), although no specialized studies on hydrogeology or intrinsic vulnerability of the karst aquifers have been carried out. However, there are a series of speleological and environmental reports that refer to waters from karst aquifers. According to Uasapud (2018), the macro-level degradation factors of karst were identified in some sectors of the system, the first being the road infrastructure by which the most sensitive areas of the karst are accessed; the second, agricultural activities that impact a large area and have led to deforestation and erosion; and the third factor, mining, which brings changes in geoforms, deforestation, erosion and siltation of watercourses. At a specific level, in relation to underground karst structures (caves), the Fundación Natura de Colombia reported that caves are affected by the discharge of effluents into the valleys from car washing activities. Moreover, they are polluted by effluents from petroleum derivatives released along roads in the region. According to Restrepo (2007) and Uasapud (2018), the association of cave water contamination with uncontrolled tourism was also detected by Cruz & Uasapud (2021) who found serious impacts to water resources due to the opening of access routes to tourist projects that were causing siltation of water sources in the cavities. Finally, Uasapud (2018) warns about the effects of farm crops and animal herds near cave areas.

For the La Danta sector (Figure 5) located in the southeast of the karst fringe, Cornare (2005) analyzed water entering the La Gruta cave, and found contamination associated with the discharge of effluents from rural houses lacking septic tanks close to these water sources. They also reported that due to the presence of quarries,

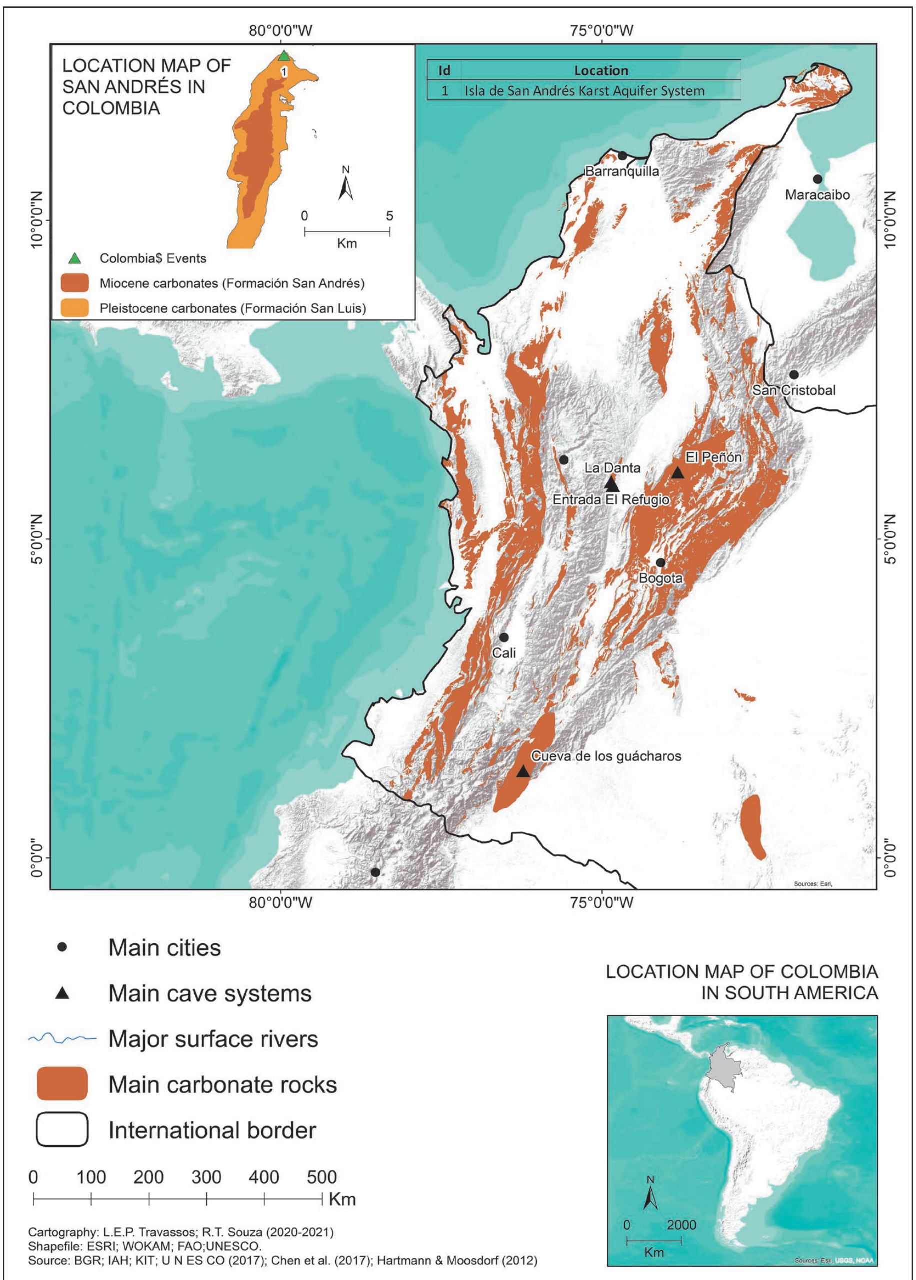

Figure 5: Detailed location of the Isla de San Andrés and the Antioquean karst.

water from the affluents of the caves has considerable amounts of particulate matter and is at risk of silting. In this same study, Cornare (2005) also points out that water coming from the La Gruta cave has a high concentration of coliforms, associated with the high amount of guano in the cave.

