

Analysis of Environmental and Social Variables as Risk Factors in the Spread of the New Coronavirus (SARS-CoV-2): A Case Study in Peru

Análisis del comportamiento de variables ambientales y sociales como factores de riesgo en la propagación del nuevo coronavirus (SARS-CoV-2): caso de estudio en el Perú

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Abstract. The new coronavirus disease (COVID-19) caused by the SARS-CoV-2 virus originated in China; the first case was reported in the city of Wuhan in December 2019, from where the virus spread to other regions of China and the rest of the world. The World Health Organization (WHO) declared the COVID-19 outbreak as an international public health emergency on January 30, 2020. The first positive case of COVID-19 in Peru was recorded on March 6, 2020 in the Lima region; the state of emergency was declared on March 16, 2020. Several studies worldwide have examined environmental and social variables associated with the spread of COVID-19. Most of these studies have analyzed individual variables; therefore, an analysis integrating these variables under clear methodological criteria is warranted. The objective of this article is to analyze a number of environmental (tropospheric NO₂ column, vertical air flow, percentage of solid waste disposed of in open dumps, and

percentage of the population with no access to basic sanitation services) and social (monetary poverty level, number of hospitals, and vulnerable population) variables directly or indirectly involved in the spread of the SARS-CoV-2 virus. Remote sensing techniques and geographic information systems (GIS), integrated under the multiparametric statistical-deterministic approach proposed by Saaty, were used to identify the regions of Peru that show the greatest susceptibility, vulnerability, and risk of spread of the SARS-CoV-2 virus. Data were compiled from global and national institutions. Data for the tropospheric NO₂ column were obtained from the Sentinel-5 Precursor satellite; vertical air flow was estimated from data collected by the Physical Science Laboratory of the National Oceanic and Atmospheric Administration (NOAA); data on the population with no access to basic sanitation services were obtained from the national statistical agency, the Instituto Nacional de

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Estadística e Informática (INEI), and on the percentage of solid waste disposed of in open dumps from the Ministry of the Environment (MINAM). Data on social variables were obtained from INEI. The prevalence of high tropospheric NO₂ values and vertical air flow values close to 0 Pa/s is directly related to the number of positive COVID-19 cases. In addition, 68% of the regions show a high or very high risk of spread of the SARS-CoV2 virus and most of these (Callao, Tumbes, Piura, Loreto, Lambayeque, Huancavelica, Amazonas, Cajamarca, Ucayali, and Huánuco, among others) are located in north and central areas of Peru. Thus, special care should be taken after the social isolation period to prevent a new outbreak and the collapse of healthcare systems. We concluded that public policies aimed at improving air quality management, integrated solid waste management, and sanitation services in the short term should be applied to reduce the risk of spreading the SARS-CoV-2 virus. This study could be replicated at a larger scale, including additional variables.

Keywords: SARS-CoV-2, Analytical Hierarchy Process (AHP), Risk Assessment, Remote Sensing, GIS.

Resumen. La nueva enfermedad del coronavirus (COVID-19) generada por el virus SARS-CoV-2 se originó en China y el primer caso reportado fue en la ciudad de Wuhan, en diciembre del 2019. El virus comenzó a propagarse en otras regiones de China y al resto del mundo. El 30 de enero del 2020, la Organización Mundial de la Salud (OMS) declaró el brote del COVID-19 como emergencia internacional en salud pública. En Perú, el primer caso positivo de COVID-19 fue registrado el 6 de marzo del 2020 en la región Lima, y se declaró el estado de emergencia el 16 de marzo del 2020. A nivel mundial se han realizado diferentes investigaciones de variables ambientales asociadas a la propagación del COVID-19 así como variables sociales; sin embargo, la mayoría de estas han sido analizadas de forma individual, por lo que es necesario realizar un análisis que integre a dichas variables bajo ciertos criterios metodológicos. Es así que el objetivo de este texto es analizar las variables ambientales (columna troposférica de NO₂, flujo vertical de aire, porcentaje de residuos sólidos dispuestos

en botaderos y porcentaje de la población sin ningún mecanismo de eliminación de excreta) y sociales (niveles de pobreza monetaria, porcentaje del número de hospitales por población y población vulnerable) que intervienen directa e indirectamente a la propagación del virus SARS-CoV-2. Para ello se utilizaron técnicas de percepción remota, sistemas de información geográfica (SIG) integrados bajo el enfoque estadístico-determinístico multiparamétrico planteado por Saaty, determinando así qué regiones del Perú presentan mayor susceptibilidad, vulnerabilidad y riesgo de propagación del virus SARS-CoV-2. Los datos fueron recopilados a partir de instituciones mundiales y nacionales; para la columna troposférica de NO₂ los datos fueron obtenidos del satélite Sentinel-5P; el flujo vertical del aire se determinó a partir de la información recolectada del laboratorio de ciencias físicas del NOAA (National Oceanic and Atmospheric Administration); la información concerniente a la población sin ningún mecanismo de excreta fue extraída del Instituto Nacional de Estadística e Informática (INEI) y el porcentaje de residuos sólidos dispuestos en botaderos se obtuvo del Ministerio del Ambiente (MINAM), mientras que los datos de las variables sociales fueron todos obtenidos a partir del INEI. Los resultados muestran que la prevalencia de altos valores de NO₂ troposférico y valores cercanos a 0 Pa/s del flujo de aire vertical presentaron una relación directa con el número de casos positivos por COVID-19, además, se encontró que el 68% de las regiones se encuentran en un nivel de riesgo de propagación del virus SARS-CoV-2 “alto” y “muy alto”, y la mayoría de estas se encuentran en el norte y centro del Perú (Callao, Tumbes, Piura, Loreto, Lambayeque, Huancavelica, Amazonas, Cajamarca, Ucayali y Huánuco, entre otras), por lo que se debería tener especial cuidado con las medidas tomadas posaislamiento social a fin de evitar un rebrote y colapso de los sistemas de salud. En la presente investigación se concluye que las políticas públicas de gestión de la calidad de aire, gestión integral de residuos sólidos y servicios de saneamiento, deben mejorar a corto plazo a fin de disminuir el riesgo de propagación del virus SARS-CoV-2. Este estudio puede replicarse a una mayor escala, incluyendo más variables.

