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# STRATEGY TO PLACE AIR QUALITY MONITORING STATIONS IN AREQUIPA INDUSTRIAL PARK

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**Abstract**

Industrial development in urban areas is a continuing problem for citizens and industries because of the constant air pollution complaints and respiratory illness. There is a lack of data in Arequipa, Peru for the environmental guidance of air quality and public health protection. The strategy proposed in this report is to determine the optimal locations of monitoring stations in Arequipa Industrial Park. Using the Analytic Hierarchy Process (AHP), we evaluated their relative preferences for locating each monitoring station. The strategy includes three main activities: 1) identification of land use (i.e., industrial, bus station, urban), and data collection (meteorology, chemical pollutants), 2) development and a hierarchy of criteria by AHP, and 3) design of the monitoring network by weighted overlay and geographic information system methods. First, three sustainable criteria (environmental, social, and economic) are evaluated with nine sub-criteria. Afterward, with the assigned weights, we obtained a random index of 0.58, a consistency index of 0.04, and a consistency ratio of 0.07. With this confirmation, sustainability was prioritized as follows: environmental (61.9%), social (28.4%), and economic (9.6%). Finally, we propose a monitoring network sustainability; it includes three monitoring stations. Competent parties can use this proposal to develop a rapid diagnostic capacity for both pollution episodes and impact the health of the industrial park Arequipa population.

*Key words:* Analytic Hierarchy Process, geographic information system, multicriteria analysis, optimal locations, sustainable criteria

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## 1. Introduction

Anthropogenic activities are considered the leading issuers of pollution in the atmosphere. By the World Health Organization (WHO) in 2006 (WHO, 2006), there is enough scientific evidence linking air pollution and adverse health effects on both plants, animals, and populations. Therefore, air pollution is considered a vital threat to human health and life quality (Lu et al., 2018). For example, in the US since 1970, prolonged exposure to $PM_{2.5}$ and sulfate were associated with the annual mortality rate in urban areas. It was recommended to collect information and continuously monitor them (Pope and Wu, 2014). Mortality due to cardiovascular diseases is caused by long and short exposure to PM. Due to respiratory diseases, mortality is caused by short exposure to ozone, nitrogen oxide, and sulfur dioxide (SWISS TPH, 2020). For these reasons, the WHO suggests that air pollutants should be measured at representative monitoring stations, which are high levels near neighborhoods, where there are emission sources such as roads, power plants, stores, supermarkets, and large stationary sources (vehicles) (Ceca et al., 2017). Especial measures are needed to be taken to reduce contamination levels to reference values for populations living in such areas. Therefore, estimates of public health benefits are considered part of the policy intervention to reduce air pollution.

The main problem in Arequipa Industrial Park

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is the accelerated and unplanned growth of industries (paper, textile, metallurgy), vehicle fleets (including the continuous automotive fleet and central bus stations), shopping centers, and food markets, which continually release harmful gases such as carbon monoxide (CO), nitrogen oxides ($NO_x$), sulfur dioxide ($SO_2$) and methane ($CH_4$) (EPA, 2017). On the other hand, the acceleration of fossil fuels used in many industries, transportation, and electrical energy, are also considered primary atmospheric pollution sources because of harmful effects on the population's health and environment. These activities also decrease agricultural, urban areas, and green parks, leading to an exponential deterioration of air quality.

Currently, air pollutant emissions generated by the industries are a persistent problem for Arequipa's inhabitants and industries because they are the origin of health, environmental, and social complaints between the stakeholders. Until 2016 in Arequipa, environmental pollution covered chemical agents from several different sources: the automotive fleet (60%), industries (21%), companies and commerce (11%), and industrial boilers (7%) (Flores, 2017). As reported by OEFA (2019), there were 86 cases of air pollution complaints, and in 76% of these complaints, municipalities and competent authorities were unable to take the correct measures and follow up on each case because of the lack of a monitoring network and ineffective control processes. Besides, air quality concerns are related to geophysical, meteorological, and socioeconomic factors, the latter due to the pressure exerted by the growth of the economy and the population.

On the other hand, it needs to consider that air quality problems are also related to geophysical, meteorological, and socioeconomic factors, the last due to the pressure exerted by the economy's growth and the population. Besides, being conditioned to economic restrictions is unheard of since, in Mumbai in 2012, it was estimated that the population's dynamic exposure to NO2 and PM10 pollutants due to health problems resulted in a total cost of USD 800 million, which is 4.24% of the GDP (Gross Domestic Product) of India (Mesbah, 2016).

In Peru, the Environmental Protection Agency (EPA) guidelines are used, which indicate that an air quality monitoring network (AQMN) should be "operated by state, tribal or local agencies to regional or local scale" (EPA, 2012). These authorities define pollutants' levels considered potentially injurious to the environment, public health, and the economy (EPA, 2012). Furthermore, monitoring networks are a requirement and their maintenance as well; that why EPA recommends assessments of monitoring networks every five years (40 CFR § 58.10, 2007).

Thus, Arequipa must create an adequate air monitoring network to protect the public welfare and the environment because the monitoring stations are considered the primary source of data for adequate environmental management of air quality and public health. On the other hand, choosing and installing appropriate locations should lead to better air quality studies and rapid diagnostic capacity. Therefore, an essential task for responsible authorities is to plan and configure a good air quality monitoring network (AQMN) effectively and systematically (Mofarraha and Husain, 2009). This task includes decisions that are sometimes complex and generally based on multidisciplinary knowledge that incorporates political, natural, social, and ethical sciences (Huang et al., 2011). As Trujillo-Ventura and Ellis (1992) mention, the complexity and size of environmental problems depend on the interconnection of their components; and the formulation of these large-scale environmental models has exceeded the ability to solve them. In addition, Modak and Lohani (1985) mention that complete models of the AQMN design are required to measure different types of synergistic pollutants simultaneously and to be able to estimate the missing values of each pollutant when it is necessary since then the economic issue has also been considered as a primary factor. Therefore, they used a multi-objective approach and multipollutant optimization, thus ensuring representative air quality patterns for each pollutant.

