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Air Quality Analysis In Pasco Peru Using Remote Sensing

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Abstract *— Air pollution has an important impact on health since it can cause health problems related to heart or lung diseases. In 2016 according to the World Health Organization (WHO), one in nine deaths worldwide was related to air pollution. In Peru, several areas are affected by air pollution. For example, the Pasco department is affected by different sources of air pollution. Considering this problem, remote sensing is an essential tool for monitoring air pollution. In this sense, the present study seeks to analyze the air quality in Pasco extracting the Aerosol Optical Depth (AOD) and the particulate matter less than 2.5 micrometers in diameter () from the aerosol satellite products of the Moderate Resolution Imaging Spectroradiometer (MODIS) that is on board of Terra satellite. These two parameters were extracted from 14 data sets of the study area in a period of analysis from 2019 until the first semester of 2021. Calculating the Aerosol Optical Depth (AOD), it was found that 57.14% of the data sets present an average value of AOD greater than the typical atmospheric values, between 0.1 and 0.15. Analyzing the maximum values, three months of 2020 show high concentrations: August presents a maximum value of 105.555 µg/m3, September presents a maximum value of 112.347 µg/m3, and November presents a maximum value of 105.555 µg/m3. Finally, Air Quality Index (AQI) was calculated from each data set; it was found that 42.86% corresponds to the category of Unhealthy.*

Keywords — *Air pollution, AOD $PM_{2.5}$, MODIS, Terra satellite, air quality index, AQI.*

I. INTRODUCTION

Air pollution is a mixture of particulate matter (PM) and gases in the air, such as nitrogen dioxide (), ozone (), and sulfur dioxide (). Some air pollutants are toxic, and inhaling them can increase health problems, such as strokes, lung cancers, and severe lung diseases [1].

According to the World Health Organization (WHO), in 2016, one in nine deaths worldwide was related to air pollution, which caused 4.2 million premature deaths [2]. On the other hand, that same year in the American continent, there were 44,000 deaths in high-income countries (HIC) and 93,000 deaths in low-and middle-income countries (LMIC) related to air pollution [3].

The World Health Organization (WHO), faced with air pollution and its impact on health, has proposed Air Quality Guidelines (AQG) [4], which identify the levels of pollution that are harmful to health and their sanitary effects. These guidelines recommend a maximum exposure of 20 µg/m3 for PM_{10} and a maximum of 10 µg/m3 for $PM_{2.5}$. In the Americas, five countries: the United States of America, Canada, Guatemala, Peru, and Bolivia, have adopted the WHO Air Quality Guidelines (AQG) to have lower levels for PM_{10} in their national legislation, and only Canada, the USA, and Guatemala for $PM_{2.5}$ [3].

Comparing compliance of the WHO ADQ between high-income countries (HIC), it is found that more than 80% of the countries evaluated to comply with the guidelines. On the other hand, only 10% of low-and middle-income countries (LMIC) complies with the ADQ guidelines in America [2,3].

In Peru, several areas are affected by air pollution; for example, Pasco is located in the mountains. It is considered the country's mining capital, as mining deposits of copper, silver, lead, and zinc were discovered. According to the General Directorate of Environmental Health (DIGESA), this area is affected by different sources of air pollution, such as emissions from heavy transport vehicles, mining, mineral clearance, and mining tailings deposits [5].

This contamination is causing severe consequences to the health of the inhabitants of Pasco. For example, in the province's capital, called Cerro de Pasco, a study was conducted by Source International and the Center of Popular Culture LABOR [6,7], and they studied the hair of 82 children (between 5 and 14 years old) to evaluate the concentration of heavy metals. The presence of 4 to 10 metals was identified in children's hair. Furthermore, 34% of children had low concentrations of zinc, selenium, and chromium, evidence of malnutrition, which is an indicator of toxic metal absorption.

Remote sensing is an important tool for monitoring air pollution; for example, in [8], air quality was studied between the years 2003 - 2017 in Colombia; data from the MODIS instrument were used to analyze the particulate matter $PM_{2.5}$ and PM_{10}, which was verified with data extracted from the Copernicus Atmosphere Monitoring Service (CAMS). As a result, a maximum of 75 µg/m3, 57 µg/m3 and 110 µg/m3 were found in $PM_{2.5}$ corresponding to Medellín, Bogotá, and Bucaramanga, which demonstrates the capabilities of CAMS and the Terra and Aqua satellites for the development of strategies against air pollution.

Similarly, in [9], satellite data from Terra, Aqua, Ozone Monitoring Instrument (OMI), and SENTINEL 5P were used to collect information such as aerosols and airborne particles caused by a fire. As a result, maximums of 35 µg/m3 in SO_2, 93 µg/m3 in NO_2, PM_{10} concentrations of up to 69 µg/m3 were obtained. These results were verified with in-situ data from OMI.

On the other hand, in [10], AOD data from the Terra and Aqua satellites were collected in order to analyze aerosol contamination in mining regions of India on the following dates: April 14 (phase 1), May 3 (phase 2), May 15 (phase 3) of 2020. A regional AOD decrease of 17% for phase 1, 22% for phase 2, 15% for phase 3, and metropolitan cities shows a decrease of 5 % for phase 1, 28% for phase 2, and 6% for phase 3.