Palabras clave: SARS-CoV-2, procesamiento de análisis jerárquico (PAJ), evaluación del riesgo, teledetección, SIG.

INTRODUCTION

The new coronavirus disease (COVID-19) caused by the SARS-CoV-2 virus is being studied by various disciplines, including environmental approaches, to investigate the relationship between SARS-CoV-2 and environmental variables (VA) such as air, water, and solid waste. Although such studies are still scarce, their results should be considered for the formulation of public policies adopted by governments.

Recent studies have shown that the concentrations — measured both on the ground and through remote sensing methods — of atmospheric pollutants showed a significant decline during the lockdown (social isolation) period (Chen, Wang, Huang, Kinney and Anastas, 2020). In addition, Ogen (2020) conducted an analysis using remote sensing and COVID-19 case fatality data for Germany, France, Spain, and Italy, and concluded that long-term exposure to NO₂ may be one of the factors contributing to COVID-19 mortality in the

regions studied. MINAM (2020a) reported that during the lockdown period in Peru, $PM_{2.5}$ values dropped to less than $10 \mu\text{g}/\text{m}^3$, these being the lowest values over the past three years. Therefore, a close relationship between the number of positive COVID-19 cases and high pollution levels is likely under regular industrial activity conditions.

There is evidence that SARS-CoV-2 can be found in feces of infected persons, which could pose a risk to human health (Guan et al., 2020; Zhang et al., 2020). Only 20% of total wastewater is treated in Latin America (Banco Mundial, 2015). According to INEI (2016), the coverage of sanitation services by the public sewerage network of Peru is 88% in urban areas but does not exceed 18% in rural areas, where septic tanks, rivers, ditches, or canals are the only means to dispose of excreta.

Nzediegwu and Chang (2020) and Van Doremalen et al. (2020) pointed out that poor solid waste management could lead to the proliferation of SARS-CoV-2 and infection of all workers involved. Open dumps prevail in Latin American countries (Ziegler-Rodriguez et al., 2019) the main goal of the study is to analyze the life-cycle environmental performance of waste disposition in three different landfills located in three distinct geographical areas of Peru: i and Scheinberg et al. (2020) regard the prevention of the spread of COVID-19 in these situations as highly important. Countries such as the US and Italy have restricted waste recycling and segregation programs (Zambrano-Monserrate et al., 2020). Decree D.S. N° 080-2020-PCM has identified the recycling of industrial inorganic solid waste as one of the priority economic activities to resume in Peru (MINAM, 2020b), where approximately 73% of solid waste ends up in open dumps (Orihuela-Paredes, 2018).

Few studies have examined social aspects potentially linked to the spread of COVID-19, such as population density, urban population, traffic jams (Ahmadi et al., 2020; Hamidi et al., 2020) the main parameters, including the number of infected people with COVID-19, population density, intra-provincial movement, and infection days to end of the study period, average temperature, average precipitation, humidity, wind speed, and

average solar radiation investigated to understand how can these parameters effects on COVID-19 spreading in Iran? The Partial correlation coefficient (PCC, and people vulnerability and poverty (Tavares and Betti, 2021). These features could be used to project future scenarios for this disease. In addition, an epidemiological analysis of the COVID-19 situation in Peru showed that some age groups (including the elderly, a vulnerable segment of the population), hospital saturation, and lack of facilities for the treatment or monitoring of COVID19 are crucial aspects in the fight against this disease CDC-MINSA (2020). That is why these variables, taken together, are key for decision-making on the measures to be taken to address this pandemic.

In view of these issues, we evaluated environmental and social variables by means of remote sensing techniques and geographic information systems, using Sentinel-5 Precursor satellite data, information products from the National Oceanic and Atmospheric Administration (NOAA) web platform, and the software QGIS. In addition, we used the analytical hierarchy process (AHP), a multi-criteria method applied for decision-making in various disciplines, including health (Requia et al., 2020) which is commonly referred to as “flattening the curve”. This study aims to address this issue by proposing a spatial multicriteria approach to estimate the risk of the Brazilian health care system, by municipality, to exceed the health care capacity because of an influx of patients infected with the COVID-19. We estimated this risk for 5572 municipalities in Brazil using a combination of a multicriteria decision-making approach with spatial analysis to estimate the exceedance risk, and then, we examined the risk variation by designing 5 control intervention scenarios (3 scenarios representing reduction on social contacts, and 2 scenarios representing investment on health care system, natural sciences (Lin et al., 2020), and engineering (Zhou and Yang, 2020).

The AHP first defines the issue to address and breaks it down into a hierarchy of decisions (Vassou, Labib, and Roberts, 2006). Then, paired comparisons between the criteria with respect to the objective are carried out in the same way for

all the alternatives with respect to each criterion, in order to rank the elements of the hierarchy according to their priority. Finally, the relative weights of the elements in each hierarchical level are estimated and the overall priority value of the alternatives and their inconsistency (coherence) are calculated (Labib, 2014).

Our study integrates the analytical hierarchy process developed by Saaty with the epidemiological triad (agent-host-environment) approach (Méndez-Martínez et al., 2018), as both are essential for grouping variables — environmental and social variables in this case — to identify the regions that are more or less susceptible to the risk of spread of SARS-CoV-2. Some regions of Peru require urgent support and assistance for the attention and control of COVID-19 cases (CDC-MINSA, 2020). That is, there are contrasting situations or realities in different regions of Peru that must be evaluated accordingly.