*The United Nations (UN)* in 1987 refers to sustainable development (SD), like the consumption of resources must be only the amount that is needed today; in this form, it will not compromise future needs. So the interconnection of the three pillars, such as environment, economy, and society, is considered essential (Giddings et al., 2002). An adequate Air Quality Monitoring Network (AQMN) has the primary goal of controlling the health and environment; therefore, establishing monitoring stations is primordial because these provide accurate and representative information (Si et al., 2016). For these reasons, we consider each of the three pillars essential pillars to develop our research.

According to Mohebali et al. (2020), the Multi-criteria decision-making (MCDM) methods can be used in environmental impact assessment; during the process, the reciprocal value compares the least dominant element with the most dominant element (Goepel, 2018). The AHP method presents greater air quality sensitivity, human health risks, land use, and economic issues (Mohebali et al., 2020). Furthermore, Huang et al. mention that the most efficient way to use AHP is taking into account environmental problems (water, air, energy, or waste), natural resources, and social sciences (Baby, 2013; Huang et al., 2011; Saaty, 2008). Consequently, the analytical hierarchy process (AHP) is chosen (Saaty, 2008); this hierarchical method connects decisions focused on measuring contributions to a goal structured in sub-objectives, attributes, and criteria, alternatives. Pisoni et al. (2008) recognize that the AHP method selects an efficient solution by considering an objective vector function of all the problem's objectives and emphasizing conflicts.

During this study, criteria are identified and developed from the AHP matrix, which are hierarchical alternatives for calculating the consistency index (CR), which must be less than or equal to 0.1. This CR confirms each sub-criterion's weighting percentage, considering the pollutants, meteorological aspects (Seinfeld, 1972), population, and emitters identified, which are also evaluated and monitored by AHP (Table 1).

The dynamics of GIS allow for the processing of multitemporal data using multivariate statistical analyses so that numerical records can be stored, which creates and develops a geodatabase. Besides, ArcGIS is a robust tool to enhance land suitability evaluation accuracy, creating thematic maps by interpolation method. For these reasons, we execute a multi-criteria GIS-based approach, which integrates environmental, economic, and social indicators (Pope and Wu, 2014). After each sub-criteria interpolation, we obtained just one thematic map and classified, including three main criteria by the weight overlay tool (includes ArcGIS), considering our percentages after each AHP matrix. Finally, in this investigation, we performed three main tasks:

1. Identification of land use (i.e., industrial, bus station, urban), meteorology data, and population focus.
2. Development and a hierarchy of criteria by AHP.
3. Design of the monitoring network by weighted overlay and geographic information system methods.

An air quality monitoring network by the AHP method and weight overlay are proposed to determine suitable air quality monitoring stations considering three main pillars by the weight overlay method.

## 2. Case study

### 2.1. Study zone

The study was carried out in Arequipa Industrial Park (Fig. 1). Its geographical center is located at 16°25'S, 71°32'4'W, and its average altitude is 2328 meters above sea level. Arequipa is affected by the famous "soot", which has light-absorbing properties that turn the energy of light into heat, which warms the air around it (EPA, 2012). The climate is dry from May until September. Wet season is from October to April and is characterized by the presence of clouds in the afternoon and some rainfall. In 2019, the maximum temperature was 26.45°C, the minimum temperature was 2.80° C, and the average temperature was 13.22°C. The maximum pressure was 76500 Pa, the minimum pressure was 75700 Pa, and the average pressure was 76152 Pa (ILRS, 2018). Around Arequipa, the maximum wind speed was 2.1 m $s^{-1}$, the minimum wind speed was 1.3 m $s^{-1}$ and the average wind speed was 1.8 m $s^{-1}$. Global solar radiation was between 850 and 950 W $m^{-2}$. Arequipa has one of the highest radiation rates in South America because of its proximity to the Atacama Desert.

### 2.2. Experimental procedure

#### 2.2.1. Criteria and sub-criteria identification and data collection

Based on the United Nations definition of sustainable development (SD) (Giddings, et al., 2002; UN, 1987) and the AHP method (Bystrzanowska and Tobiszewski, 2018), three sustainable criteria are recognized.

Then, for each criterion, we select environmental sub-criteria (Mesbah, 2016) (pollutants, emission sources, meteorology) (Huang et al., 2011), social (population) (Pope and Wu, 2014), and economic (Fig. 1) (Baby, 2013; Chalabi et al., 2017; Hacioglu et al., 2016; Kumar and Kumar, 2016; Lu et al., 2018; Mesbah 2016; Rotatori et al., 2011).