Herrán et al. (2018) report affirms that in Colombia there are estimated reserves of 5,848 km^3 of water in various aquifers, but that there is still little knowledge, insufficient monitoring, and little technical and academic examination of the subject. This means that it is still not possible to properly manage groundwater resources in Colombia.

Sufficient information is only available for 30.8 % of the country's aquifers. For the remaining 69.2 % there is no or insufficient information and these include most karstic systems in the country.

Specialized hydrogeology studies exist for the Antioquen region but access to these documents is limited because many were conducted by mining companies that do not provide public access to the documents.

In the Department of Santander, the karst is located in the northern part of the Cordillera Oriental. Geologically, it is above limestone from sedimentary formations, highlighted by the Formación Rosablanca. In this department, at least 218 karst geoforms are reported (Galvis-Gómez, 2018). The karst of the Department of Santander is one of the most studied in the country, and the region of El Peñon in Vélez province has the most reports and specialized studies. Between 2015 and 2019, several expeditions were conducted in the region and include notes about biospeleology, and data on water quality in the karst system, concluding that it has good quality in the upper part of the system. However, water quality decreases in the lower part, possibly due to geogenic effects or contamination (Rodríguez & Lasso, 2019).

Based on these studies, there are other considerations about water quality in karst aquifers and caves. Zafra-Otero et al. (2019) report conditions suitable for human consumption in the waters coming from the karst aquifers of Zapatoca, El Peñón and Lebrija. However, the municipality of La Belleza reports high sewage contamination of the waters from its karst aquifer.

San Andrés Island has a karstic geological system formed by calcareous rocks known as the San Andrés and San Luis Formations, which are free aquifers connected hydraulically and which are in the form of pock-

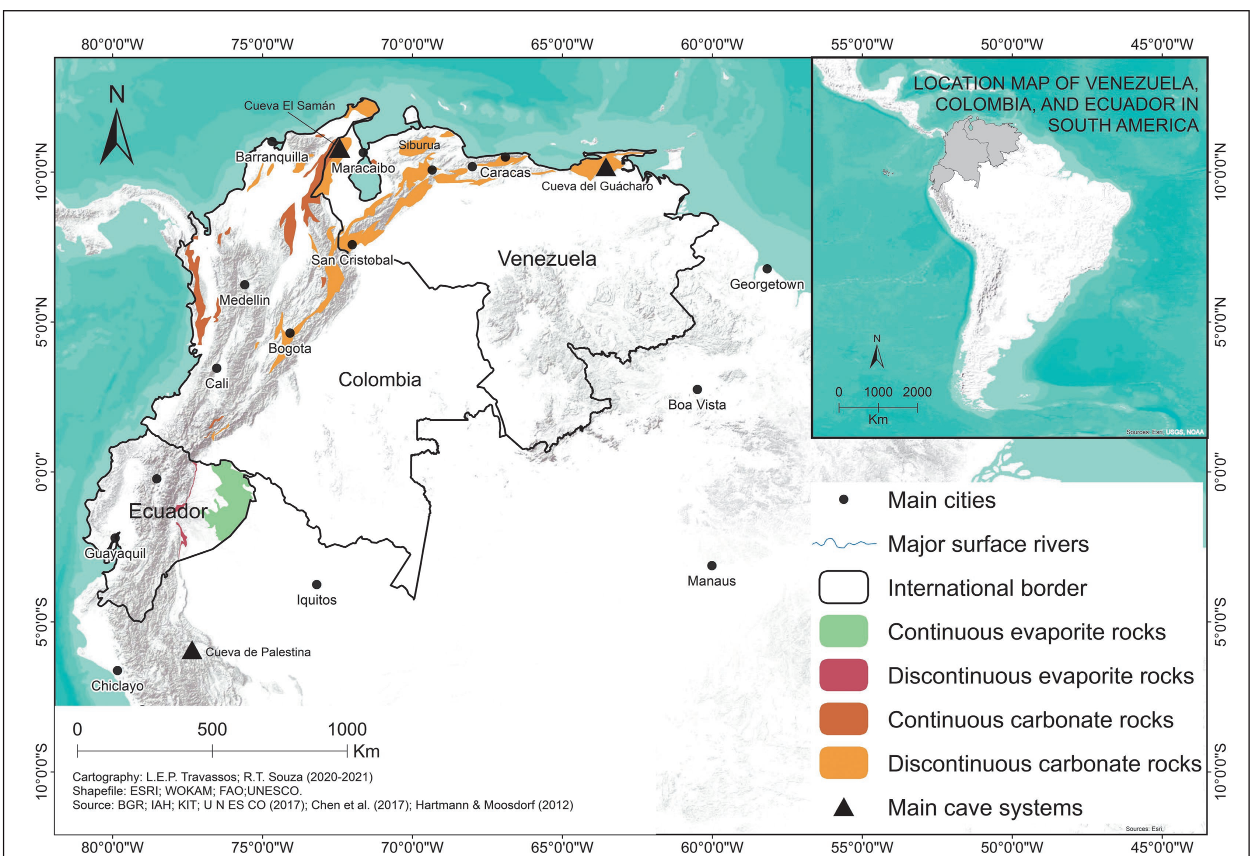

Figure 6: General locations of karst areas of Colombia, Venezuela and Ecuador.

ets, floating on water with higher salinity or forming an interface of fresh and saltwater. They are recharged by infiltration of rainwater that enters through the cavernous regions that connect the surface with groundwater levels (Corrales, 2017).