Finally, in [11], a study was developed to evaluate the precision of the Aerosol Optical Depth (AOD) data from the MODIS sensor aboard the Aqua and Terra satellites, comparing them with data from the AERONET (Aerosol Robotic Network) station in the city of Huancayo in Peru from July to October 2019. It is essential to mention that Huancayo is located in the center of Peru in the middle of the Andes mountain range. When comparing the AOD and AERONET data obtained for the study area, the correlation coefficients (R) obtained were 0.794 for the Aqua satellite data and 0.796 for the Terra satellite data. As can be seen, the R values obtained in both cases are high, which means that the MODIS sensor performs optimal AOD recovery in the study area and period.

Given the problem in Pasco and the capabilities of remote sensing for monitoring air pollution, the present study seeks to analyze the air quality in Pasco using aerosol satellite products of the Moderate Resolution Imaging Spectroradiometer (MODIS). MODIS is on board of Terra and Aqua satellites, which will allow us to obtain the Aerosol Optical Depth (AOD) and extract the particulate matter less than 2.5 micrometers in diameter ($PM_{2.5}$) to create Air Quality Maps of the study area.

This study has the main objective of developing an air quality analysis, which will allow us to identify the areas most affected by pollution, generate identification maps of the affected areas in Pasco to propose measures to reduce this air pollution. Thus, the first step of a future monitoring system of air quality in Pasco will be developed since the inhabitants need to be aware of contamination levels because many children suffer from very severe health problems due to the constant exposure to this contamination.

II. AIR QUALITY ANALYSIS

A. Study Area

Pasco is a department of Peru located in the highlands of the Andes mountain range at 4380 meters above sea level. It is composed of three provinces: Pasco, Daniel Alcides Carrión and Oxapampa [12]. Pasco province is composed of 13 districts, and their capital is Cerro de Pasco. Daniel Alcides Carrion province comprises eight districts, and their capital is Yanahuanca. And Oxapampa province is composed of 9 districts, and their capital is Oxapampa.

Fig. 1 Selected study area

According to the National Institute of Statistics and Informatics (INEI) [13], it has 304 158 inhabitants and has been considered the mining capital of Peru since the century XVII, since copper, silver, lead, and zinc mining deposits were discovered.

Unfortunately, since the last century, Pasco has been polluted by different sources of atmospheric pollution, such as emissions from heavy transport vehicles and public transport, mining exploitation, mineral waste, and mining tailings [14,15].

For 2019, the Ministry of Energy and Mines of Peru (MINEM) reports that 1,154 mining concessions have been granted in the department of Pasco; 17 units are in production, and 40 are in exploration. The mining investment in the department of Pasco was US$ 177 million for the year 2018. [16]

According to the Ministry of Energy and Mines of Peru (MINEM) in 2021 [17], the number of formalized mining entities in the department of Pasco is 41, of which eight are in the province of Pasco, four are in the province of Daniel Alcides Carrión, and 29 are located in the province of Oxapampa.

The Ministry of Energy and Mines indicates that for 2019 in the department of Pasco, there are eight main mining units in operation [18], as can be seen in Fig. 2, these main mining units are located mainly in Pasco province, of which 50% are underground mining units and the other 50% are surface mining units. The main products extracted by these mining units are zinc, silver, copper, lead, gold, arsenic, bismuth, and kaolin.

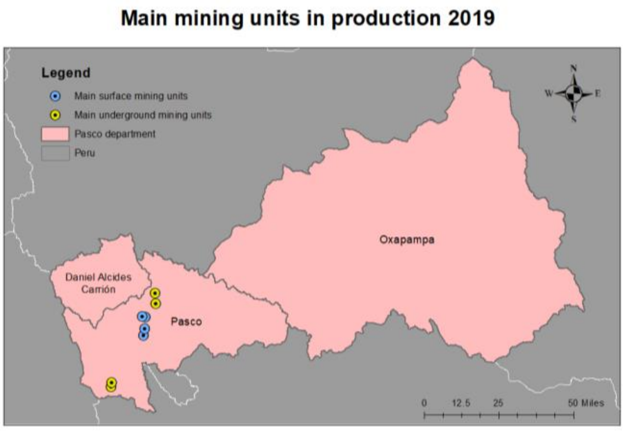

Fig. 2 Main mining units in production in Pasco 2019

According to the state agency, Activos Mineros [15], Pasco province concessions 74% of its territory for extractive mining activities. It is estimated that there are 78 million tons of tailings dispersed in 115 hectares of Pasco province. This contamination is causing severe consequences to the health of the inhabitants of Pasco, which has been known since 1990 when the General Directorate of Environmental Health (DIGESA) [14,15] detected that children between 6 and 8 years old had high levels of lead in their blood, this value oscillated 15.5 µg/dl when what is allowed by the World Health Organization is 10 µg/dl.

Besides, according to the General Directorate of Environmental Health (DIGESA) in 2005 [19], the suspended particles discharged in Pasco's atmosphere had a mineral composition where iron, manganese, zinc, lead, and copper predominated. The total of particles was estimated at 3737 Tm/year. 56% of the emissions correspond to the type PM_{10}, and at least 99.8% were because of the mining activity in the area.

