Science of the Total Environment 624 (2018) 189–200

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Air quality modelling in Catalonia from a combination of solar radiation, surface reflectance and elevation

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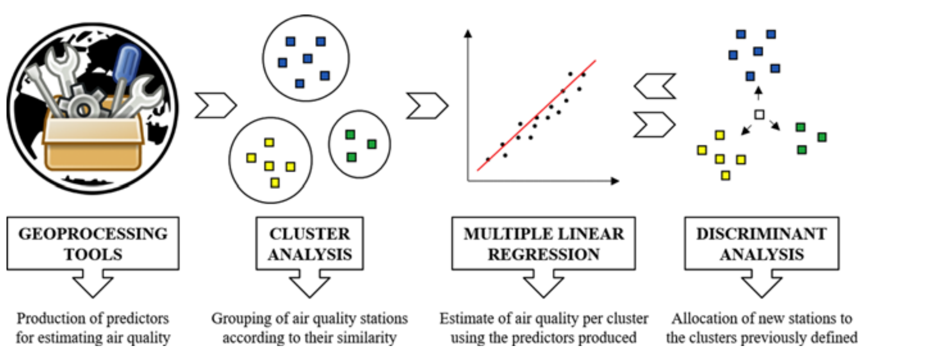
HIGHLIGHTS

- A new approach was conceived to model air quality in the region of Catalonia.
- The proposed methodology combined geoprocessing tools and multivariate statistics.
- Air quality was predicted from solar radiation, surface reflectance and elevation.
- The results provided highly accurate predictions of air quality at ungauged zones.
- The presence of irradiated built-up areas was found to endanger air quality.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 25 October 2017
Received in revised form 5 December 2017
Accepted 12 December 2017
Available online xxxx

Editor: P. Kassomenos

Keywords:
Air quality
Elevation
Geoprocessing tools
Multivariate statistics
Solar radiation
Surface reflectance

ABSTRACT

Air quality in developed areas is being increasingly compromised by the effect of urbanization, which is favouring the presence of atmospheric pollutants derived from human-induced activities. Land cover change is one of the consequences most closely associated with urbanization, leading to a growing presence of dark built-up surfaces. The target of this investigation was to model the Catalonian Air Quality Index (CAQI) from the combined effect of the surface reflectance capacity of urban surfaces with solar radiation and elevation. Geoprocessing tools were used to produce the information required to characterise these variables in the buffer areas surrounding 75 different air quality monitoring stations located across the region. Cluster analysis and Multiple Linear Regression (MLR) were applied to group these stations according to their similarity and replicate the annual mean values of CAQI recorded in Catalonia in 2011, respectively. Finally, discriminant analysis enabled assigning ungauged areas to the cluster and MLR model that best fitted their solar radiation, surface reflectance and elevation features. The implementation of this approach resulted in highly accurate predictions of CAQI, providing a mechanism of identification of areas having a number of days with poor air quality during the year. Since these areas were related to the presence of land cover types with high sunlight absorption, the proposed methodology was suggested to support the adoption of measures aimed at controlling urban air pollution based on replacing built-up surfaces by green infrastructure.

1. Introduction

Rapid population growth and urbanization are contributing to increasing air pollution in urban areas, particularly in developed countries (Han et al., 2016). Most of this pollution stems from human-related

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https://doi.org/10.1016/j.scitotenv.2017.12.139
0048-9697/

activities, such as energy consumption, industrialization or transportation, and is a source of risk to health, since it might eventually lead to cardiovascular and respiratory diseases (Andersen, 2017; Vardoulakis et al., 2003). In consequence, increasing attention is being paid to the impacts of urbanization on the environment, with emphasis on its alterations in terms of land cover (Alphan, 2003; Dewan and Yamaguchi, 2009) and solar radiation (Alpert and Kishcha, 2008; Wang et al., 2017) as potential threats for air pollution.

The development of land cover regression models for estimating air pollution has become a rich discipline in the field of atmospheric environment during the last 20 years. The pollutants addressed in these models included Nitrogen Oxides (NO_x) (Briggs et al., 2000; Gonzales et al., 2012; Muttoo et al., 2018; Stedman et al., 1997), Ozone (O_3) and Particulate Matter (PM) with diameter of <10 (PM_{10}) (Beelen et al., 2009) and 2.5 μm ($PM_{2.5}$) (Lee et al., 2017; Liu et al., 2016; Ross et al., 2007), Sulphur Dioxide (SO_2) (Amini et al., 2014) and Volatile Organic Compounds (VOC) (Wheeler et al., 2008). Besides a land cover-related variable, these studies considered other predictors, such as traffic, altitude, population, meteorology or precedent emissions. Their estimates reached coefficients of determination between 0.36 and 0.97, based on data recorded in a series of monitoring stations during sampling periods ranging from a few weeks to a whole year.