The concepts of susceptibility, vulnerability, and risk used herein follow the definitions of the *Centro Nacional en Prevención de Riesgos de Desastres* (National Center for Disaster Risk Prevention, CENEPRED), the leading body of the Peruvian National System for Disaster Risk Management. Thus, our susceptibility analysis encompasses those factors causing a greater or lesser predisposition for event occurrence in a given geographic area; our vulnerability analysis examines the exposure, fragility, and resilience of the population and their livelihoods; finally, the risk analysis leads to the identification and characterization of hazards, and the analysis of vulnerabilities (CENEPRED, 2015).

OBJECTIVE

The objective of this study was to analyze environmental and social variables that might directly or indirectly influence the spread of SARS-CoV-2, by using remote sensing techniques, geographic information systems, and the multiparametric statistical-deterministic approach proposed by Saaty (1980). The scope of the study is country-wide, encompassing the 25 regions of Peru.

MATERIALS AND METHODS

Environmental Variables

Tropospheric NO₂ Column (CTNO₂)¹

CTNO₂ data were obtained from the tropospheric monitoring instrument (TROPOMI) on board the Sentinel-5 Precursor satellite (Eskes et al., 2019). Typical long-term exposure to NO₂ was defined as a 3.5-month period, that is, from January 1 to March 14, 2020, one day before the lockdown period in Peru was declared (Diario Oficial El Peruano, 2020). Data for the period March 16 to April 20 were also analyzed to identify changes in NO₂ concentration. Average NO₂ concentrations for each period were calculated with the Google Earth Engine platform. The resulting raster datasets were exported and processed in a geographic information system (QGIS) to calculate the average per pixel for each region of Peru.

Vertical Air Flow - Omega (FVA)

The FVA parameter is analyzed in the troposphere; we used omega data produced by NCEP/NCAR Reanalysis 1 (National Centers for Environmental Prediction/National Center for Atmospheric Research) and downloaded from the web platform of the Physical Sciences Laboratory of the National Oceanic and Atmospheric Administration/Earth System Research Laboratories (NOAA/ESRL) (<https://psl.noaa.gov/>, last visited April 30, 2020). The data analyzed were the omega monthly means for 2019 at 850 hPa (~1500 m elevation). The working hypothesis was that regions where negative omega values prevail would be favored with better air circulation and dispersion of pollutants, which would prevent their stagnation on the surface by carrying them to higher elevations. In contrast, atmospheric pollutants will have a longer permanence in regions where omega values are either positive or close to 0 (atmospheric stability).

¹ In this article, the acronyms regarding the variables studied refer to the name in Spanish (translator's note)

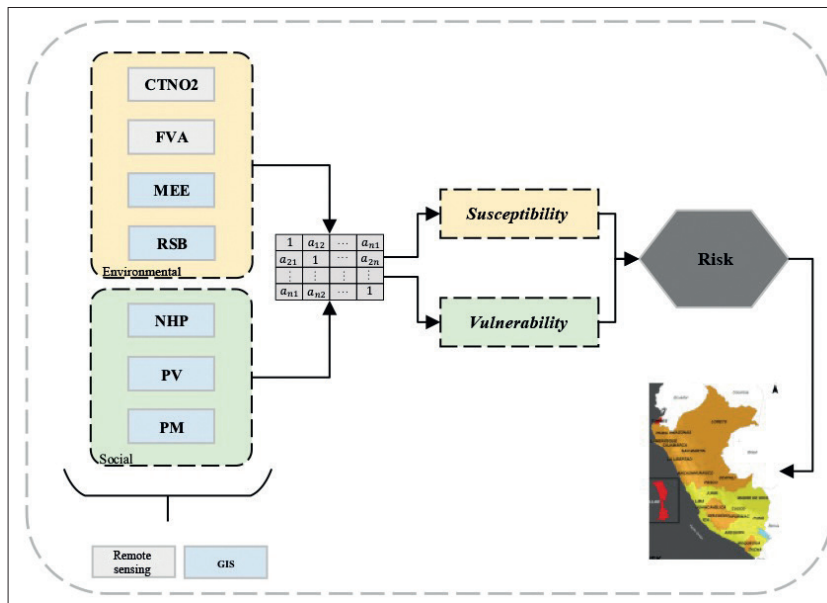


Figure 1. Environmental and social variables included in the AHP to evaluate the risk of spread of SARS-CoV-2 in the regions of Peru. Source: Compiled by the authors.

Population with No Access to Basic Sanitation Services (MEE)

Data used were the number of inhabitants per region with no access to sanitation services through the public sewerage network. These data were obtained from INEI (2016).

Percentage of Solid Waste Disposed of in Open Dumps (RSB)

This variable denotes the percentage of solid waste that is disposed of in sites lacking proper sanitary measures (open dumps). Data on the percentage of solid waste disposed of in open dumps in each region of Peru were obtained from Orihuela Paredes (2018).

Social Variables

Vulnerable Population (VP)

Data on the size of vulnerable population were obtained from chapter 1 of the *Perfil Sociodemográfico del Perú, 2017* (Sociodemographic Profile of Peru, 2017) compiled by the national statistical agency, the Instituto Nacional de Estadística e Informática (National Institute of Statistics and Informatics, INEI). The vulnerable population amounts to 38.29% of the total population of Peru and includes children under 14 years of age and

adults aged 60 years or older. These segments of the population are deemed vulnerable because they fall into economically inactive age classes supported by economically active age groups (INEI, 2017). In addition, according to CDC-MINSA (2020), the +60-year age class is related to an increased mortality risk from COVID-19.

Number of Hospitals (NHP)

Peru has 19,859 healthcare facilities (INEI, 2018) spread across the 25 regions. Data on the number of hospitals, the main type of healthcare facility receiving people infected with COVID-19, were used for this study. These data were obtained from INEI (<http://m.inei.gob.pe/estadisticas/indice-tematico/health-sector-establishments/>, last accessed on May 17, 2020). The data were expressed as number of hospitals per 100,000 inhabitants based on the population size recorded in the latest population census.