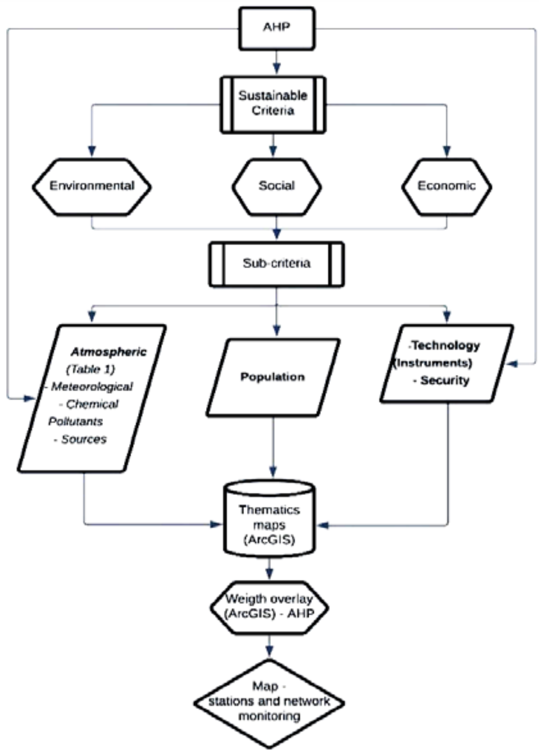


**Fig. 1.** Methodological setting

Within each sub-criterion, we see the need to collect and create data and design the thematic maps of land use (types of activities and emission sources), meteorological information (wind speed, temperature, relative humidity, precipitation, topography) (MINEM, 2016), pollutants chemicals (CO, PM10, NO2, H2S) (Fig. 3a, b, c, and d), population centers and costs (technology and security) (Pope and Wu, 2014). These are a guide that is necessary to keep these criteria independent at the beginning of the process. Moreover, in the end, all the collected variables must be combined by weight overlay. On the other hand, it is essential to consider possible obstructions in the study area and nearby buildings and trees, rivers that could affect airflow, and congested traffic areas (Chalabi et al., 2017; Hacioglu et al., 2016).

#### 2.2.2. Development of criteria and modeling using the Analytic Hierarchy Process (AHP)

The AHP decomposes a complex decision problem into smaller sections, creating a hierarchical tree, and therefore AHP is considered a multi-objective analytical tool. According to the hierarchy levels, each element is evaluated by its preferences relative to the next highest level (Hacioglu et al., 2016). The intensity of preference between two elements is based on the Saaty scale, ranging from 1 to 9 (Saaty, 1994). This scale allows evaluating the advantage of one element over another by using the characteristic or equated property. The minimum value is 1 (equal importance), and the maximum value is 9 (extreme dominance of an element). The AHP algorithm consists of 4 phases: (1) Setting the hierarchic structure of sustainability, (2) Calculations of the relative and absolute weights, for which information was collected from 3 professionals in an excel matrix, (3) the analysis coherence, and (4) the construction of the eventual classification (Baby, 2013; Hacioglu et al., 2016; Saaty, 2008). For the confirmation, AHP uses the consistency index (*CI*) and the consistency relation (*CR*), defined in Eqs. (1-2) (Saaty, 2008):

$$CI = \left(\frac{\lambda_{max} - n}{n-1}\right) \quad (1)$$

$$CR = \left(\frac{CI}{RI}\right) \quad (2)$$

where: $\lambda_{max}$ – maximum eigenvalue; $n$ – number of parameters in the matrix; $RI$ – random index (Mofarraha and Husain, 2009).

*2.2.3. Design of monitoring network using satellite image information, ground level concentrations and GIS*

The geographic information system (GIS) is a tool that helps you understand geography and make smart decisions. GIS also helps us organize and select necessary data for specific tasks and the entire project. Besides, GIS manages statistical and spatial data to provide us a tool that shows the relationship between air quality and population (health), environmental, and emission sources. ArcGIS is used to enhance, process, and interpret satellite imagery, combined with geographic tools that provide real images and geospatial research data (Pope and Wu, 2014).

On the other hand, remote sensing is a widespread technique in soil classification, air quality, temperature, and others. The most common and easily acquired are the Landsat MSS, Landsat TM, ETM+, SPOT HRV, and Sentinel (Alföldy et al., 2007; Verma et al., 2009). Besides, some special sensors monitor air quality, such as Aura and Sentinel 5. Because of it is needed to review each sensor's properties that must be considered before image processing. For our study, the use of Landsat 8 images is essential because it is necessary to generate information for the classification of land use as well as: urban zone, sources of emission, trade, roads, population (Fig. 1) and generate a digital elevation model (DEM). Based on the need for correctly georeferenced satellite images, we use high precision GSP with the DELTA-GT3 receiver and the Choke Ring antenna (JAVAD, 2012a; 2012b).

The data collected from the three measured sources (environmental, social, and economic) is archived and linked in an ArcGIS database system. Where each collected data is georeferenced, that is, stored in geographic coordinates. The creation of the database in a GIS is designed for planning a temporary air quality network: that is, it works as a decision tool, and it is necessary due to the lack of data in our study area, and there is a reference monitoring station more than 8 km from the industrial zone.

We use GIS to examine industrial activities in the area, meteorological data, the existing emissions inventory, and the study area's baseline information (Fig. 2). In addition, we considered possible obstructions, such as nearby buildings, which could affect airflow, high traffic areas, and industrial zones (Hacioglu et al., 2016). With the data obtained in the temporary stations (Fig. 2), we create interpolated maps used as the primary reference for the atmospheric sub-criterion. Simultaneously, the rest of the data obtained are also interpolated as a baseline where the probabilistic (ordinary and universal kriging) is applied, which generate data for the classification according to each factor, so we establish five values that help us to reassign them in each classified map, which are: optimal (5), very adequate (4), adequate (3), acceptable (2) and unacceptable (1) (DIGESA, 2015; MINEM, 2016; Réquia, et al., 2015). Within each sub-criterion, each layer has the same numerical fixation and pixel size (5x5 m). Finally, the weight overlay function is applied with the weighting percentage obtained by the AHP method (Fig. 3). The final decision differs from multicriteria analysis, interpolation diagrams, and weight overlay (Rotatori et al., 2011).

## 3. Results and discussion

Based on the data obtained, we generated average, maximum, and minimum contamination values (every 1 hour, 8 hours, and 24 hours) by following the Peruvian regulations (MINAM, 2017). According to our methodological procedure, we design sub-criteria (Table 1) inside the three criteria sustainable, which are pollution (environmental), social (health), and economy.