These indicators did not improve for 2016, as a study by Source International and Centro de Cultura Popular LABOR identified between 4 and 10 metals in children's hair in the area [6,7,20].

In addition, according to the Regional Health Directorate (DIRESA) [12], the department of Pasco reports that 60.6% of children under three years of age suffer from anemia, and 24.8% report chronic child malnutrition, placing the department of Pasco in third place at the national level in both indicators. For experts, malnutrition and anemia are indicators of heavy metal poisoning in Pasco children [7]. Furthermore, the anemia indicator demonstrates exposure to high and prolonged levels of heavy metals [21].

Therefore, the study area selected for this research is the department of Pasco and its three provinces.

B. Data Sets

NASA's Earth Observation System (EOS) program comprises the Terra satellite, launched in December 1999, and the Aqua satellite, launched in May 2002 [22]. One of the multiple remote sensors onboard both satellites is MODIS (Moderate Resolution Imaging Spectroradiometer).

The MODIS instrument onboard the Terra and Aqua satellites provides 36 spectral bands with wavelengths from 0.405 µm to 14.385 µm, obtaining two-band images with a nominal resolution of 250 m at nadir, with five bands at 500 m and the remaining 29 bands at 1 km [23]. In addition, it has a radiometric resolution of 12 bits and a temporal resolution that provides global coverage every one or two days.

For the present research, the atmospheric aerosol product of the MODIS instrument onboard the Terra satellite will be used; this is a level 2 product (MOD04) and monitors the optical thickness of the ambient aerosol. The product MOD04_L2 is provided with a spatial resolution of 10 km at nadir, and the product MOD04_3K is provided with a spatial resolution of 3 km [24]; both products are available in MODIS Collection 6.1. It is important to highlight that the aerosol product required to obtain the ambient aerosol optical properties for developing the present study, at level 2, is only available in two spatial resolutions, 10km, and 3km. Besides, as mentioned in [25] in earlier collections, only one aerosol product existed (MOD04_L2) at 10 km resolution. In Collection 6, the Dark Target aerosol algorithm was used to create a new 3 km aerosol product (MOD04_3K), which will be used for the present study.

The Quality Assurance (QA) of the data sets obtained indicates the quality of the image recovered by the sensor. The quality assurance scale goes from 0 (poor quality) to 3 (good quality) for ground products. A QA of 3 is suggested for ground products and is recommended for use in the quantitative analysis [26, 27]. In the present study, all the data sets obtained presented a QA of 3.

The data sets used for the present analysis can be seen in Table 1:

Table 1. Selected datasets

Year	Date	DataSet
2019	29/05/2019	MOD04_3K.A2019149.1545.061.2019150013911
	30/06/2019	MOD04_3K.A2019181.1545.061.2019184031520
	15/08/2019	MOD04_3K.A2019227.1555.061.2019228035134
	18/09/2019	MOD04_3K.A2019261.1545.061.2019262012932
2020	28/01/2020	MOD04_3K.A2020028.1520.061.2020029012525
	25/03/2020	MOD04_3K.A2020085.1515.061.2020086011757
	20/07/2020	MOD04_3K.A2020202.1530.061.2020203011820
	30/08/2020	MOD04_3K.A2020243.1525.061.2020244012415
	12/09/2020	MOD04_3K.A2020256.1455.061.2020257011405
	5/11/2020	MOD04_3K.A2020310.1555.061.2020311012555
2021	20/02/2021	MOD04_3K.A2021051.1535.061.2021054234446
	8/03/2021	MOD04_3K.A2021067.1535.061.2021068033810
	15/04/2021	MOD04_3K.A2021105.1500.061.2021106015222
	27/05/2021	MOD04_3K.A2021147.1535.061.2021148014157

A total of 14 data sets from 2019, 2020, and 2021 were processed from the study area in Pasco. This department is located in the coordinates 10°25'47.17"S and 75°09'30.40"W.

Pasco is a region that has presented a persistent cloud cover throughout the years of study; this was the main problem since MODIS is a passive sensor affected by the cloud cover [28]. According to [24, 29], the MODIS Aerosol Optical Depth retrieval algorithm has a stage to determine which pixels are cloudy to develop a cloud mask and filter the cloud cover. After the cloud mask stage, as explained in [30, 31], if there are less than twelve cloud-free pixels in a box of 20 x 20 pixels, then no AOD is calculated. Due to this procedure in the AOD retrieval algorithm, it is not convenient to process cloudy images since AOD data are often missing in cloudy pixels.

For this reason, only those products that present a cloud cover of less than 15% were selected to develop a correct analysis of the presence of aerosols in the study area. In order to monitor the cloud cover in Pasco, the EOSDIS Worldview portal of NASA was used, identifying the dates with the appropriate cloud cover for the analysis.

Finally, the MODIS aerosol data sets were downloaded from the NASA Earthdata web portal through the LAADS web application at the following link: https://ladsweb.modaps.eosdis.nasa.gov/.