Monetary Poverty (PM)

PM data were provided by INEI (2019). These data classify the regions into five classes that denote the percentage of the population that cannot afford a basic food basket or has no food.

ANALYTICAL HIERARCHY PROCESS (AHP)

Table 1 lists the environmental and social variables analyzed to evaluate the risk of spread of SARS-CoV-2 in the regions of Peru. The variables were first standardized and the relative weight of each was estimated by constructing a matrix to make pairwise comparisons of all the variables as to their importance using a 1-to-9 rank scale, where 1 denotes that the variables are equally important and 9 that the first variable is far more important than the second. The analysis of environmental variables yields a map showing the susceptibility to the spread of the SARS-CoV2 virus; the vulnerability map was derived from the analysis of social variables. Finally, the product of both maps yields the final risk map. Additional analyses were carried out to examine the relationship between the number of positive COVID-19 cases in each region and the environmental and social variables.

RESULTS

Environmental Variables

Figure 2 shows the distribution maps of tropospheric NO₂ before and after the lockdown period in the regions. Figure 3 shows the map of vertical air flow-omega (Pa/s), and Figure 4a shows the number of positive COVID-19 cases, CTNO₂, and FVA. The largest number of positive COVID-19 cases were found in Lima (20,048 cases), Callao (2,933), Lambayeque (1,814), Piura (960), and Loreto (881). Some of these regions also showed high mean tropospheric NO₂ concentrations prior to the lockdown period: Callao (41 µmol/m²), Lima (16 µmol/m²), and Lambayeque (10 µmol/m²). In addition, vertical air flow in these regions was close to 0.

Figure 4b shows that Loreto and Ucayali were the regions where MEE accounted for over 40% of the total population; these were also among the ten regions with the largest numbers of positive COVID-19 cases. In contrast, more than 98% of the inhabitants of Callao, Lima, and Tacna has

Table 1. Variables analyzed.

Type	Variables	Abbreviation	Units	Source
Environmental	Tropospheric NO ₂ column	CTNO ₂	mol/m ²	(ESA, 2020)
Environmental	Vertical air flow	FVA	Omega, Pa/s	(NOAA, 2020)
Environmental	Proportion of solid waste disposed of in open dumps	RSB	Percentage of solid waste disposed of in open dumps per region	(Orihuela Paredes, 2018)
Environmental	Population with no access to basic sanitation services	MEE	Percentage of the population with no access to basic sanitation services per region	(INEI, 2016)
Social	Monetary poverty	PM	Group of monetary poverty of the region	(INEI, 2019)
Social	Number of hospitals	NHP	Number of hospitals per 100 000 inhabitants	(INEI, 2018)
Social	Vulnerable population	VP	Vulnerable population per region	(INEI, 2017)
Social	Number of positive COVID – 19 cases*	-	Population infected with COVID-19 per region	(MINSA, 2020)

* As of April 28, 2020.

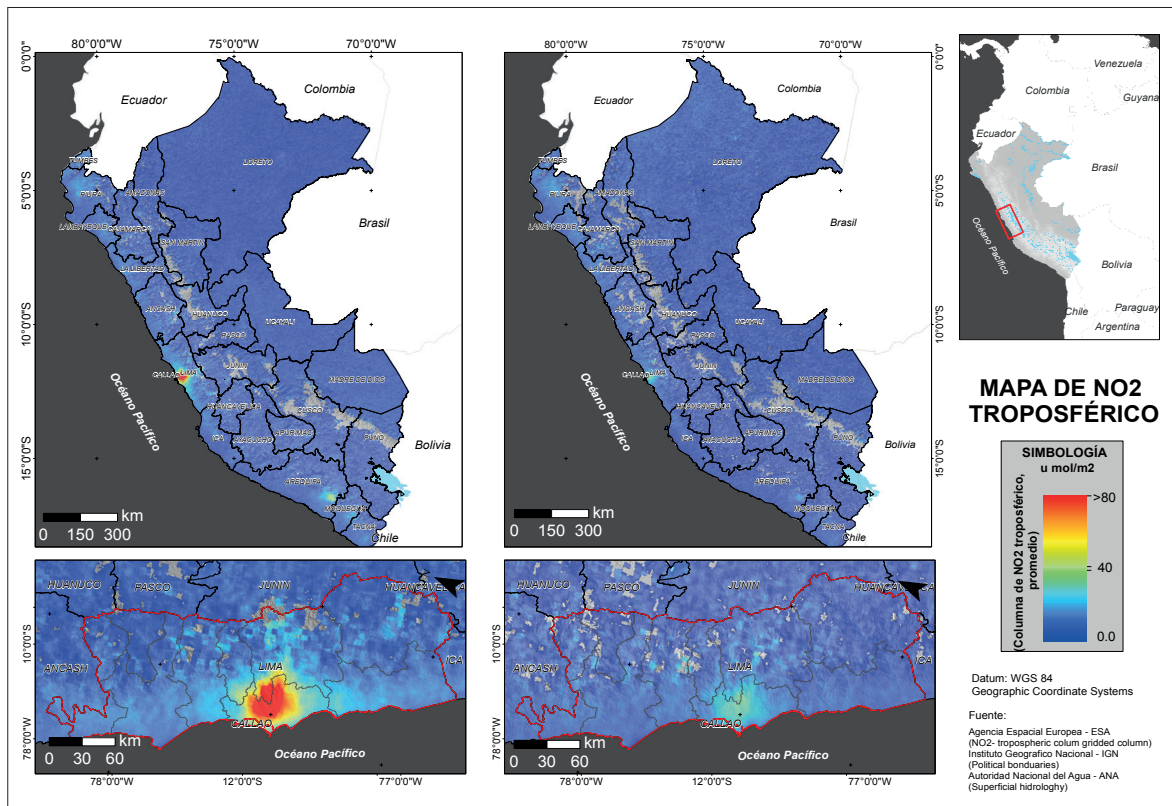


Figure 2. Changes in the concentration of tropospheric NO₂ in the regions of Peru. Panels a1 and a2 show NO₂ concentration before the lockdown period in Peru and the Lima regions, respectively. Panels b1 and b2 show NO₂ concentrations after the lockdown period for Peru and Lima, respectively.

access to basic sanitation services. However, the Callao and Lima regions had the largest number of people affected by COVID-19.