We evaluate three criteria and nine sub-criteria, considering four sub-criteria within the atmospheric criteria and two sub-criteria within the economic criteria, and one is within the social criteria, with their respective weights (DIGESA, 2015; MINEM, 2016) (Table 1 and Fig. 1). Based on the recommended consistency index (CR), it must be less than or equal to 0.1 for these results to be valid. As a result, $\lambda_{max}$ = 3.09 and the number of criteria (n) = 3, we obtain a random index = 0.58, CI = 0.04 and CR = 0.07. With this CR, which is less than 0.1, we confirm that the assigned weights are correct to have consistency, thus obtaining the final weighted scores and classifications in terms of sustainable criteria. The environmental criterion has the highest percentage (61%), the social criterion has the second highest (28.4%), and the economic criterion is followed by the other two, thus being the lowest (9.6%) (Table 2).

The AHP method applied in each criterion and sub-criterion allows us to determine the percentage of influence or weight (Table 2) and obtain thematic maps of the weighted overlay concerning the assigned locations. On the map, we can see green colors for the optimal areas and red for the unacceptable areas; orange and yellow colors can also be a medium option (Fig. 3a, b, and c). As these maps show, the optimal zones are close to or within the focus of the emission sources' influence. Finally, we obtain a sustainable map that provides optimal areas to locate the monitoring stations and a network of air quality monitoring stations, shown in green; this map shows the process's result (Fig. 3d).

Of the weights obtained by the AHP method, for the atmospheric sub-criterion and its sub-criterion (Fig. 2 and Table 2), the emission sources sub-criterion has 40% importance, 37% of the chemical pollutants, and 23% of the meteorological data. On the other hand, the results and data obtained in the temporal stations serve to confirm that the maximum concentrations of $PM_{10}$, $CO_2$, $NO_2$, and $SO_2$ collected in Arequipa were recorded in January, May, and October 2019, thus ruling out the influence of the altitude in the study area.

However, they were related to industrial activity, food markets, bus stations, and wind direction.

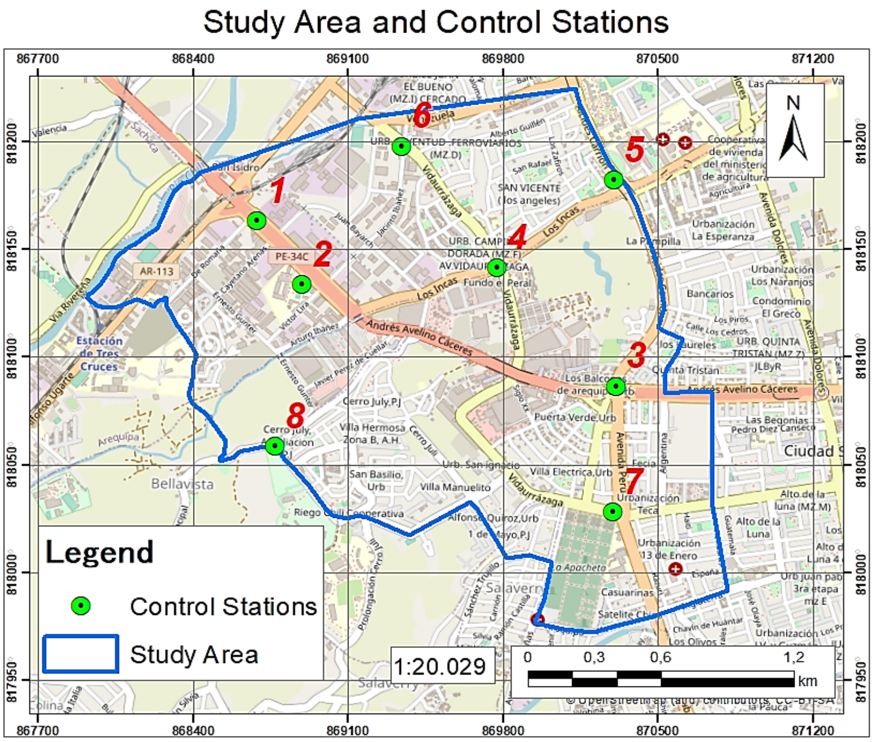


**Fig. 2.** Location of study area and temporary control stations

**Table 1.** Criteria for the evaluation and identification of potential monitoring sites (DIGESA, 2015; MINEM, 2016)

| ***Social*** | ***Environmental*** | | | | ***Economic*** |
|---|---|---|---|---|---|
| | ***Atmospheric*** | | | | |
| | | | ***Sources*** | | |
| | ***Meteorological*** | ***Chemical Pollutants*** | ***Fixed*** | ***Mobile*** | |
| Population (Our data) | Wind direction (Meteoblue, 2019) | $PM_{10}$ (our data, Table 3 and 4) | Industrial (USGS, 2019; our processing) | Vehicles (USGS, 2019; our processing) | Technology - Instruments |
| | Wind speed (NASA, 2019) | $PM_{2.5}$ | Agricultural (USGS, 2019; our processing) | | Access routes (USGS, 2019; our processing) |
| | Temperature (NASA, 2019) | Sulfur dioxide (our data, table 3 and 4) | Urbanization (USGS, 2019; our processing) | | Electricity supply |
| | Relative humidity (NASA, 2019) | Carbon monoxide (CO) | Bus station (USGS, 2019; our processing) | | Maintenance |
| | Precipitation (NASA, 2019) | Nitrogen dioxide ($NO_2$) (ESA & EarthData, 2019; our processing) | Food markets (USGS, 2019; our processing) | | Security (our data) |
| | Solar radiation | Ozone | | | |
| | Altitude DEM (USGS, 2019) | Hydrogen sulfur ($H_2S$) | | | |
| | Vertical temperature profile (ILRS, 2018) | Benzene (from vehicles) | | | |

Besides, a higher concentration of pollutants in the northeast (NE) part of our study area which coincides with the wind direction (more hours in this direction (NE)) (Fig. 4). All these records and observations served us as a decision reference to reassign each map's classification values. Finally, a suitable air quality monitoring network and three stations are designed (Fig. 3d).