C. Treatment of Satellite Images

Once the data sets from the MODIS instrument have been downloaded, it is necessary to develop the treatment of these images to extract the necessary information. The procedure developed for the treatment of the data sets can be seen in Fig. 3:

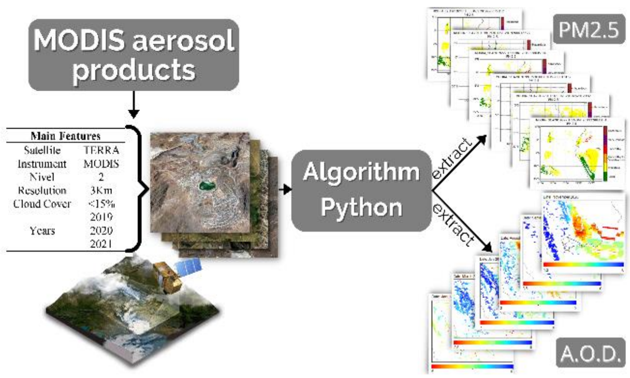

Fig. 3 Block diagram for treatment of the images

As shown in Fig. 3, to automate the treatment of the MODIS aerosol products, an algorithm in Python was developed to extract the Aerosol Optical Depth (AOD) and the values of the study region.

The Aerosol Optical Depth is the quantitative estimate of a load of aerosols present in the atmosphere. This optical measurement is made from the top of the atmosphere to the Earth's surface in a vertical column of 10 km2 [32].

As commented in the previous section, the aerosol data of the MOD04 product was used, a level 2 product that provides several Science Data Sets (SDSs), including the Optical_Depth_Land_And_Ocean, which is retrieved using the Dark Target Algorithm [23].

The algorithm generated in Python to treat the images, mentioned in Fig. 3, has the following flowchart:

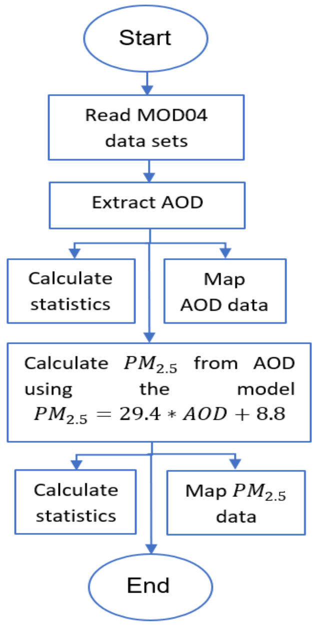

Fig. 4 Flowchart of the Python algorithm to treat the images

The algorithm programmed in Python has the function of reading the MOD04 data sets of the selected study area. In the second stage, the algorithm will extract the AOD data from the SDS of Optical_Depth_Land_And_Ocean. Then in a third stage, statistics of the AOD values will be calculated, and the extracted AOD data will be mapped. Subsequently, the $PM_{2.5}$ values will be calculated from the AOD data using a simple linear model, statistics will be calculated, and air quality maps will be developed.

Regarding the methodology to convert the data from AOD to $PM_{2.5}$, as seen in [33], there are different $PM_{2.5}$ prediction models from the satellite Aerosol Optical Depth (AOD), each of these approaches has its advantages and limitations. For the present study, the following linear regression equation was used to calculate $PM_{2.5}$ from AOD:

$$PM_{2.5} = Slope * AOD + Intercept \quad (1)$$

It is important to mention that investigations have been carried out to determine the AOD-$PM_{2.5}$ relationship for different parts of the world. Most of the investigations have been developed for North America and some Asian countries. At the moment, there is no local relationship established for Peru; that is why the slope and intercept values used for the AOD-$PM_{2.5}$ relationship used in the present study were extracted from [34] and is the following:

$$PM_{2.5} = 29.4 * AOD + 8.8 \quad (2)$$

In order to map air quality categories based on the extracted values $PM_{2.5}$, the Air Quality Index (AQI) defined by the Environmental Protection Agency (EPA) of the United States of America was used.

Daily AQI Color	Levels of Concern	Values of Index	Description of Air Quality
Green	Good	0 to 50	Air quality is satisfactory, and air pollution poses little or no risk.
Yellow	Moderate	51 to 100	Air quality is acceptable. However, there may be a risk for some people, particularly those who are unusually sensitive to air pollution.
Orange	Unhealthy for Sensitive Groups	101 to 150	Members of sensitive groups may experience health effects. The general public is less likely to be affected.
Red	Unhealthy	151 to 200	Some members of the general public may experience health effects; members of sensitive groups may experience more serious health effects.
Purple	Very Unhealthy	201 to 300	Health alert: The risk of health effects is increased for everyone.
Maroon	Hazardous	301 and higher	Health warning of emergency conditions: everyone is more likely to be affected.

Fig. 5 Air Quality Index

The AQI is established for five air pollutants, including carbon monoxide, nitrogen dioxide, sulfur dioxide, ground-level ozone, and particle pollution, including $PM_{2.5}$ and PM_{10}. This index is divided into six categories, each with a specific color and with different levels of concern for health [35].

III. RESULTS

After developing the image treatment stage of the 14 data sets, the values of Aerosol Optical Depth and $PM_{2.5}$ of the study area were obtained for the three years of study. The results were mapped and can be observed in this section.

Table 2 can be observed the average and standard deviation of AOD in the study area.