Figure 4b shows that RSB is over 65% in the regions with the largest number of positive COVID-19 cases (Lima, Callao, Lambayeque, Piura, Loreto, among others). In general, more than 45% of solid waste is disposed of in open dumps in almost all regions, except for Callao, where it is 0%, as no such spaces exist therein (MINAM, 2020c).

Social Variables

Figure 5a shows that, on average, NHP ranges between 1 and 2 in all regions, even in the five regions with the largest number of positive COVID-19 cases. PV was lower in the five regions with the largest cumulative number of positive

COVID-19 cases. PV ranged between 30% and 45% in all regions.

Figure 5b shows that Lima, Callao, La Libertad, Piura, and Loreto are the regions with the largest number of positive COVID-19 cases and these fall in classes 2 to 4 of PM (on a 5-class scale, where 1 are the regions with lowest PM, and 5 the regions with highest PM).

Analytical Hierarchy Process

Susceptibility to SARS-CoV-2

Table 2 shows the relative weights estimated from the pairwise comparison matrix. CTNO₂ and FVA are the most important variables, with relative weights of 0.435 and 0.407, respectively, followed by MEE with 0.106 and, finally, RSB with 0.052. The consistency ratio index (CR) was 0.032, indicating a fair degree of con-

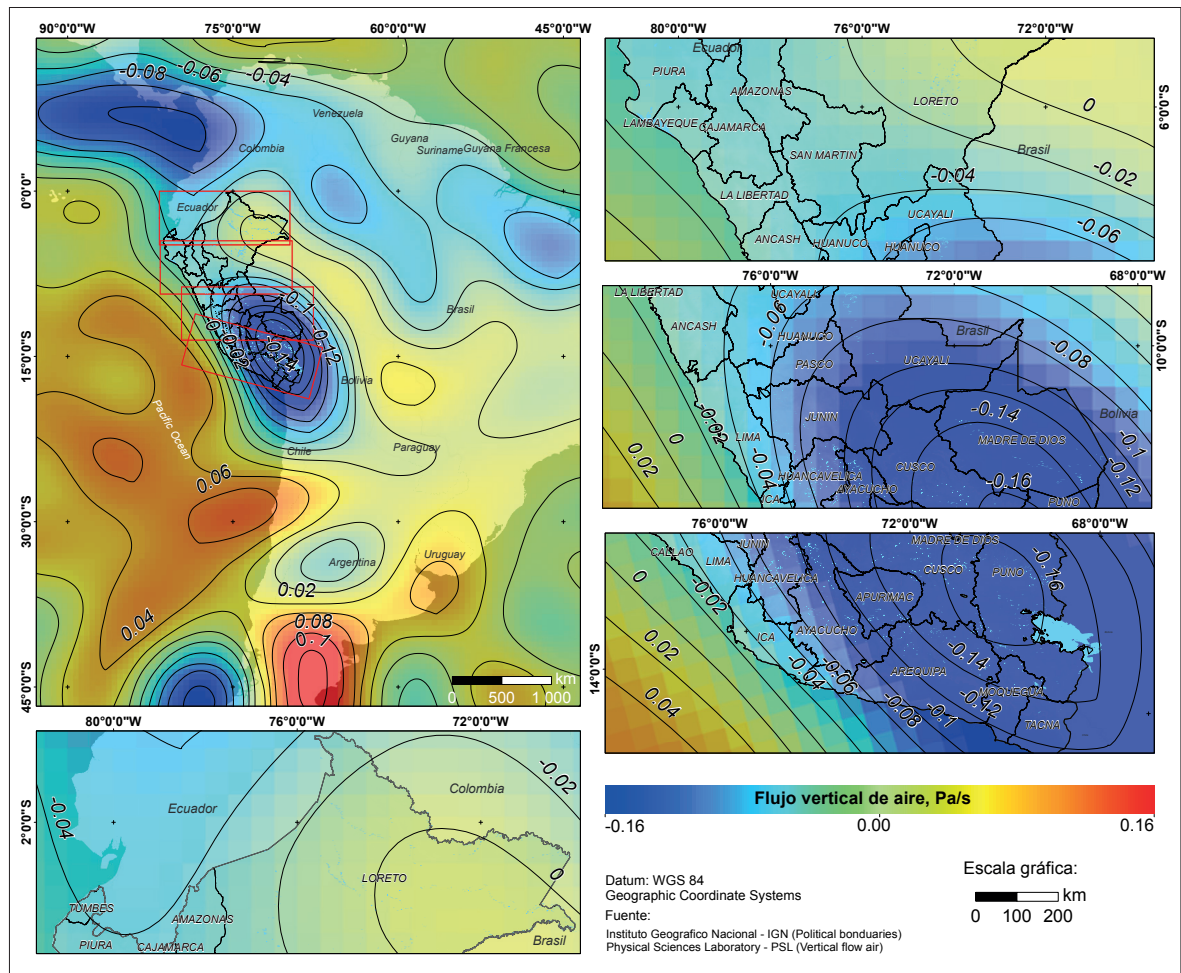
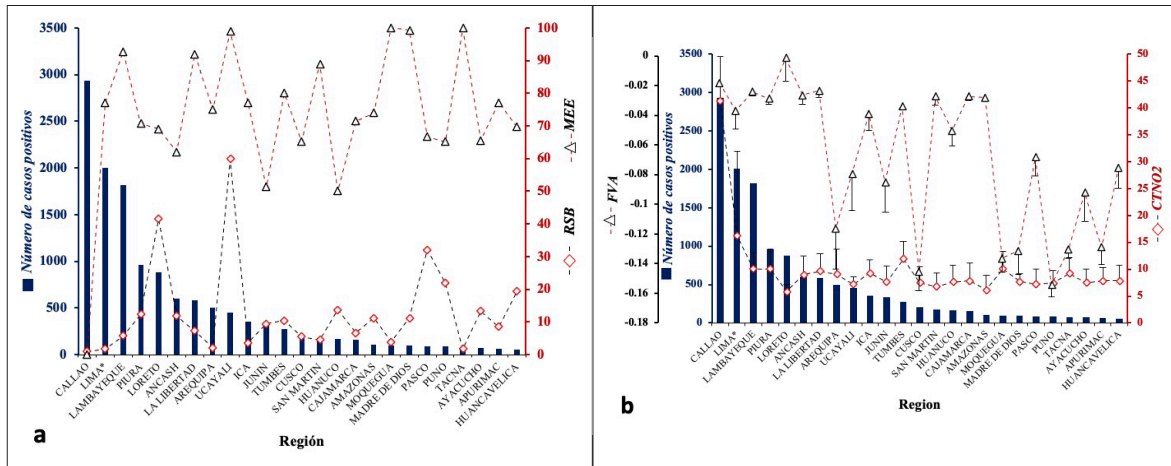