According to this study by Corrales, the main water source for San Andrés Island (Figure 5) is the karst aquifer system that has high contamination levels; about 80 % of the aquifer is contaminated. The main contaminants are related to the poor disposal of solid and liquid waste on the surface from sewage, hog farms and other agricultural activities. Nationally, San Andrés Island is the only territory with the particularities mentioned above and current urban development is placing great pressure and demand on underground water resources.

It is worth mentioning that the only study found about the threats, vulnerability and risks for the island related to contamination of karst aquifers was that of Corrales, 2017. This study sought to apply the COP methodology (Vías et al., 2006) to assess the vulnerability of the aquifer. However, the lack of sufficient data to apply the methodology led to use of the generalist GOD method (Foster, 1987). Figure 5 shows the main locations where relevant karst features are found in Colombia and Figure 6 shows general karstic areas in Colombia, Venezuela and Ecuador.

3.5. ECUADOR

Although 13.45 % of Ecuadorian territory is covered by karst, and 54.4 % of the water used in the country comes from groundwater sources (Terán et al., 2021), no study on vulnerability to contamination of karst aquifers in the country has been found. However, researchers from the Universidad Regional Amazónica Ikiam are forming a specialized group to study the Ecuadorian karst system.

3.6. PERU

Peru has 15.4 % of its surface territory covered by karst terrain and although it has the third largest karst area in South America (Goldscheider et al., 2020), see Figure 7, the available studies are scarce since most were conducted by mining companies and the information is not made public. According to Hada et al. (2017) groundwater accounts for approximately 36.3 % of water consumption in the country. The sole scientific study available in the literature was conducted by Evans et al. (2005) and includes aquifer vulnerability mapping in karst terrain at the mining site called Antamina, but no intrinsic karst