Table 2. Aerosol Optical Depth (AOD), Particulate Matter ($PM_{2.5}$) and Air Quality Index in the study region

Year	Date	DataSet	AOD Average	AOD Maximum	AOD Standar deviation	Max. PM 2.5 (μg/m3)	AQI	AQI Category
2019	29/05/2019	MOD04_3K.A2019149.1545.061.2019150013911	0.068	0.808	0.071	32.555	94	Moderate
	30/06/2019	MOD04_3K.A2019181.1545.061.2019184031520	0.091	0.782	0.062	31.791	92	Moderate
	15/08/2019	MOD04_3K.A2019227.1555.061.2019228035134	0.313	3.409	0.299	109.025	179	Unhealthy
	18/09/2019	MOD04_3K.A2019261.1545.061.2019262012932	0.312	1.737	0.251	59.868	153	Unhealthy
2020	28/01/2020	MOD04_3K.A2020028.1520.061.2020029012525	0.203	5.000	0.137	155.800	206	Very Unhealthy
	25/03/2020	MOD04_3K.A2020085.1515.061.2020086011757	0.166	2.603	0.128	85.328	166	Unhealthy
	20/07/2020	MOD04_3K.A2020202.1530.061.2020203011820	0.121	1.147	0.083	42.522	118	Unhealthy for Sensitive Groups
	30/08/2020	MOD04_3K.A2020243.1525.061.2020244012415	0.344	3.291	0.288	105.555	177	Unhealthy
	12/09/2020	MOD04_3K.A2020256.1455.061.2020257011405	0.9	3.522	0.438	112.347	180	Unhealthy
	5/11/2020	MOD04_3K.A2020310.1555.061.2020311012555	0.216	1.269	0.214	46.109	127	Unhealthy for Sensitive Groups
2021	20/02/2021	MOD04_3K.A2021051.1535.061.2021054234446	0.223	1.269	0.118	46.109	127	Unhealthy for Sensitive Groups
	8/03/2021	MOD04_3K.A2021067.1535.061.2021068033810	0.166	1.665	0.075	57.751	152	Unhealthy
	15/04/2021	MOD04_3K.A2021105.1500.061.2021106015222	0.099	1.036	0.079	39.258	110	Unhealthy for Sensitive Groups
	27/05/2021	MOD04_3K.A2021147.1535.061.2021148014157	0.094	0.726	0.064	30.144	89	Moderate

It is essential to mention that typical atmospheric values are between 0.1 and 0.15. Also, AOD values that are greater than 0.5 constitute high aerosol loading [36].

As shown in Table 2, the maximum average value of AOD in the data sets analyzed was registered in 2020 with a value of 0.344 and a standard deviation of 0.288. As can be observed, there is no data set analyzed that presents an average value of AOD greater than 0.5. In other words, there is no high aerosol loading predominantly in the data sets of the period analyzed. However, it can be seen that 57.14% of the data sets present an average value of AOD greater than the typical atmospheric values, between 0.1 and 0.15. Besides, 35.71% of the data sets present an average value of AOD lower than the typical atmospheric values.

Analyzing the column of the maximum value of AOD in Table 2, it can be observed that the maximum value registered in the study area corresponds to the year 2020 with a value of 5,000 and a standard deviation of 0.137. This value indicates that there are some portions of the image where high aerosol loading is being recorded. Besides, it can be seen that 100% of the data sets present a maximum value of AOD greater than the typical atmospheric values, between 0.1 and 0.15. Even it can be mentioned that maximum AOD values are greater than 0.5, thus constituting high aerosol loading.

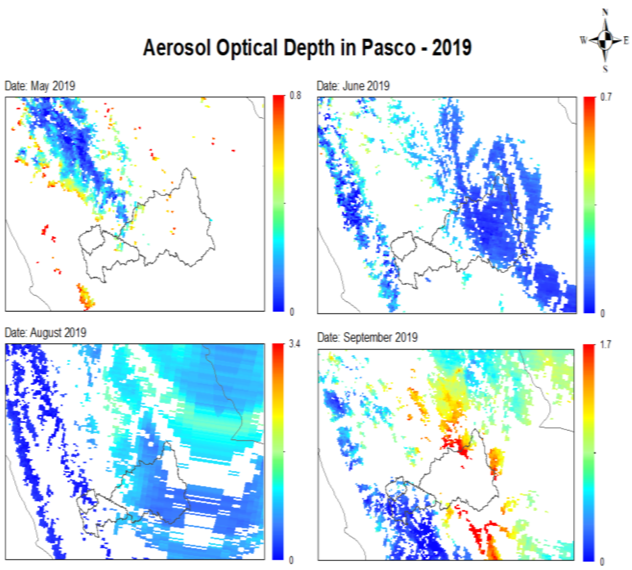

Fig. 6 Aerosol Optical Depth in Pasco - 2019

For 2019, images of the four months with a cloud cover of less than 15% were analyzed to measure the aerosols present in the atmosphere. These months were May, June, August, and September.

The maximum value of AOD in 2019, according to Table 2, was recorded in August, with a value of 3.409 and a standard deviation of 0.299. Also, in the same month, the maximum average value of AOD with a value of 0.313. The second maximum value of AOD of 2019 was recorded in September with a value of 1.737, an average of 0.312, and a standard deviation of 0.251.