Figure 3. Vertical air flow - omega (Pa/s) at 850 mb. Panel a shows vertical air flow for a large part of South America. Enlargements in panels b, c, d, and e show vertical air flow characteristics in the regions of Peru. Values close to 0 Pa/s can be observed in b, c, and d.

Table 2. Pairwise comparison matrix, relative weights, and consistency ratio of the influence of the variables on the susceptibility to the SAR-CoV-2 virus.

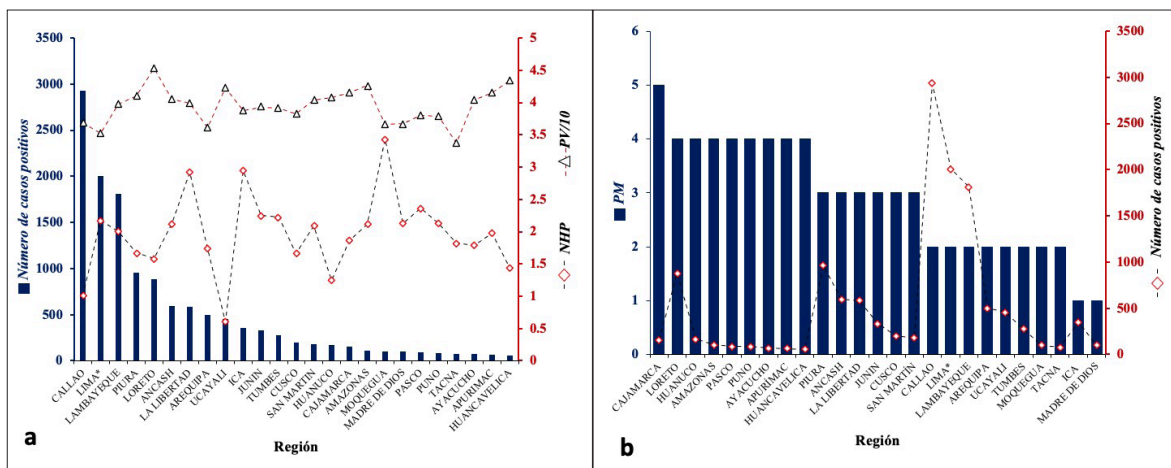
Variables	Pairwise comparison matrix				Relative weight
	CTNO2	FVA	MEE	RSB	
CTNO2	1.00	1.00	5.00	8.00	0.435
FVA		1.00	5.00	6.00	0.407
MEE			1.00	3.00	0.106
RSB				1.00	0.052

Consistency ratio (<0.08) = 0.032.



*Number of persons infected with COVID-19 in the Lima region is shown divided by 10.

Figure 4. Behavior of environmental variables in relation to the cumulative number of positive COVID-19 cases at the regional level in Peru. a) behavior of CTNO2 and FVA in relation to the number of people infected with COVID-19; b) behavior of MEE and RDB in relation to the number of people infected with COVID-19.



*Number of people infected with COVID-19 in the Lima region is shown divided by 10.

Figure 5. Behavior of social variables in relation to the cumulative number of COVID-19 cases at the regional level in Peru, including the constitutional province of Callao. a) Behavior of NHP and PV in relation to the number of COVID-19 cases; b) behavior of PM in relation to the number of COVID-19 cases.

sistency in the weight assigned to the variables analyzed.

The four driving environmental variables were included into an index of susceptibility (IS_{SC2}) of the regions to the SAR-CoV-2 virus; the index was constructed as the weighted sum of the four variables, as shown in Equation 1.

$$IS_{SC2} = 0.43 \times TCNO2 + 0.407 \times VA - 0 + 0.106 \times WED + 0.052 \times SWO \quad (1)$$

Vulnerability to SARS-CoV-2

Table 3 shows the relative weights assigned to the vulnerability variables through the AHP. NHP was the most important variable, with a relative

Table 3. Pairwise comparison matrix, relative weights, and consistency ratio of the influence of the variables on the vulnerability to the SAR-CoV-2 virus.

Variables	Pairwise comparison matrix			Relative weight
	NHP	PV	PM	
NHP	1.00	2.00	4.00	0.557
PV		1.00	3.00	0.320
PM			1.00	0.123

Consistency ratio (<0.04) = 0.017.

weight of 0.584, followed by PV with 0.297 and PM with 0.118.