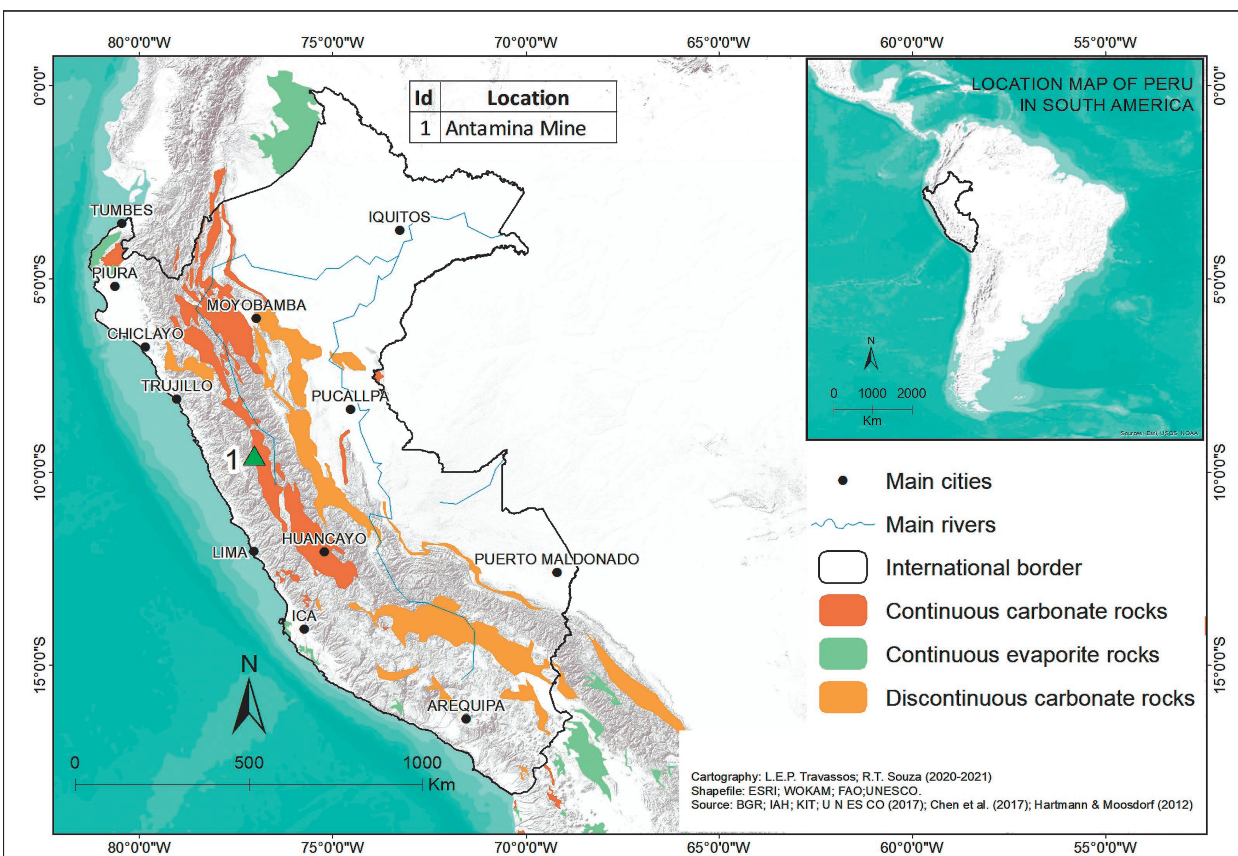

Figure 7: Location of the karst areas in Peru and site study of vulnerability in the Antamina Mine.

aquifer vulnerability method was applied. The contamination vulnerability mapping at Antamina consisted of geological and karst mapping, geophysical surveys, geochemical testing, dye-tracer studies, drilling and aquifer testing and the results were used to optimize waste rock management at the site to minimize potential impacts on groundwater resources (Evans et al., 2005).

Another study conducted by Herrera et al. (2006) in the Peruvian karst zone located in the Apurímac region concerns only the protection of natural resources, including groundwater, related to a large mining project called Las Bambas de Apurímac.

3.7. CUBA

In terms of territorial extension covered by karst rocks, Cuba has of all the countries in this study Cuba has the highest percentage of this type of rock, 67 % (Gainza et al., 2019), as depicted in Figure 8.

Karst aquifers are extremely important to Cuba, given that 33 % of all available drinking water comes from underground sources. Of these, 91 % originates from karst aquifers (Rodríguez & Ortega, 2021). According to these authors, the main hydrographic basin for Havana City is the Almandares River basin, which covers an area of 470 km^2 and includes the Vento Karst hydrogeological compartment. More than 75 % of the drinking water supply in the country's capital, Havana, comes from aquifers in that basin (Ibarguren et al., 2011), which is where the most environmental studies are found. Speleological studies, and those of contamination of surface and underground waters, deforestation and erosion, stand out. Among the main causes of contamination of Cuban groundwater resources is the release of untreated effluents into drainage networks that infiltrate and reach groundwater (Valcarce & Rodríguez, 2021; Valcarce et al., 2020; Gainza et al., 2019, Ibarguren et al., 2011).

Several methods of assessing the intrinsic vulnerability to contamination of karstic aquifers have been applied in the Cuban karst; including RISK (Döerfliger et al., 2004), EPIK (Döerfliger et al., 1999), PC (Gainza et al., 2019) and a vulnerability quantification method based on the electrical conductivity of the superficial layers constituting the vadose zone (Garcia et al., 2018).

The RISK methodology was developed for karstic aquifers that is a modification of the EPIK method. The acronym used for the method indicates that it considers four variables: R-type for the lithology of the aquifer, I-leakage condition, S-protective coverage of the aquifer, and K-karstification factor. This method was modified for use in the Almendares-Vento watershed (Valcarce et