*Particulate matter ($PM_{10}$)*: According to Peruvian legislation (MINAM, 2017), the 24-hour mean concentration of $PM_{10}$ in ambient air should not exceed 100 μg $m^{-3}$, and the annual mean should remain below 50 μg $m^{-3}$. The World Health Organization (WHO) suggests that the 24-hour mean should remain below 25 μg $m^{-3}$ (WHO, 2006). The highest concentration of $PM_{10}$ measured in this study was close to 180 μg $m^{-3}$ at station 2, inside the study area center. The lowest concentration measured was 80 μg $m^{-3}$ at station 8, outside the study area (Table 3). The concentrations at all stations exceeded both MINAM and WHO guidelines, indicating a low air quality in Arequipa Industrial Park (Table 3 and Table 4). This finding accords with a report by the Regional Health Directorate of Arequipa (DIGESA) from 2007 to 2012 (DIGESA, 2015). DIGESA had established five monitoring stations throughout Arequipa, but just one station in Industrial Park.

Although DIGESA mentioned that average daily $PM_{10}$ concentrations during these years did not exceed the Peruvian norm, the maximum daily values exceeded the 100 μg $m^{-3}$ ECA value in all years and reached up to 342 μg $m^{-3}$. On the other hand, we cannot confirm the direct source of PM. Still, a correlation with traffic intensity can be considered due to internal combustion vehicles (diesel, gasoline, and gas). The recorded PM fractions are high near traffic zones and even more in routes for heavy vehicles (Roba et al., 2014).

*Nitrogen dioxide and sulfur dioxide:* The concentrations of $NO_2$ and $SO_2$ did not show significant variation (Table 3). For example, station 2 measured concentrations of $NO_2$ from 65 to 70 μg $m^{-3}$ and concentrations of $SO_2$ from 40 to 45 μg $m^{-3}$ during the three measurement periods (January 5, May 5 and October 5) (Table 4) (García et al., 2013). The Peruvian norms (ECA) suggest sampling $NO_2$ hourly, with a suggested maximum of 200 μg $m^{-3}$, and annually, with a suggested maximum of 100 μg $m^{-3}$.

**Table 2.** Weight criteria of three primary pillars and atmospheric sub-criterion by AHP method

| ***Criteria*** | | ***Weight criteria*** |
|---|---|---|
| Sustainable | Social | 0.28 |
| | Environmental | 0.62 |
| | Economic | 0.10 |
| Sub-criteria | | |
| Environmental | Meteorological | 0.23 |
| | Chemical Pollutants | 0.37 |
| | Sources | 0.40 |
| Chemical Pollutants | $PM_{10}$ | 0.31 |
| | $NO_2$ | 0.35 |
| | $SO_2$ | 0.16 |
| | $CO_2$ | 0.18 |
| Meteorology | Precipitation | 0.28 |
| | Wind speed | 0.39 |
| | Temperature | 0.16 |
| | Relative Humidity | 0.16 |
| Sources | Industrial | 0.24 |
| | Agriculture | 0.12 |
| | Urbanization | 0.19 |
| | Buses stations | 0.20 |
| | Food markets | 0.10 |
| | Mobil | 0.15 |

**Table 3.** Annual average pollutants measured at control stations around Arequipa Industrial Park

| ***Stations*** | ***1*** | ***2*** | ***3*** | ***4*** | ***5*** | ***6*** | ***7*** | ***8*** |
|---|---|---|---|---|---|---|---|---|
| Latitude | 16°25'6.63"S | 16°25'16.08"S | 16°25'30.65"S | 16°25'13.06"S | 16°24'59.57"S | 16°24'54.97"S | 16°25'49.60"S | 16°25'40.53"S |
| Longitude | 71°32'54.66"W | 71°32'47.67"W | 71°31'59.58"W | 71°32'18.00"W | 71°32'0.46"W | 71°32'32.84"W | 71°31'59.76"W | 71°32'51.27"W |
| $CO_2$ ppm | 1232.44 | 1446.00 | 1366.67 | 1046.19 | 807.64 | 700.25 | 1413.77 | 788.12 |
| $PM_{10}$ μg $m^{-3}$ | 105.37 | 177.16 | 159.51 | 132.52 | 84.57 | 87.33 | 140.39 | 79.66 |
| $NO_2$ μg $m^{-3}$ | 70.57 | 68.06 | 62.07 | 87.86 | 55.32 | 42.90 | 48.24 | 45.28 |
| $SO_2$ μg $m^{-3}$ | 41.11 | 42.32 | 38.13 | 42.89 | 18.44 | 11.38 | 21.46 | 20.53 |

They suggest daily sampling, with a suggested maximum of 250 µg $m^{-3}$, for $SO_2$. In general, the concentrations of $SO_2$ and $NO_2$ were low in Arequipa (Table 4), which could indicate a decrease in pollution caused by coal combustion and vehicle emissions. WHO guidelines call for lower values than the ECA, but with a difference in mean measurement periods, or frequency. In other words, the WHO suggests using hourly and annual samples for $NO_2$, and daily and 10-minute samples for $SO_2$. Following ECA guidelines, we could say that Arequipa Industrial Park maintains adequate air quality. Nevertheless, according to WHO guidelines, Arequipa Industrial Park needs to improve urban air quality. Data from Arequipa could be compared with data from other cities (Hao and Wang, 2012). These high standard values would highlight that the Peruvian norms are more robust and tolerant. We think that this is due to a large number of industries in study zona (Fig. 5E) and perhaps due to Peru's industrial heyday.