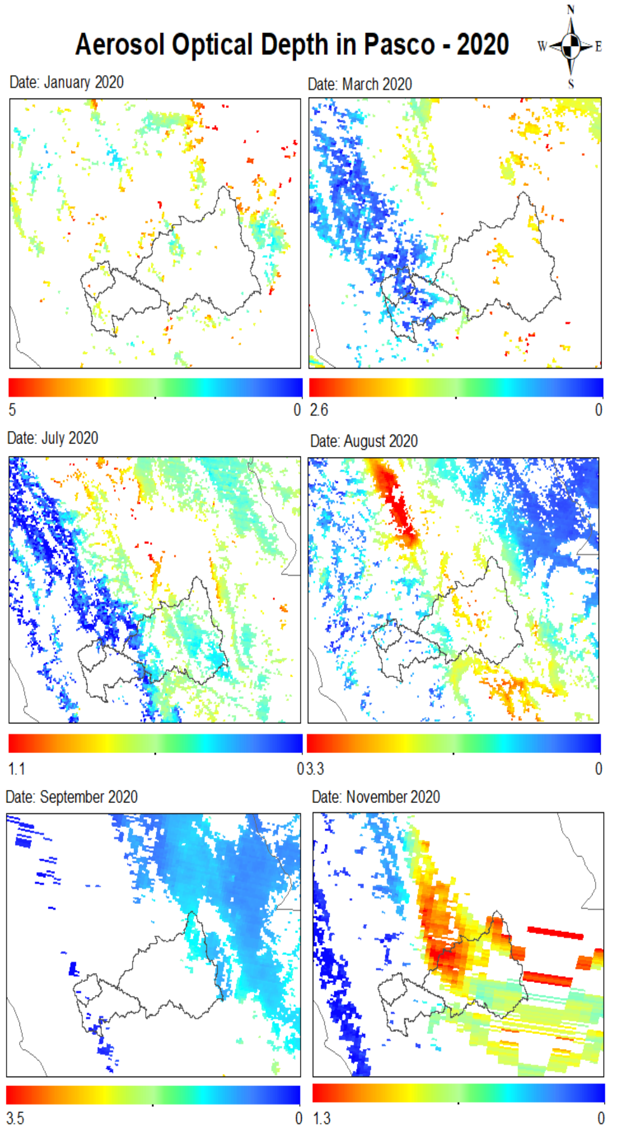

Fig. 7 Aerosol Optical Depth in Pasco - 2020

In 2020, images of six months were analyzed. The months that presented high levels of AOD in the study area, according to Table 2, were January and August. In August, the average value was 0.344. It is essential to mention that this value was the maximum average value of AOD between the six months analyzed. In the same month, it was recorded a maximum AOD value of 3.291 and a standard deviation of 0.288. Furthermore, in January, it registered an average value of 0.203, a maximum value of 5.000, and a standard deviation of 0.137.

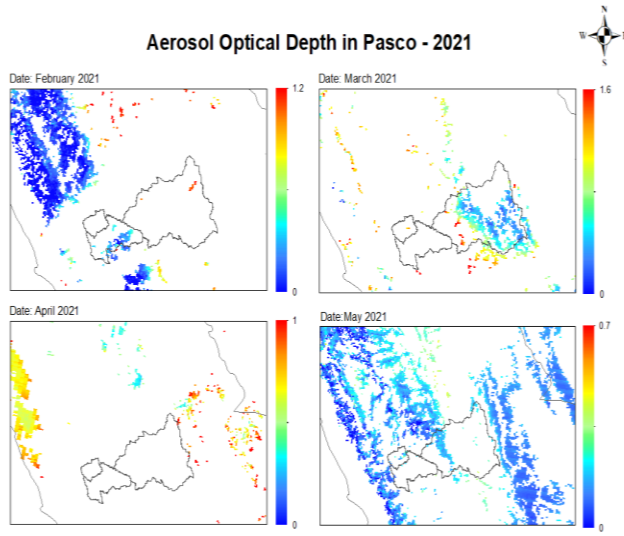

Fig. 8 Aerosol Optical Depth in Pasco - 2021

For 2021, only images from the first semester were analyzed, from which the data sets from February to May were selected since they had a cloud cover of less than 15%. Analyzing these data sets, it can be seen that, according to Table 2, the maximum average value was recorded in February with a value of 0.233, a maximum value of 1.269, and a standard deviation of 0.118.

In addition, the algorithm developed in Python obtains the $PM_{2.5}$ values of the analyzed data sets. In Table 2 can be seen that the highest maximum value $PM_{2.5}$ was registered in January 2020 with a value of 155.8 µg/m3. According to EPA, the calculated Air Quality Index for this registered value is 206 and has the category of very unhealthy since it causes a significant increase in respiratory effects in the general population.

Below, the mapping of air quality categories in the study region from 2019 to the first semester of 2021 is shown.