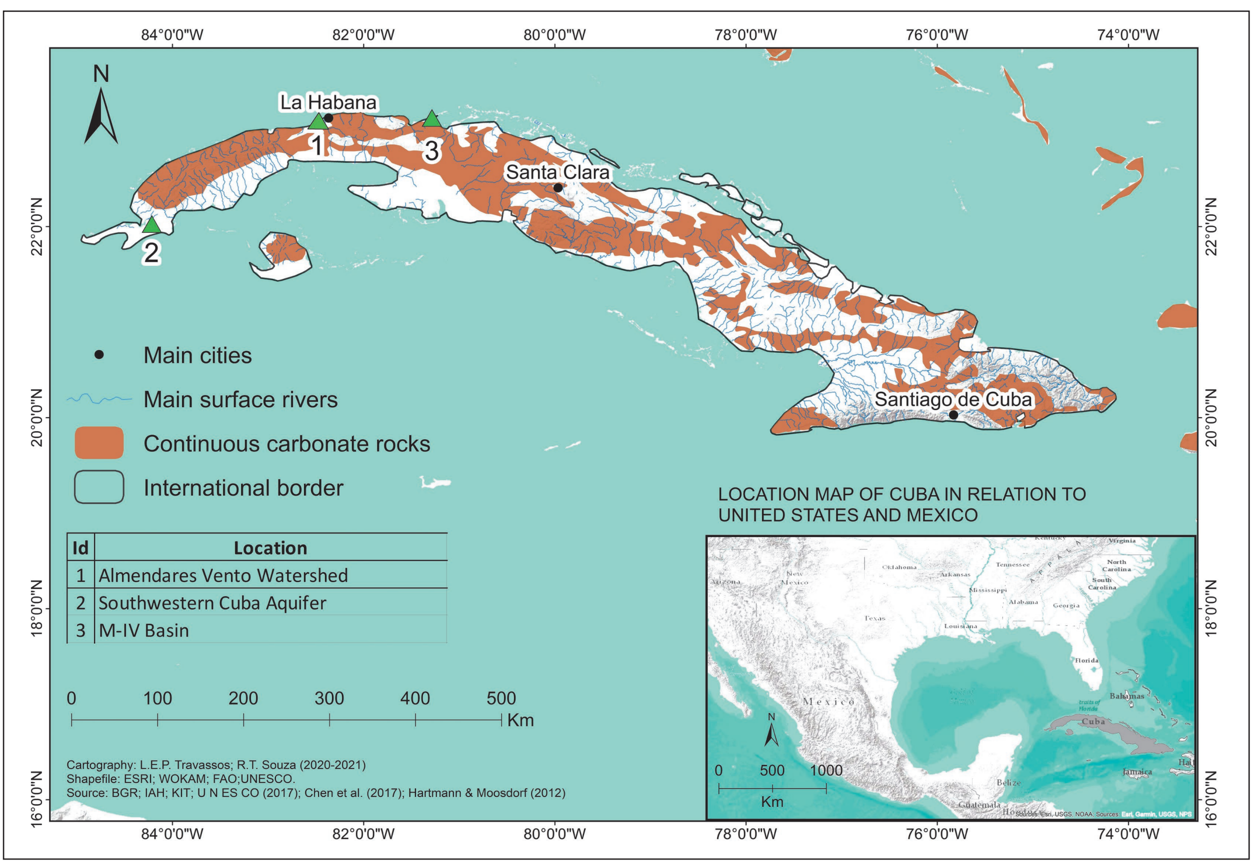

Figure 8: Extension of karst rock in Cuban territory and sites where intrinsic vulnerability methods were developed.

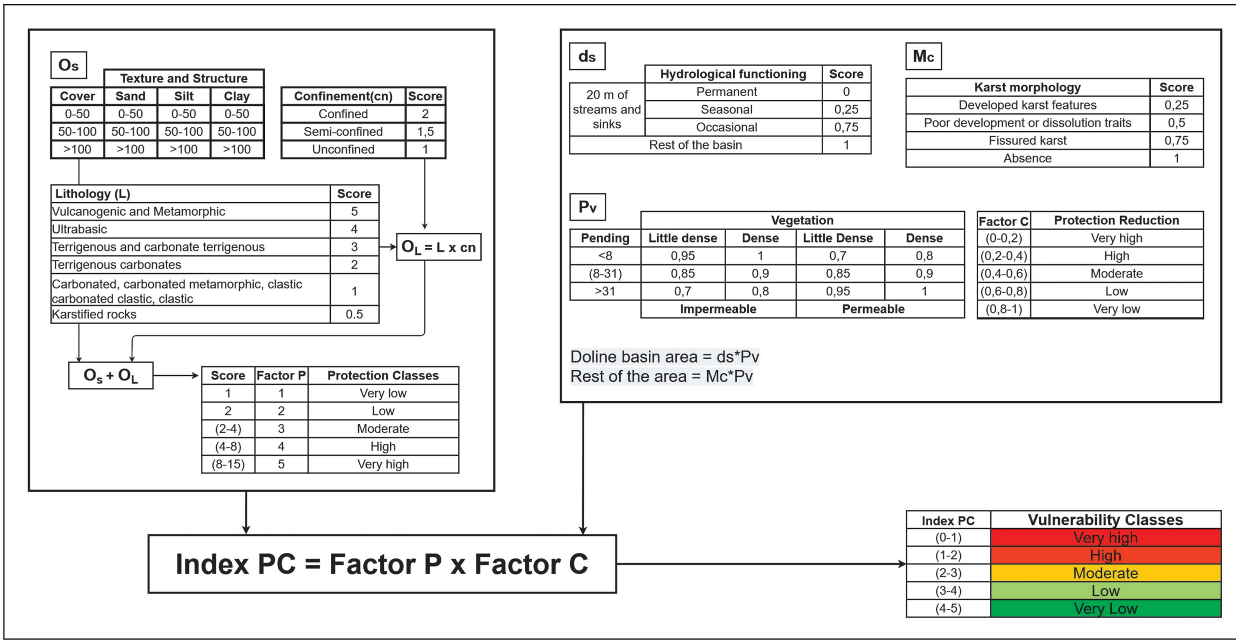

Figure 9: PC methodology calculation flowchart (Modified from Gainza et al., 2019).

al., 2020), introducing the capacity of the soil to protect the karst aquifer according to its potential degree of erosion determined by the EVERC method (Vega & Febles, 2008), which assesses erosion in karst regions. It was also applied in its original version in the M-IV basin that encompasses part of the province of Matanzas, and the cities of Cárdenas and Varadero (Valcarce & Rodríguez, 2021). The PC method simplifies the European COST Action 620 approach and is adapted to local conditions in Cuba that were applied to the Vento karst aquifer. This methodology groups the natural aquifer protection factors (P) and the flux concentration (C). The lithological factor of parameter O of the COP methodology (Vías et al., 2006) was kept as in the original methodology to consider part of the protection given to the aquifer as identified by (P) in the PC methodology. The topography factor was changed to three classes (PC) instead of four classes (COP). Figure 9 shows the flowchart for calculating the methodology. The PC method is very similar to methodology modified for application in tropical karst regions by Nguyet & Goldscheider, 2006.