*Carbon dioxide:* In Peru, there is no threshold for the control and assessment of $CO_2$. To give an opinion on the values obtained, we used the WHO's suggestions (WHO, 2017), which indicate a $CO_2$ concentration of 300 ppm as a threshold. Station 3 measured $CO_2$ concentrations up to 1736 ppm in May (Table 4). Moreover, the annual average of $CO_2$ is 1446 ppm in Arequipa Industrial Park. Fig. 3d shows that station 1 is within the study area center, where there are significant population activities. The concentrations at this station exceed the annual average by almost 400%. We suppose that these high concentrations result from metallurgical, textile and paper industries, the central bus station, markets, and a paint factory. Our research confirms that Arequipa Industrial Park is an active source of pollutants.

Moreover, to obtain a better database, we suggest creating a good network of continuous and complete air quality monitoring of all contaminants that consider the different production areas in Arequipa Industrial Park (Fig. 3). Just as our study developed and executed it as a test. Our model can be applied to different interests of measurement, control, evaluation, and detection.

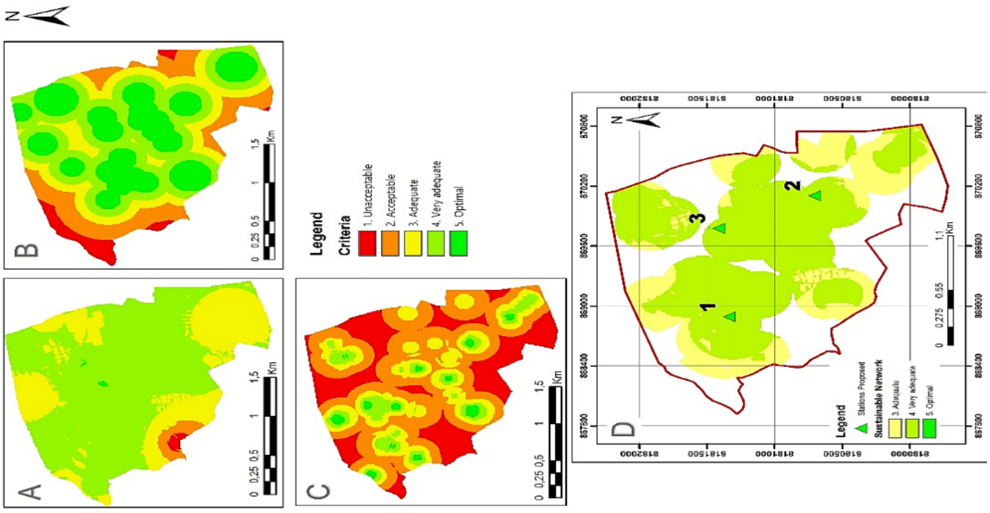


**Fig. 3.** Classification map prioritized by each sustainability criteria, (a) Environmental. (b) Social. (c) Economic. (d) Sustainable air monitoring station with proposed stations

**Table 4.** Pollutants measured at control stations around Arequipa Industrial Park

| ***Stations*** | | ***1*** | ***2*** | ***3*** | ***4*** | ***5*** | ***6*** | ***7*** | ***8*** |
|---|---|---|---|---|---|---|---|---|---|
| $CO_2$ | 2019.01.05 | 1234.13 | 1567.40 | 1345.20 | 984.50 | 824.80 | 753.40 | 1436.30 | 819.80 |
| | 2019.05.05 | 1452.76 | 1535.60 | 1736.50 | 969.58 | 795.82 | 780.06 | 1410.00 | 786.75 |
| | 2019.10.05 | 1010.42 | 1235.00 | 1018.30 | 1184.50 | 802.30 | 567.30 | 1395.00 | 757.80 |
| $PM_{10}$ | 2019.01.05 | 102.65 | 173.98 | 153.45 | 154.47 | 80.32 | 78.01 | 141.02 | 78.67 |
| | 2019.05.05 | 114.68 | 182.83 | 164.66 | 126.74 | 93.41 | 100.34 | 138.72 | 81.23 |
| | 2019.10.05 | 98.79 | 174.68 | 160.42 | 116.36 | 79.98 | 83.65 | 141.42 | 79.07 |
| $NO_2$ | 2019.01.05 | 70.97 | 68.45 | 62.46 | 88.23 | 55.70 | 43.29 | 48.63 | 45.67 |
| | 2019.05.05 | 70.00 | 67.49 | 61.50 | 87.32 | 54.78 | 42.33 | 47.67 | 44.71 |
| | 2019.10.05 | 70.76 | 68.24 | 62.25 | 88.02 | 55.49 | 43.08 | 48.42 | 45.46 |
| $SO_2$ | 2019.01.05 | 40.48 | 40.87 | 37.79 | 41.46 | 17.80 | 10.74 | 20.02 | 19.07 |
| | 2019.05.05 | 41.38 | 41.76 | 37.72 | 42.35 | 18.73 | 11.67 | 20.95 | 20.00 |
| | 2019.10.05 | 41.47 | 44.34 | 38.87 | 44.85 | 18.79 | 11.72 | 23.42 | 22.50 |

**Units: $CO_2$ (ppm), $PM_{10}$, $NO_2$ and $SO_2$ (µg $m^{-3}$)*

*Meteorology:* in this case are used temperature, relative humidity, precipitation, wind speed, and wind direction (Meteoblue, 2019); These data helped us to understand the three-dimensional relationship that exists between them since they influence the period of the permanence of pollutants, chemical reactions between pollutants and compounds in the atmosphere (Langstaff, et al., 1987; MINEM, 2016). Besides, the weight by APH method (Table 2). Wind speed is of slight importance concerning precipitation (Table 2), Our study needs to obtain data on wind speed and precipitation for better interpolation; relative humidity and temperature have the same importance (16%). We consider the wind direction of vital importance, for which it was not interpolated, or its weight was found by the AHP, because these data help us in the immediate decision to assign the stations, but not the network (Fig. 4), (Hacioglu et al., 2016; MINAM, 2017; Weeberb et al., 2015).

