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Identifying redundant monitoring stations in an air quality monitoring network

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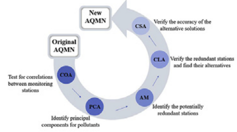
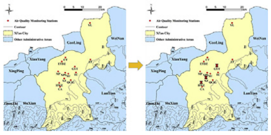
GRAPHICAL ABSTRACT

An integrated method is developed to identify the redundant stations in AQMN using a combination of correlation analysis, principal components analysis, an assignment method, the cluster analysis, and correspondence analysis. The new method is applied to Xi'an city's AQMN as a case study. The layout of AQMN of Xi'an city can be optimized since three redundant stations (XZ, GYT, and HWZ) have been identified and removed.





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ABSTRACT

The monitoring information provided by air quality monitoring networks (AQMNs) supports air quality assessment and improvement planning in urban environments. The existence of redundant monitoring stations in an AQMN not only determines the cost of pollution monitoring, but also determines the integrity of pollution information monitoring and the accuracy of air quality assessment. In this study, we developed a method of identifying redundant monitoring stations using a combination of correlation analysis, principal components analysis, an assignment method, the cluster analysis, and correspondence analysis. We used (i) correlation analysis to determine whether the pollution information captured by a monitoring station was correlated with that of other stations, so as to determine whether the AQMN had redundant monitoring stations; (ii) principal components analysis to classify the pollution information and initially identify potentially redundant monitoring stations using the assignment method; and (iii) cluster analysis to identify alternative combinations of redundant monitoring stations. Finally, we verified the alternative combinations by means of a correspondence analysis to determine the final stations which were redundant. We used data on six pollutants (particulates smaller than 2.5 µm ($PM_{2.5}$), 10 µm (PM_{10}) in diameter, sulfur dioxide (SO_2), nitrogen dioxide (NO_2), ozone (O_3), and carbon monoxide (CO)) at 13 environmental monitoring stations in Xi'an city, China, in 2016. The analysis identified three redundant stations (Xiao Zhai, Guang Yun Tan, and the Hi-Tech West Zone), and alternatives for each of the redundant stations. Therefore, the method described in this paper can effectively optimize the layout of an AQMN, thereby improving the integrity of the monitoring information and decreasing the cost.

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1. Introduction

In recent years, serious air pollution has become a global problem that is triggering both official anxiety and public concern. The problem is especially challenging for developing countries. According to *Environmental Performance Index: 2016 report* (http://epi.yale.edu/reports/2016-report) released by Yale University in the United States, China, as the nation "hardest hit" by global air pollution, ranked second to last in terms of its air quality. China faces an air pollution problem characterized by high levels of ozone (O_3), fine particulate matter ($PM_{2.5}$), and acid rain, which have had serious adverse effects on human health, normal production activity, and daily life. Therefore, air pollution is a major social problem that must be effectively controlled. To solve the problem, it's first necessary to obtain accurate air quality information, since this provides the basis for identifying problem and their sources, thereby letting managers formulate an air pollution control strategy. To provide this data, countries around the world have established air quality monitoring networks (AQMNs). Since the early 1970s, when the United States implemented its *Clean Air Act*, the country has gradually established a real-time AQMN with stations at local, state, and national levels, which now consists of more than 4000 sub-stations (https://www.epa.gov/outdoor-air-quality-data). The European AQMN is divided into two major complementary systems: the European Monitoring and Evaluation Program (EMEP, http://www.emep.int/), which covers all of the EU countries and the monitoring network within each country. EMEP has 126 monitoring stations in 28 countries, which focus not only on rural and background values, but also on the migration and transformation of regional pollution. The EU member states have also established their own monitoring networks, such as the United Kingdom's AQMN (https://uk-air.defra.gov.uk/networks), with a total of 395 monitoring stations, Germany's AQMN has a total of more than 900 stations (https://www.umweltbundesamt.de/en/topics/air/measuringobservingmonitoring), and Germany's 16 federal states include an additional 550 stations, Austria's AQMN includes 237 monitoring stations (https://www.air,ac.at/en/reach-fields/environmental-and-crisis-disaster-management/uwedat). Starting with the *Air Pollution Control Act* of 1968, Japan began construction of a local AQMN and gradually developed and established a national monitoring network that now covers the whole country (http://www.eic.or.jp/). As of 2004, Japan has established 1487 sulfur dioxide (SO_2) monitoring stations, 1880 nitrogen oxides (NO_x) monitoring stations, 1193 photochemical oxidants monitoring stations, 1910 particulate matter (PM) monitoring stations, and 401 carbon monoxide (CO) monitoring stations (Zhong et al., 2007).