Garcia et al. (2018) used secondary geophysical data (electrical resistivity) and electrical conductivity values of representative soils in the study area. They compared them with the vulnerability indexes of the AVI method (Van Stempvoort et al., 1992) to complete a vulnerability map of the aquifer in southwestern Cuba.

3.8. MEXICO

In Mexico, about 25 % of the territory's surface (Figure 10) is covered by karst (Goldscheider et al., 2020) and about 38.7 % of water utilized is groundwater (IMTA, 2019), mainly from limestone and to a lesser extent gypsum, which is found from the coast to the interior of the country, where deposits are observed at altitudes of up to 3,000 m, practically in all climate types existing in the country. Some of the karst is distributed in mountainous regions along the Sierra Madre Oriental, the Sierra Madre del Sur, in Chiapas and in other large regions in the Yucatán Peninsula (Lugo et al., 1992; Espinasa-Pereña, 2007). In the Rio La Venta watershed, Chiapas, Kovarik et al., 2017 applied an adaption of the hazard-pathway- target method to create the first groundwater vulnerability map (GVM). This study was carried out using a European Approach, specifically the COP method (Vías et al., 2006) with modifications from the Slovene Approach (Ravbar & Goldscheider, 2007). Modifications from the Slovene Approach were incorporated to refine the accuracy of the COP method. The main parameter that was adapted was soil to consider its effective field capacity which combine the four categories of soil texture types mentioned in the COP method into two categories: loamy/silty and clayey/sandy (Ravbar & Goldscheider, 2007).

The Yucatán Peninsula has the most extensive continuous limestone outcrop in Mexico, characterized by a "Platform Karst" with a "flat" appearance with elevations exceeding 400 m above sea level (Espinasa-Pereña, 2007) and with a complex hydrogeological system, from which the population is supplied with water for consumption (Bautista et al., 2011).

Despite their extension, karst aquifers have not received the attention they deserve in the country. Studies of intrinsic vulnerability to contamination of karstic aquifers have been conducted mainly for the state of Yucatán. Nevertheless, the first evaluations were carried out by applying methodologies designed for porous aquifers.

Pérez & Pacheco (2004) applied the DRASTIC method and defined only two vulnerability classes, an upper class for most of the study area and an extreme class for the coastal region. These authors recommend using a methodology that considers specific variables for the karst system. A map with only two classes (high and extreme) does not reflect the complexity and heterogeneity of the Yucatecan karst and therefore is not suitable for decision-making about the management of local water resources. Ceballos & Ávila (2004) also modeled the karstic aquifer of the Yucatan using DRASTIC, AVI and GOD. The results showed that DRASTIC was the methodology most suitable for characterizing the intrinsic vulnerability in the state of Yucatán based on the available hydrogeological data. Díaz et al. (2014) prepared risk and hazard maps for the Yucatán based on a vulnerability map obtained with the DRASTIC method. In this study, aquifer's contamination risk, calculated considering vulnerability and harzard, was classified as very high for the municipalities of Mérida, Progreso and Dzidzantún.

Based on studies by Pérez & Pacheco (2004), Gijón-Yescas (2007) adapted the DRASTIC method. They used only four variables: water table depth, soils, topography and impact on the vadose zone (DSTI); the variables selected resulted from validation with multiple regression analysis and the analytical hierarchies method. Thus, the resulting vulnerability map presented three vulnerability classes (moderate, high and extreme). However, though the map presents a better differentiation than the previous one (Pérez & Pacheco, 2004), it is still not known if they include the particularities of the karst relief. Albornoz-Euán et al. (2017) also applied the modified DRASTIC method to evaluate the vulnerability of the aquifer under climate change conditions considering the parameters temperature and precipitation. To model regional variations, current (2015-2039) and future (2075-2099) periods were used to calculate evapotranspiration, and recharge, and to simulate vulnerability with the DRSTIL index. The parameters of the DRSTIL index are water depth (D), recharge (R), soil (S), topography (T), impact to the vadose zone (I) and land use (L). Each of the parameters is weighted from 1 to 5 according to its importance. The parameters are divided into classifications according to the pollu-