The three variables analyzed were integrated into an index of vulnerability (IV_{SC2}) to the SAR-CoV-2. The index was constructed as the weighted sum of the three variables, as shown in Equation 2.

$$IV_{SC2} = 0.557xNHP + 0.320xVP + 0.123xMP \quad (2)$$

The product of the susceptibility and vulnerability values yields values representing the risk level to the SAR-CoV-2 virus (CENEPRED, 2015). Figure 6 shows regional-level maps of susceptibility, vulnerability, and risk to the SAR-CoV-2 virus; values in these maps were classified into four levels (low, medium, high, and very high) for easier interpretation (Pourghasemi, Pradhan and Gokceoglu, 2012) landslide locations were identified by aerial photographs and field surveys, and a total of 78 landslides were mapped from various sources. Then, the landslide inventory was randomly split into a training dataset 70 % (55 landslides).

Lambayeque, Callao, Tumbes, and Lima showed a very high susceptibility to the spread of SARS-CoV-2. In addition, La Libertad, Piura, Loreto, Ancash, Cajamarca, Amazonas, Ica, San Martín, Huancavelica, and Pasco showed a high susceptibility. Most of these regions are located in the northern part and the central coast of Peru. The rest of the regions exhibit a medium or low (Cusco region) susceptibility. All the regions with very high susceptibility are located on the coast of Peru.

Huancavelica, Huánuco, Ucayali, Amazonas, and Loreto showed a very high vulnerability to the spread of SARS-CoV-2. Four other regions located

in southern Peru (Moquegua, Apurímac, Cusco, and Arequipa), two in central Peru (Pasco and Callao), and four located to the north (Tumbes, Piura, Cajamarca, and Ancash) exhibited a high level of vulnerability. All the other regions showed medium to low vulnerability.

The Callao and Tumbes regions showed a very high risk level. Piura, Loreto, Lambayeque, Huancavelica, Amazonas, Cajamarca, Ucayali, Huánuco, Ancash, Moquegua, Pasco, Ayacucho, San Martín, La Libertad, and Apurímac were under a high risk. All other regions exhibited a medium risk level.

DISCUSSION

Environmental Variables

CTNO₂ maps for the regions of Peru showed notable reductions in NO₂ levels from pre- to post- lockdown periods. The magnitude of these reductions as up to three times higher in regions with high population density, intense industrial activity, and large motor car fleet such as Arequipa, Callao, Lima, and Piura. The highest tropospheric CTNO₂ values were recorded in coastal regions (north, center, and parts of the south), some of them in Lima, Callao, Lambayeque, and Piura, regions where the largest numbers of positive COVID-19 cases were recorded.

The lowest CTNO₂ values were found in the Amazonas region — one of the ten regions with fewest confirmed cases of COVID-19. This suggests a likely direct relationship between CTNO₂ and the number of confirmed COVID-19 cases, as shown by Ogen (2020). In addition, Wu et al.

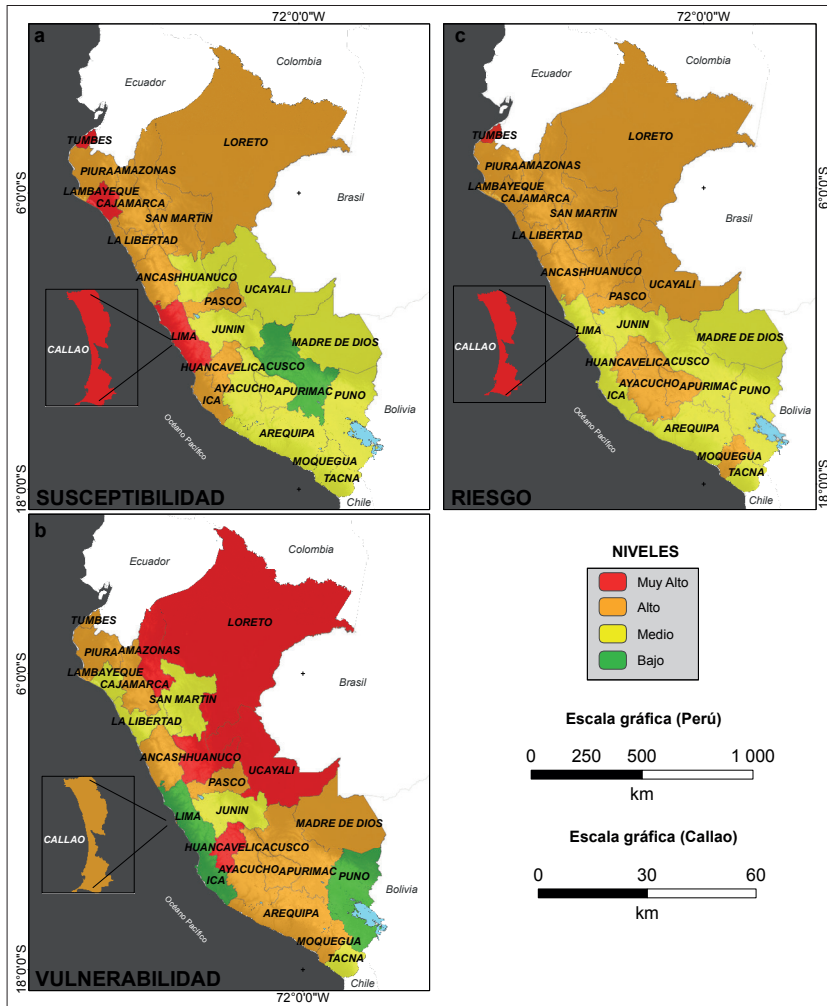


Figure 6. Maps showing levels of a) susceptibility, b) vulnerability, and c) risk to the spread of the SARS-CoV-2 virus.

(2020) mentioned that long-term exposure to poor air quality might exacerbate the COVID-19 symptoms, and even the mortality risk from this disease.