The predominant wind direction is towards the Northeast of the city, with a speed of up to 28 km*h$^{-1}$, but most of the year, it is less than 19 km*h$^{-1}$ and between 0 and 5 km*h$^{-1}$ in our study area.

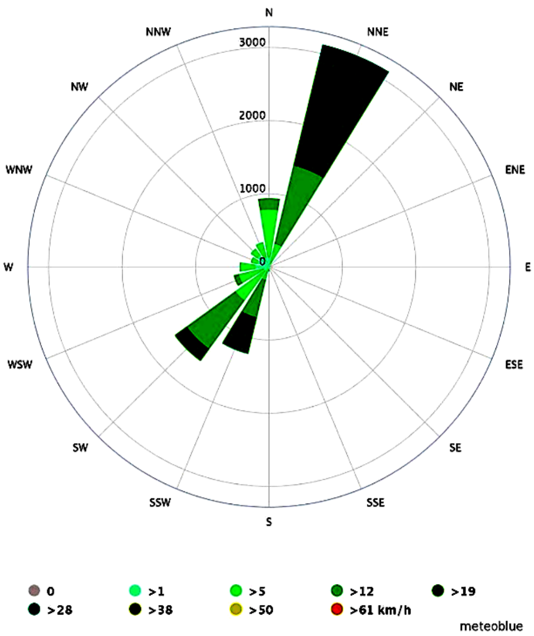


**Fig. 4.** Wind direction in Industrial Park Arequipa (Meteoblue, 2019)

*Health and environmental complaints:* The WHO stated that mortality has increased due to air pollution in cities with industrial development (SWISS TPH, 2020; WHO, 2006). This affirmation is also reported in Arequipa, where citizens today report asthma problems, irritation of the eyes, nose, throat, headaches, allergies, and lung cancer, which ten years ago were not common as they are now. Therefore, no controlled air contamination is one of the leading causes affecting public health; as Apaza (2018) mentioned that $NO_2$ caused more than 55% of IRAS in Arequipa. Based on the regional government's reports of Arequipa (SINIA and OEFA, 2020) and public health damage. The general data of air quality do not focus on the real situation; sometimes, it is over understanding that there is no damage to public health either the environment. Hence, if one network's information could support corresponded decisions, there would not be struggles for functions (evaluation, control, planning, and sanctions). For this situation, our suggested map by the AHP method helps find a responsible issuer to evaluate and control the complaints' implications.

On the other hand, there are pieces of equipment in Arequipa specific locations that are only activated when there is a more significant complaint. Then, there is never any real data on an event that has caused the complaint. We believe that this dire situation does not help the authorities and other stakeholders to make decisions or improve environmental conditions. With the data obtained and generated for our research, we can assume an increase in respiratory diseases; since the sources of emission and pollutants (Fig. 5) are very close to the affected population and the range of the pollutants over height the thresholds establish by EPA; Therefore, the industrial zone should be relocated or control better emissions by a good air quality network (Giddings et al., 2002; Kumar and Kumar, 2016).

*A sustainable air monitoring network:* The green areas indicate the possible places to be used as optimal and suitable for a station; on the contrary, the blank spaces within the study area indicate unacceptable regions (Fig. 3d). As shown in Fig. 3a, b, and c, there is no direct interference from emission sources or activities until now. While Fig. 3a shows the environmental criterion, the optimal zones are broad; we have more selection options. Fig 3b, the social criterion, shows a change slightly; our optimal zones are reduced. In Fig. 3c, the economic criterion dramatically reduces our options, having fewer optimal zones. In general, when applying the AHP method and the weight overlay tool (ArcGIS, 2018), there are optimal, very adequate, and adequate options to define the monitoring stations and possible network (Fig. 3d). With these results, we can validate the consistency index of 0.07 by the methodology widely (Saaty, 2008). As Pope and Wu (2014) mentioned, a sustainable evaluation provides effectiveness to many other indicators. The spatial patterns are useful for evaluating and performing a network and its stations since it helps identify efficiencies and deficiencies in each sustainable criterion in time and space.

Meanwhile, Trujillo-Ventura and Ellis (1992) specified that an AQMN should maximize the obtaining of information. Decision-makers assign them levels of importance as required, for which they focused four objectives per pollutant, using kriging interpolation and minimizing the estimation error by multiobjective mathematical programming method. Therefore, we could briefly confirm, the need for an AQMN has had limitations since then. It has not been solved until now, identifying only more limitations, so much so that today we suggest a sustainable AQMN.

For the design of adequate, sustainable air quality monitoring stations, we consider the three sustainable criteria (Table 2), for which with the AHP method, its importance weight was calculated, which can be used and applied quickly, efficiently, and effective in different areas (urban, rural, specific areas) (Weeberb et al., 2015). The sub-criteria (table 1) expanded our variables, so we had to apply the AHP method (Fig. 1) repeatedly. In the case of the atmospheric sub-criterion, which is the broadest, it was necessary to take temporary samples of the chemical pollutants (Fig 5a, b, and c), meteorological (Meteoblue, 2019) and identify the emission sources (Fig. 5e) in the study area, because there are no reference data. As Trujillo-Ventura and Ellis (1992) stated, it is necessary to know the concentration of pollutants, which serve as a basis for estimating optimal interpolation. Furthermore, it is essential to identify the spatial variability since it is different from the concentration of the individual pollutants. Where multi-objective methods are flexible and work according to a decision-maker's preference (Modak and Lohani, 1985), in this paper, we implemented a sustainable point of view: society, environment, and economics (Table 1), thus obtaining an AQMN design. Since using the weighted superposition method, it is necessary to generate classified and compatible maps to create spheres of optimal areas for monitoring stations' locations (Pope and Wu, 2014).