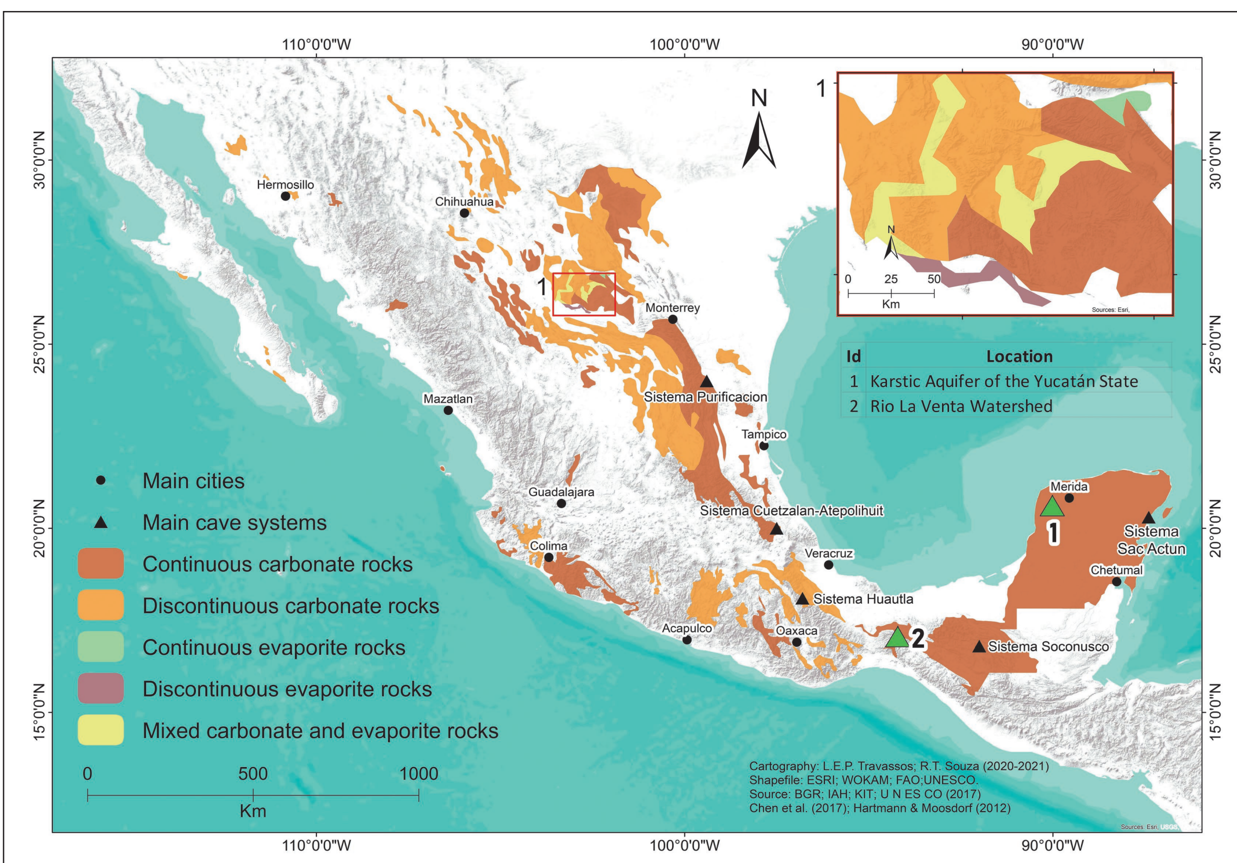

Figure 10: Mexican karst areas and sites where intrinsic vulnerability methods were developed.

tion impact and have a score from 1 to 10. The results of vulnerability modeling for groundwater contamination in scenarios of climate change, indicate an increase in moderate vulnerability and a reduction in high vulnerability due to lower recharging. The first examples described were the pioneering studies on vulnerability to groundwater contamination for the Yucatán. Although they recognized the importance of addressing this issue, an approximation of the heterogeneity of the Yucatecan territory was not achieved because the methodology used did not consider variables for karst areas.

The IKAV method (Moreno-Gómez et al., 2019) is an integrated karst aquifer approach that include dilution and aquifer residence time in the vulnerability analysis. It was applied in the Yucatan karst aquifer to estimate changes in current and future scenarios. To promote evaluation with different methods for comparison purposes, the authors used the DRISTPi (Jiménez-Madrid et al., 2019), KARSTIC (Davis et al., 1994), RISKE (Petelet-Giraud et al., 2000), and Slovene Approach (Ravbar & Goldscheider, 2007). The results demonstrate agreement between the methods for the high and very high vulnerabilities, while results for moderate vulnerabilities are questionable due to the influence of depth to the unsaturated zone, soils, precipitation and slope.

Bolio-Barrios et al. (2011) applied the EPIK methodology to the large karst plains of the Yucatán (the southern portion of the region was not evaluated). It should be noted that the EPIK method is designed to assess intrinsic vulnerability to contamination at large scales (greater than 1:25,000) so that Bolio-Barrios et al. (2011) needed to adapt the method to be able to apply it to a large area using data on a smaller scale. The adaptation made to for the EPIK method for application in the Yucatán consisted of considering the geomorphological regions at a 1:25,000 scale as reported by Bautista et al. (2005) as a cartographic base. This adaptation constituted a first approximation to the use of a geomorphological approach (relief-soil relationship). Thus, four vulnerability classes were outlined: extreme, very high, high and medium. Coinciding with the ring of cenotes in the zone of extreme vulnerability, the surface is represented in the map by Bolio-Barrios et al. (2011). It can be affirmed that it is underestimated because the soils were considered qualitatively by the scale of the study (1:25,000). The “dolines” group was found to be in the “very high vulnerability” class and to have smaller surfaces for the reason explained above. The “high” class has the largest surface area, followed by the “middle” class, which covers an area of the plains between 30 and 40 m above sea level.

Aguilar et al. (2016b) designed the Yucatecan Karst Aquifer Vulnerability Index (IVAKY) to evaluate contamination. This index has a geographic approach integrating factors and attributes related to the karstic conditions of the Yucatan region.

The factor with the greatest weight was karstic depressions, which was incorporated through an analysis of the typology and density of depressions (Aguilar et al., 2016a).