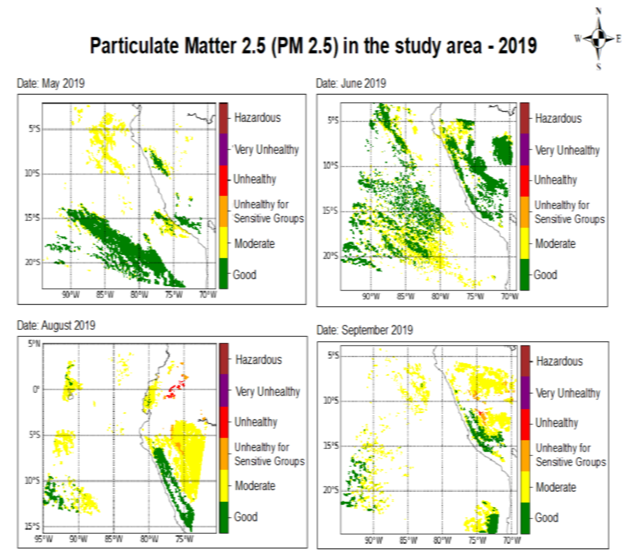

Fig. 9 Particulate Matter $PM_{2.5}$ in the study area – 2019

As shown in Fig. 9, four months of the year 2019 were analyzed, although it can be observed in the region a predominance of the categories of good air quality colored with green and moderate air quality colored with yellow. However, according to Table 2, it can be seen that August and September present maximum values of $PM_{2.5}$ 109.025 µg/m3 and 59.868 µg/m3, respectively, which are values categorized as unhealthy and colored with red in the map. The data for September is most relevant since these high concentrations $PM_{2.5}$ are located near Pasco.

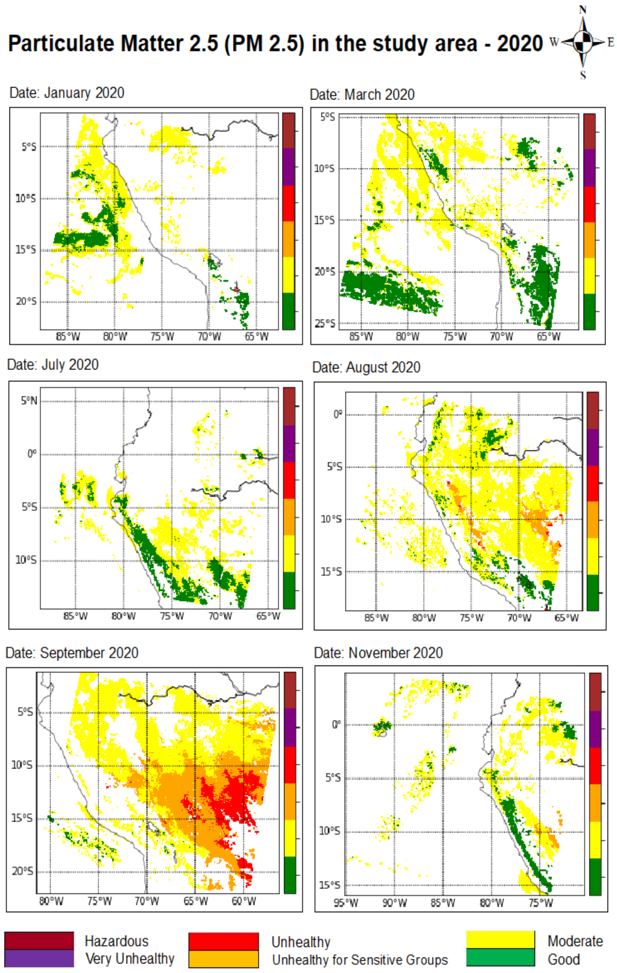

Fig. 10 Particulate Matter $PM_{2.5}$ in the study area - 2020

In Fig. 10, the analysis of six months of the year 2020 can be observed. There is a predominance of concentrations categorized as good and moderate colored with green and yellow in the air quality maps, respectively, but three months show high concentrations $PM_{2.5}$ in large areas near Pasco. According to Table 2, the month of August presents a maximum value of $PM_{2.5}$ 105,555 µg/m3 categorized as unhealthy, the month of September presents a maximum value of $PM_{2.5}$ 112,347 µg/m3 categorized as unhealthy and the month of November presents a maximum value of $PM_{2.5}$ 105,555 µg/m3 categorized as unhealthy for sensitive groups.

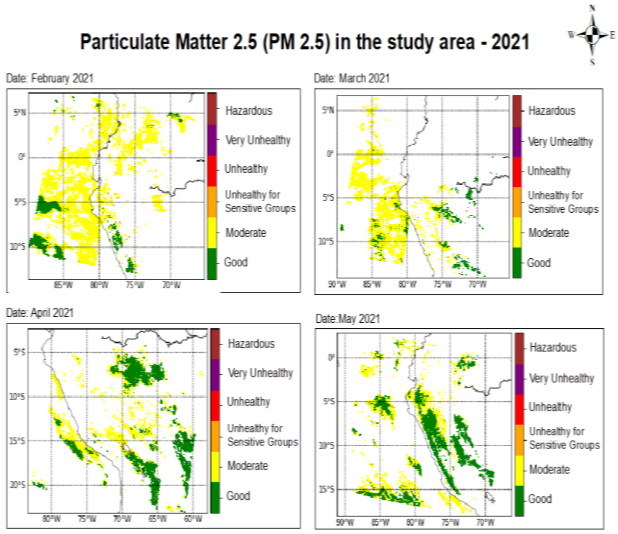

Fig. 11 Particulate Matter $PM_{2.5}$ in the study area - 2021

In Fig. 11, it can be seen the analysis of four months of the year 2021. In the air quality maps, it can be observed that there is a predominance in the studied region of concentrations categorized as good colored with green and moderate colored with yellow. According to Table 2, the month of March presents the highest maximum value $PM_{2.5}$ of the year 2021 with a value of 57.751 µg/m3, categorized as unhealthy and colored with red, but it can be observed in the air quality maps that these high concentrations do not occupy large areas.