The highest FVA value, <-0.02 Pa/s (close to 0) was found in Loreto, one of the five regions with the largest numbers of positive COVID-19 cases. In contrast, the lowest FVA value (> -0.16 Pa/s) was observed in Puno, one of the five regions with fewest positive COVID-19 cases. This suggests a likely direct relationship between the regions with more stable FVA (which favors the buildup of pollutants) and the number of positive COVID-19 cases.

In summary, we found that high CTNO₂ values and FVA values very close to 0 Pa/s prevailed in the

regions with the largest numbers of positive COVID-19 cases. That is, conditions of atmospheric stability prevail in those regions, which boost the buildup of atmospheric pollutants, including NO₂, near the ground. Wang et al. (2020) mentioned that environmental conditions may be linked to the rate of spread of SARS-CoV-2 and the severity of the disease.

Regions such as Loreto and Ucayali showed MEE values above 40%. According to SUNASS (2015), these two regions lack wastewater treatment plants with disinfection treatment. The regions on the Peruvian coast, where the largest numbers of positive COVID-19 cases have been observed, show MEE $<15\%$. These findings do not

support a relationship (direct or inverse) between MEE and the number of positive COVID-19 cases. Nevertheless, the lack of access to basic sanitation services could give rise to public health issues related to COVID-19 contagion, as the virus has been reported to be present in feces from infected people (Ahmed et al., 2020; Medema et al., 2020; Rosa et al., 2020; Wu et al., 2020; Wurtzer et al., 2020; Zhang et al., 2020).

The Loreto and Ucayali regions showed RSB values over 40%. Although no direct relationship was found between this factor and the number of positive COVID-19 cases at the regional level, special precautions should be taken in the management of solid waste from people infected with COVID-19 as this is a potential transmission route (Association of Cities and Regions for Sustainable Resource Management, 2020; SWANA, 2020). Van Doremalen et al. (2020) pointed out that the time the virus remains in stainless steel, plastic, cardboard, and copper waste materials, is possibly related to the number of positive COVID-19 cases, since the virus can remain active in these types of solid wastes for several hours. Therefore, the solid waste recycling measure adopted by the Peruvian government (through decree D.S. N° 080-2020-PCM) may increase the number of cases of COVID-19 infections in workers involved in solid waste management.

Social Variables

NHP showed no apparent relationship with the number of positive COVID-19 cases. The health emergency caused by COVID-19 has put the Peruvian healthcare systems to the test, where the number of healthcare human resources (RHS) is only 1.3 per 100,000 inhabitants (Diario Gestión, 2018), whereas the Pan American Health Organization (PAHO) suggests that RHS should be at least 2.3 per 100,000 inhabitants (PAHO, 2015). The World Health Organization (2020) such as SARS-CoV and MERS-CoV, in mind and in consultation with member states. This information will help national authorities to i pointed out that saturated healthcare systems lead to exacerbated morbidity and higher disability and mortality from both COVID-19 and other preven-

table and treatable conditions. Despite multiple efforts by the government, the healthcare system of Peru is approaching its capacity limit (El Diario, 2020).

The VP ranges between 30% and 45% in all regions. According to Vohora (2017), vulnerable populations are at greater risk during adverse scenarios. We found that the regions with the largest numbers of positive COVID-19 cases are located in the northern areas of Peru and fall into MP classes 2, 3, and 4. Ahmed et al. (2020) mentioned that socioeconomic disadvantages and inequalities become more evident during epidemics. The economic impact of COVID-19 in Peru has led to higher unemployment rates (Vinelli and Maurer, 2020).

Analytical Hierarchy Process

This study used the AHP to combine environmental and social variables. We found a high or very high risk of spread of SARS-CoV-2 mostly in northern and central Peru, as well as in some southern regions. This results from the high vulnerability and susceptibility levels found in those regions.

The results from our model might be limited by the relatively few variables analyzed; nevertheless, this is the first study that examines environmental and social variables for Peru and showing, in relatively simple terms, results that are consistent with those reported by CDC-MINSA (2020). The latter study found that 60% of the regions of Peru should strengthen their care and control of COVID-19 cases; our study found that 68% of the regions are at high or very high risk of spread of SARS-CoV-2. In addition to the areas identified by CDC-MINSA (2020), our results suggest that the San Martín and Ayacucho regions should also be included among the priority areas. The study by Yaser Burhum (2020) showed that, as of 16 May 2020, all regions of Peru had an R index greater than 1, indicating that SARS-CoV-2 was still in the propagation stage. This could be related to the influence of environmental and social variables such as those analyzed in our study — and others not yet analyzed — on the virus propagation.

CONCLUSIONS

Our findings support the conclusion that CTNO₂ and FVA are directly related to the number of positive COVID-19 cases in all regions of Peru. However, other environmental and social variables show a direct relationship only in some regions. Thus, the effects of these variables supplemented each other in the AHP.

Social and environmental variables that may be related to the spread of SARS-CoV-2 were jointly analyzed in the AHP. Our findings are consistent with those from previous studies (CDC-MINSA, 2020; Burhum, 2020). We also conclude that, based on the variables analyzed, 68% of the regions exhibit a high or very high risk of spread of SARS-CoV-2, and such regions are mainly found in northern Peru. Therefore, special care should be taken during the post-lockdown period in regions such as Callao, Tumbes, Piura, Loreto, and Lambayeque to avoid a new outbreak and collapse of the healthcare systems.

Based on our results, we believe that the government should more vigorously promote public policies aimed at improving air quality, integrated solid waste management, and sanitation services through the public — urban and rural — sewerage network, to reduce the risk of spread of SARS-CoV-2. Given the little scientific evidence currently available, such measures should be carried out for precautionary purposes. Furthermore, we also suggest that the deficit of healthcare human resources and infrastructure should be addressed, and the social gaps should be diminished. The methods used in this study could be replicated at different scales, even including additional variables according to the reality of each study area.

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