The second factor of importance were the edaphic landscapes that are closely related to the karstic relief (Bautista et al., 2015). The analysis considered the environmental functions of soils as a natural contaminant attenuator (Aguilar et al., 2011; Aguilar & Bautista, 2011; Delgado-Carranza et al., 2011).

The third most important factor was the climate considering the humidity index (pp/Et$_o$) that expresses the excess monthly rainfall (Delgado et al., 2017), which is much more precise than annual precipitation.

For each factor, a conceptual model of the attributes that influence the vulnerability or protection of the karstic aquifer was developed. A map was created from each conceptual model. The three factors were then integrated into a vulnerability map to provide a

Table 1: Overview of the information.

Country	% of groundwater usage	% of karst area	Number of sites where vulnerablihy esessmeni is done	Total size of area assessed (km^2)	Methods being applied
Brazil	17.7	3.1	9	8,369,9	DRASTIC, COP, EPIK
Argentina	30	1.62	-	-	-
Peru	36.3	15.4	1	93	-
Venezuela	40 20			-	-
Colombia	30.8	9.83	1	26	COP, GOD
Ecuador	54.4	13.45	-	-	-
Cuba	33	67	5	11,437	RISK, PC, EPIK KARSTIC, IVAK, DRASTIC, EPIK,
Mexico	38.7	25	13	165	IKAV, PI, COP, PaPRika, GVM, DRSTIL, Slovene Approach

better differentiation of the vulnerability of the aquifers (Aguilar et al., 2014; 2016b).

The vulnerability map developed from the IVAKY method represents the intrinsic vulnerability of the aquifer and serves as a cartographic basis for preparing various pollution risk scenarios depending on the type of threat or contaminant load.

To test different European methods for modelling intrinsic vulnerability for karst aquifers, Moreno-Gómez et al., 2018 applied EPIK, PI, COP and PaPRIka to a single area in the Yucatan karst. Although the methods depicted similarities regarding moderate vulnerability, none of the methods are congruent with regional characteristics. Adaptations of these methods or a new integrated methodology is needed to estimate groundwater vulnerability in the Yucatan karst area, especially for the moderate class that is influenced by uncertainty of unsaturated zone thickness and a shallow water table.

In the Yucatan, groundwater is the sole source of drinking water (Martínez-Salvador, 2019), which simulated the testing of multiple karst vulnerability methods. Table 1 summarizes the information presented about each country studied.

CONCLUSIONS

The studies of karst regions conducted in South America and the Caribbean are almost entirely based on the COST Action 620 approach and despite differences in the soil layer such as thickness, mineralogy, and pH, methods based on European approach continue to be used because of the lack of specific methods suitable for the region. Moreover, considerable research is still required, including improved information about the size of karst areas in each country, for example, Colombia.

In Brazil, studies of intrinsic vulnerability to contamination of karstic aquifers are still incipient, with most studies conducted with methodologies not adapted to the tropical environment, except for the study by Souza (2020). The studies are concentrated in the karst in the Bambuí Group, of the Lagoa Santa Formation, and to the north, in the Una Group in the Carbonatic Basin of Irecê (Salitre Formation). Current methodologies, as mentioned by Souza (2020) and Moreno-Gómez (2018), demonstrate that they must be adjusted to apply to the Yucatán Peninsula and Lagoa Santa karst areas to match soil features and other regional characteristics of karst infiltration.

In Cuba, research on intrinsic vulnerability to groundwater contamination is reported, using methodologies based on the COST Action 620 approach, but adjusted to the hydrogeological conditions of each karstic aquifer studied. In this country, some efforts to apply a methodology more specific to the environmental conditions were made by Gainza et al. (2019) and Valcarce et al. (2020). In this country, where karst plays an important role in water supply for the population, some attempts to apply a methodology more specific to Cuba's environmental conditions were made by Gainza et al. (2019), while the rest of the methodologies reported in the literature are similar to those used in Europe.

Colombia and Argentina lack specialized studies on intrinsic vulnerability of karst aquifers, and most studies found are related to speleology and environmental variables. In these countries, researchers agree that it is necessary to characterize and assess the vulnerability to contamination of karst aquifers for better understanding, conservation and management of this important natural resource.

In Peru, with the second largest karst area in South America, few studies in karst hydrogeology and intrinsic vulnerability have been conducted and those found are not accessible to the public because they belong to private mining companies.

Mexico has the most studies on intrinsic vulnerability to contamination of karstic aquifers, including a methodology created that is suitable to local conditions in the state of Yucatán. The studies developed by Yameli et al. (2016b) worked with specificities of soils that cover carbonate rocks. It is noteworthy that there are great differences between these karst formations and European Mediterranean karst.

In the other countries in this study, Venezuela and Ecuador, the existing karst areas are not yet known in detail. In this sense, this study demonstrated the need to create a group of researchers to join efforts to support studies of intrinsic vulnerability to contamination of karst aquifers in the region. This will allow sharing knowledge in an effort to create methodologies more suitable to the environmental conditions in these countries.

This study led to a consensus among the authors that an investigative group should be created to examine the protection of karst aquifers in the region, and which can try to develop a methodology appropriate to South American and Caribbean countries.

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