IV. DISCUSSION AND CONCLUSIONS

Pasco is one of the 24 departments of Peru that is currently being affected by air pollution. The regional authorities indicate that the primary sources of contamination are diverse. However, since Pasco is predominantly a mining department, the leading causes of air pollution are mining extraction activities, mineral removal, mining tailings deposits, and emissions from heavy transport vehicles that transport the mineral.

Air pollution in Pasco is causing the contamination of soil, water sources, and of course, it is causing severe consequences on the inhabitants of this department. This negative impact has been evidenced by health authorities of Peru and non-governmental organizations that found the presence of 4 to 10 metals in the hair of 82 children between 5 and 14 years old and found evidence of malnutrition, which is an indicator of toxic metal absorption [6,7].

The present study analyzed the air quality in Pasco from 2019 to 2021, extracting the Aerosol Optical Depth (AOD) and the particulate matter less than 2.5 micrometers in diameter ($PM_{2.5}$) processing 14 aerosol satellite products from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard of Terra satellite.

It was evidenced by calculating the Aerosol Optical Depth (AOD) that 57.14% of the data sets present an average value of AOD greater than the typical atmospheric values, between 0.1 and 0.15. Besides, 35.71% of the data sets present an average value of AOD lower than the typical atmospheric values. Finally, in the study period analyzed, AOD average values greater than 0.5 were not found, so it could be said that there is no high aerosol loading predominantly in the data sets analyzed.

However, months with high maximum AOD values have been found, such as September 2019, which presented a maximum AOD value of 1.737. On the other hand, August and November 2020 presented AOD values of 3.291 and 1.269, respectively. Finally, the month of March 2021 presented a maximum AOD value of 1.665. Evaluating the maximum AOD values, it was found that 100% of the data sets analyzed present maximum AOD values greater than 0.5, which constitutes a high aerosol load, but analyzing the resulting air quality maps, it can be observed that they do not cover predominant areas.

Analyzing the maximum values $PM_{2.5}$ for the study area and analyzed period, three months of 2020 show high concentrations of $PM_{2.5}$ in large areas close to Pasco. August presents a maximum value of $PM_{2.5}$ 105.555 µg/m3. Besides, the month of September presents a maximum value of $PM_{2.5}$ 112.347 µg/m3. Finally, the month of November presents a maximum value of $PM_{2.5}$ 105.555 µg/m3.

Furthermore, the Air Quality Index (AQI) was calculated from each data set analyzed, and it can be mentioned that 21.43% corresponds to the category of Moderate, 42.86% corresponds to the category of Unhealthy, 28.57% corresponds to the category Unhealthy for sensitive groups, and 7.14% corresponds to the category Very unhealthy.

As one can observe in this work, remote sensing is an essential tool for monitoring air pollution and creating air quality maps to identify the areas most affected by pollution.

Something important to mention is that different $PM_{2.5}$ prediction models from the satellite Aerosol Optical Depth are developed mainly for North America and Asia but not for Peru; this is due to the lack of ground stations that validate the aerosol data retrieved by satellites. For example, AERONET (Aerosol Robotic Network) is a federation of terrestrial remote sensing aerosol networks that collects distributed observations of ground-level spectral aerosol optical depth (AOD). Nevertheless, it is crucial to indicate that the only station installed for Peru is in Huancayo [37], approximately 200 km from the study area selected for the present study in Pasco.

The results from this work will allow the corresponding authorities to obtain air quality information with a broader spatial coverage to propose measures to reduce this air pollution and make better decisions based on satellite information. Besides, the population will be aware of these concentration levels and the health risk of constant exposure to this type of contamination.

As was mentioned before, the data set used for the present study, MOD04, is provided with a spatial resolution of 10 km (MOD04_L2); this resolution worked well for global analyses. On the other hand, the product MOD04 is provided with a spatial resolution of 3 km (MOD04_3K); this resolution is mainly for regional air quality analysis. However, for future work, it is recommended to use a high spatial resolution for local analysis in the different departments of Peru.

As was mentioned, Pasco is a region where clouds are persistent throughout the year; it is for this reason that it was difficult to pick cloud-free regions since analyzing cloudy areas can cause that MODIS, a passive sensor, could misclassify aerosol. Future work recommends using active sensors like the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO); this satellite can provide information on the vertical distribution of aerosols but with very limited coverage.

Finally, as future work, it is proposed to analyze the Ozone Monitoring Instrument (OMI) to obtain nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) measurements in order to evaluate the presence and concentration of these air pollutants in Pasco, Peru.

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