The construction of China's AQMN started in the mid-1970s, continued through the mid-to late 1980s with urban monitoring stations based on large-scale construction of the network, and in the early 1990s, entered an adjustment and optimization period. The initial national AQMN consisted of 103 urban air monitoring stations, which focused on SO_2, NO_x, and inhalable PM. Since 2000, the monitoring stations have been improved to support daily air quality and forecasting work. On 5 June 2001, China identified 47 key environmental protection cities for which daily air quality and forecasting is performed. China has attached great importance to its AQMN and has increased its investment in the network. Since the implementation of the "Three-Step" program approved by the State Council in 2012 for construction of the network, the Ministry of Environmental Protection has issued *Opinions on Strengthening the Construction of Environmental Air Quality Monitoring Capacity* (http://www.zhb.gov.cn/gkml/hbb/bwj/201203/t20120327_225226.htm), the *Environmental Air Quality Standard* (GB 3095-2012) (http://kjs.mep.gov.cn/hjbhbz/bzwb/dqhjbh/dqhjzlbz/201203/t20120302_224165.htm), *A letter to the construction of the national air quality monitoring sub-station for the national region* (http://www.zhb.gov.cn/gkml/hbb/bgth/201508/t20150831_309085.htm), and other documents related to the national environmental AQMN to further improve the work. In December 2015, the Ministry of Finance and the Ministry of Environmental Protection issued the *Opinions on the Implementation of the Opinions for Supporting the Reform of the Environmental Monitoring System* (finance construction [2015] No. 985), which proposes completion of the relevant work on national monitoring stations by 2018. According to the Ministry of Environmental Protection's 2016 annual government information disclosure report (http://www.zhb.gov.cn/gkml/hbb/bgg/201703/W020170526412551421731.pdf), the country's 338 prefecture-level cities have now released real-time monitoring data for 1436 stations. China has now established a multi-level AQMN that covers all regions of the country. However, China's sustained and rapid socioeconomic development has led to complex new regional pollution problems. Moreover, there are many problems with the existing city-based AQMN, particularly in term of suboptimal layout of the monitoring stations. The construction of each monitoring station costs about 1.5×10^6 RMB, in addition to large daily operating costs. Thus, if redundant monitoring stations exist in AQMN, the cost of obtaining their monitoring data will be higher than necessary. In addition, the monitoring stations are mostly concentrated in central urban areas, so the AQMN provides insufficient monitoring of pollution in the suburbs and in transboundary areas, which leads to inaccurate overall assessments of regional air quality. To solve this problem, we initiated the present study, with the goals of optimizing the monitoring station layout and decreasing the cost in a city's AQMN. To do so, we developed a method to identify redundant monitoring stations, as this identification is the first step in optimizing the AQMN layout.

2. Literature review

Principal components analysis (PCA) and cluster analysis (CLA) have become the most common methods for solving AQMN efficiency problems, such as identifying similar pollution sources, similar pollution behaviors, and redundant monitoring stations (D'Urso et al., 2013). Gramsch et al. (2006) were the first to research the air quality management that studied the seasonal trends and spatial distribution of particles smaller than 10 μm (PM_{10}) and O_3 in Santiago de Chile by combining PCA with CLA; in this way, their study showed that the city had four large sectors with dissimilar air pollution behaviors. Pires et al. (2008a, b) used PCA and CLA to locate the key pollution sources by combining this identification with wind data, and to identify similar pollution behavior of SO_2, PM_{10}, nitrogen dioxide (NO_2) and O_3 in the Oporto Metropolitan Area. On the basis of previous research, some mathematical models have constructed based on PCA for the relationships between pollutants and contamination features (Huang et al., 2012), or an AQMN optimization model by using PCA (Olvera et al., 2012). These studies demonstrated the power of PCA and CLA to support such analysis. However, PCA and CLA alone fail to account for certain factors, and particularly the fact that the data on certain pollutants monitored by two or more monitoring stations may be strongly correlated. As a result, it may be possible to improve on the PCA and CLA results by also accounting for these correlations, and the underlying factors responsible for causal relationships among pollutants.

Correlation analysis (COA) is widely used by researchers because it reveals the existence of potential relationships between variables, thereby offering a quantitative comparison of the strength of the relationships between multiple variables. Li et al. (2016) used COA to study variation of the PM_{10} concentration and its correlation with meteorological factors in Nanning city. Zhan et al. (2017) use COA to explore the delay in spatial transmission of pollutants in the Pearl River Delta region and its correlation with meteorological and geographic factors. Correspondence analysis (CSA) is often used to study the water environment or geographic areas. For example, Shao et al. (2013) used CSA to study the diversity of bacterial communities in areas of China's shallow Taihu Lake with different nutrient status. Jin et al. (2016) adopted CSA and CLA to divide an ecological area into sub-areas based on seasonal variation in environmental factors.