Specific investigations have also been conducted to explore the relationships between solar radiation and air pollutants. Gómez-Carracedo et al. (2015) suggested that the presence of photochemical reactions during the hours of maximum solar radiation favoured an increase in O_3, which coincided with the inferences achieved by Chou et al. (2007). In contrast, Shen et al. (2014) argued that O_3 was weakly correlated to solar irradiance due to the low concentrations of NO_x. Wang et al. (2005) found that secondary compounds of $PM_{2.5}$ exhibited high concentrations in summer as a result of strong solar radiation, a relationship which was confirmed by Vardoulakis and Kassomenos (2008) and Hajizadeh et al. (2017), who also reported positive correlations between solar radiation and $NO_{x,}$ Carbon Monoxide (CO) and Benzene, Toluene, Ethylbenzene and Xylene (BTEX). However, these results differed from those yielded by a later study undertaken by Kassomenos et al. (2014), which indicated that the correlations between solar radiation and $PM_{2.5}$ and PM_{10} concentrations were not statistically significant.

The target of these works highlighted the lack of integrated approaches for evaluating air quality considering variables related to both land cover and solar radiation. To fill this gap, this research combined solar radiation, surface reflectance and elevation factors to model the Catalonian Air Quality Index (CAQI). This index was selected because its calculation includes the most commonly found air pollutants in urban daily life, such as CO, Nitrogen Dioxide (NO_2), O_3 and PM_{10} (Chen and Kan, 2008), and the data registered through its consideration is open access and widely available. In particular, the proposed methodology was tested and validated using the data recorded in 75 monitoring stations located in the region of Catalonia during 2011.

2. Methodology

The proposed methodology was conceived as a sequential combination of different multivariate statistical techniques, whose application was founded on data produced using Geographic Information Systems (GIS), as illustrated in Fig. 1. Hence, the set of factors or predictors identified as potential contributors to air pollution were generated through a series of geoprocessing tools framed within the discipline of spatial analysis. Then, a number of clusters were identified according to the values of these predictors across different air quality stations. This enabled maximising the prediction accuracy of the subsequent regression models built per cluster to estimate air quality. The last step concerned the application of discriminant analysis to validate the proposed approach by allocating different stations to the clusters whose regressions equations maximised their fit to observed values of air quality.

2.1. Framework

By 2017, Catalonia covered 32,106.5 km^2 and had 7477.131 inhabitants distributed among 947 municipalities (idescat.cat, 2017). This region is very dense and highly industrialised, circumstances that have favoured exceeding European air quality standards in 2015 and 2016 (Secció d'Immissions, 2015, 2016), especially in the Metropolitan Area of Barcelona, where two thirds of the population resided by 2017. The surface exposed to pollution levels above those legally permitted reached 24,000 km^2 in 2016, almost 75% of the whole area of Catalonia (Ceballos et al., 2015). These facts justified the need for developing new methods and approaches to help better manage air pollution in this region.

Air quality supervision in Catalonia is carried out by the Air Pollution Monitoring and Forecast Network, which consists of a series of stations aimed at measuring the levels of contamination reached across the region in relation to main atmospheric pollutants. Informing about the measurements of these stations per pollutant is a time-consuming and complex task, due to the technical details involved in the understanding and provision of these data. For this reason, a public information system based on an Air Quality Index (CAQI) was implemented in Catalonia since January 1995, in order to communicate population about the

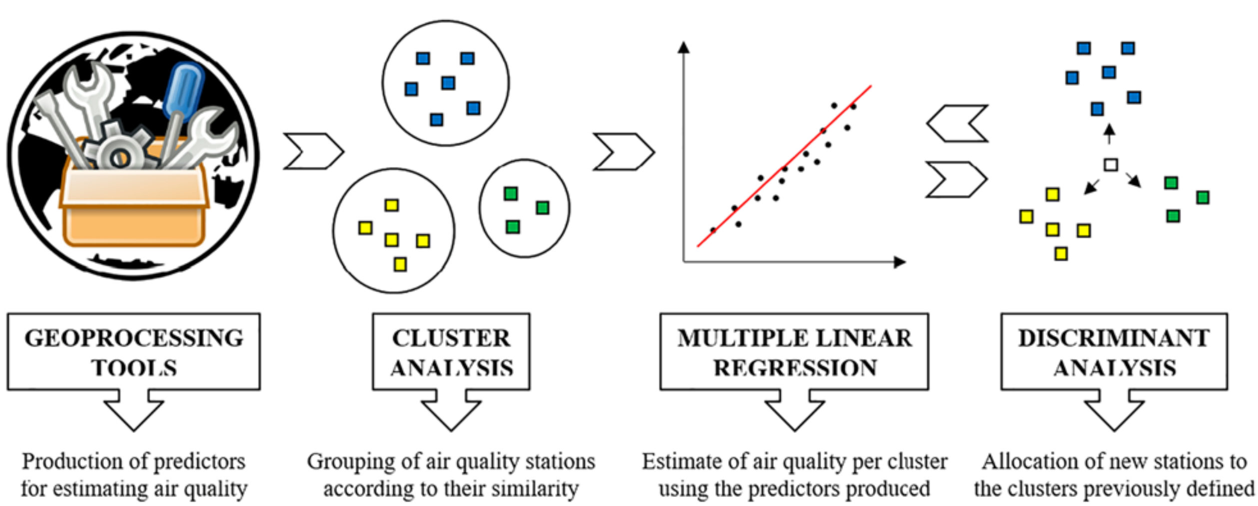

Fig. 1. Flowchart for the design and application of the proposed methodology to predict air quality.