The results improve when we create thematic maps using the ArcGIS weighted overlay method to improve visual analysis (Weeberb et al., 2015). With the collection and recollection of data to complete our study, we confirm the high levels of emission of chemical pollutants in the area, which concern public health and the environment (Chalabi et al., 2017; Verma et al., 2009). As Figures 3d and 5e show, the monitoring stations have a high probability of being installed around the industrial zone and food markets (commerce). There is something unusual; it is how far it is from the bus stations.

On the other hand, it is also necessary to know if the amount of money invested in implementing and active management of a monitoring network is less or greater than the amount of money spent (Fig. 3c) on people with respiratory diseases; in both cases, political and sanitary intervention is necessary to reduce air pollution (Verma et al., 2009).

Therefore, with this methodology, the combination of the AHP method and ArcGIS tools can be widely used to establish monitoring stations and their subsequent design of an air quality network, confirming a station in leeward, a windward, and in the middle of the study area, which is established with our final maps (Fig. 3d). Finally, the variables weighted by AHP are not always applied with the sustainability criteria; they can also be used in specific cases, such as just industries, supply markets, schools, and buildings.

## 4. Conclusions

In our proposal of an air quality monitoring network for Arequipa Industrial Park, we considered three criteria, which consisted of environmental (61.9%), social (28.4%), and economic (9.6%) factors, to find a solution to the persistent and complex air quality problem in this area where current regulations cannot be used to penalize those responsible for the emission of contaminants due to a lack of historical data.

At present, Arequipa Industrial Park does not have any monitoring network type, making a more highly recommended model difficult.

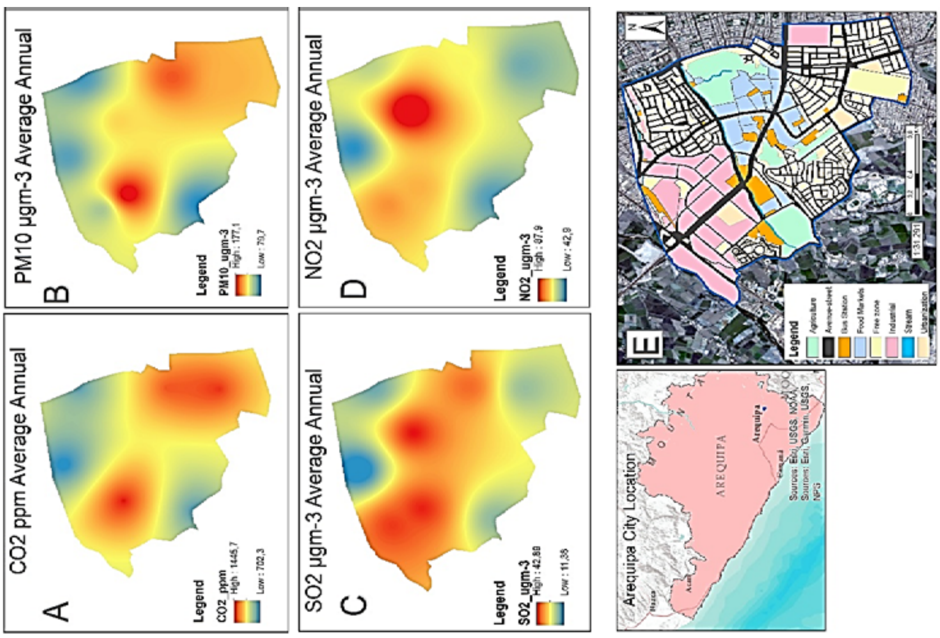

**Fig. 5.** Environmental Criterion - Atmospheric sub-criterion. Images a, b, c, d show pollutants concentration. The image (e) shows emission source identification map

Therefore, this network is proposed to initiate continuous data recording and provide an air quality baseline for administrative management.

AHP method with ArcGIS can prioritize and provide suitable sites for monitoring stations and facilitate their implementation and estimate their costs. We can continue the process of investigating and monitoring over a long period through the multitemporal integration of georeferenced satellite images and pollutant concentration data.

This methodology can improve the urban air quality environmental management plan in Arequipa, which must provide solutions to environmental problems and offer complete data in real-time. With the reference of available data, the responsible authorities will be ready to make the right decisions during the currently accelerated and disorganized urban and industrial growth that has caused a progressive deterioration of public health and the environment. In future studies, we suggest that the distribution of pollutants should be considered according to the type of source, related economic activities, and the population involved to establish a baseline to serve as a reference. For reference data, the origins of transport, transport flows, industrial plans, urban waste, morphology, or others can be included, which can be transferred in unmodified form to one database. The proposed method can be evaluated and applied to find the appropriate location of urban and rural monitoring stations in any part of Arequipa. The creation of new standards alone is not a solution. There must be compliance with these new policies by stakeholders, authorities, and companies.

With the AHP method and the sustainable application, we emphasize the weighting of weights, in addition to all the qualitative criteria, they become quantitative, with which subsequent evaluations are facilitated. Sustainable criteria and recommended sub-criteria can provide quality information, help develop a rapid diagnostic capacity for pollution episodes, determine the affected areas, estimate the concentration of pollutants and possible contamination sources.

Finally, it is necessary to consider using an integrated approach of biotechnology, bio-sustainability, or green chemicals to utilize sustainable, recyclable, and degradable raw materials fully. Besides, stakeholders need an adequate plan to control air quality, economical, urban, and rural development in real-time and space.

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