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Urban atmospheric environmental capacity and atmospheric environmental carrying capacity constrained by GDP–$PM_{2.5}$

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ABSTRACT

China faces a contradictory period of economic development and environmental protection, with it being essential to control total emissions within the limit of atmospheric environmental capacity (AEC) by promoting atmospheric environmental carrying capacity (AECC). This implies that well-calculated AEC and AECC values are the key macro-criteria for improving environmental quality and supporting the challenging coordinated development of economy and environment. When considering compound air pollution characterised as fine particulate matter ($PM_{2.5}$), conventional methods are not capable of calculating AEC and AECC, but the system dynamics (SD) method retains the advantage of simplicity in resolving complex problems. In the present study, we first describe the background and definitions of AEC and AECC, which are different from Western concepts, and their dialectical relationships. Then, with the statistical data from Wuhan city in 2014, we establish an 'economy–energy–atmospheric environment' dynamic model using the SD method, which does not need to simulate the complicated physicochemical processes of atmospheric transmission and diffusion. Instead, it uses the pollutants' proportionality factors and conversion rates to establish quantitative connections among different types of variables. Finally, we simulate the dynamic trends of gross domestic production (GDP), $PM_{2.5}$, and six air pollutant emissions between 2015 and 2030 in four different scenarios and calculate the results of AEC and AECC constrained by GDP and $PM_{2.5}$.

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1. Introduction

China's rapid and extensive economic development over the past three decades has caused serious environmental pollution, with compound air pollution characterised as fine particulate matter ($PM_{2.5}$) being especially conspicuous in recent years. $PM_{2.5}$ is the particulate matter floating in the air for an extended period whose diameter is less than 2.5 μm. $PM_{2.5}$ is formed by a variety of air pollutants such as sulphur dioxide (SO_2), nitrogen oxides (NO_x), non-methane volatile organic compounds (VOCs), ammonia (NH_3) and dust, thus severely affecting people's health and social and economic development (Pui et al., 2014; Kiesewetter et al., 2015; Oxley et al., 2015; Li et al., 2016a,b). The Chinese government has implemented the Interim Targets 1 of the Air Quality Guidelines (the lowest) established by the World Health Organization (WHO) as the 'qualified' level of $PM_{2.5}$ concentration according to the present conditions (WHO, 2005). In 2012, the new Chinese National Ambient Air Quality Standard (NAAQS) was amended and issued by the Ministry of Environmental Protection of China (MEP). In the NAAQS, the annual average $PM_{2.5}$ concentration Grade II limit is 35 μg/m^3, with the 24-h average concentration Grade II limit being 75 μg/m^3 (MEP, 2012).

Currently, in the background of the economic slowdown (called 'new normal' in China), the Chinese government would like to improve environmental quality and ensure a coordinated development of economy and environment through the utilisation of total emission control systems and environmental quality control systems (Zhang et al., 2013, 2014). Essentially, the calculation of environmental capacity is the key connection between these two systems. In 2015, an important document, the Integrated Reform Plan for Promoting Ecological Progress, issued by the Communist Party of China Central Committee and the State Council emphasised that regional development must be constrained within its environmental capacity and that the use of the restricted environmental carrying capacity supports greater social and economic development for the future. This implies that a well-calculated atmospheric environmental capacity (AEC) and atmospheric environmental carrying capacity (AECC) establish the foundation for

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controlling total emissions, improving environmental quality and guaranteeing coordinated economic development (Wang et al., 2015; Zhang and Hao, 2016).

However, the current calculations of AEC and AECC have some complications. On the one hand, a minority of government administrators still consider gross domestic production (GDP) growth to be more important and ignore environmental protection. The environment-related statistical and monitoring data are usually inaccessible and some historical data may be missing. Moreover, no effective laws demand that mandatory information be made public, which results in difficulty in analysing AEC and AECC. On the other hand, some environmental scholars regard the AEC and AECC analysis as technically cumbersome because the traditional physicochemical methods are not suitable for calculating AEC characterised as compound air pollution. For example, the A-P value method, a widely used AEC calculation method in China, is apt only for the determination of air pollutants produced by burnt coal and is not suitable for compound pollutants. The third-generation air quality models such as the Community Multiscale Air Quality model are widely used by weather departments and are a tool for early warning forecast of air quality. These models can also be used to predict the short-term AEC characterised as $PM_{2.5}$, however, they are not suitable for long-term predictions, which require a large quantity of data such as emission source data and meteorological data and a large amount of computer processing (Xue et al., 2013; Djalalova et al., 2015; Zhang et al., 2016). Moreover, timely control of air pollutant emissions after early warning signals and forecasting is not enough. Annual average $PM_{2.5}$ concentrations, not daily concentrations, are preferable as the first consideration when measuring the regional long-term air quality. The AEC and AECC calculations that are constrained by GDP and $PM_{2.5}$ are a complicated systematic problem that needs to be analysed so that it considers all aspects of the complex system, such as reference to economy, society, energy use and the environment. When dealing with complex systems, physicochemical methods have an inevitable disadvantage, namely that the economic and social systems cannot be integrated into an environmental model (Vafa-Arani et al., 2014), and these methods are unable to calculate AECC thresholds. Therefore, a system dynamics (SD) method is an appropriate approach for the study of complex systems, because it retains the advantage of simplicity in resolving complex problems (Radzicki and Taylor, 1997; Neuwirth et al., 2015).

To date, in the literature, we have not found any explicit calculations for the annual regional AEC and AECC thresholds constrained by $PM_{2.5}$ using the SD method (Feng et al., 2013; McKnight and Finkel, 2013; Chateau et al., 2015; Gao et al., 2016; Sahin et al., 2016). In 2014, we created an 'economy–atmospheric environment' dynamic model for the 'Pollution Characteristics and Prevention Counter Measures of $PM_{2.5}$' project in Dongguan City, Guangdong province. The predicted results had a well-guiding significance, concluding with a good evaluation. Appointed by the Wuhan Environment Protection Science Research Institute (WEPSRI) in 2015, we commenced a study of AEC and AECC analysis for Wuhan city. Compared with Dongguan, Wuhan city has a larger geographical area, greater population and more complicated circumstances. The subsystems of economy and atmospheric environment in the model for this city were improved, and an energy subsystem was added to the SD model. By adjusting the energy consumption and industrial growth rates, the development of industry and energy can be directly predicted. Improvements made to the model optimised the operability of the model, i.e. the readability of the AEC and AECC thresholds. This shows that adjusting the structure of industry and energy plays an important role in improving environmental quality.

In the present study, we clarify the definitions of AEC, atmospheric environmental stress (AES) and AECC, expand the concept of AECC and describe its dialectical relationship that is constrained by GDP and $PM_{2.5}$. We also establish an 'economy–energy–atmospheric environment' dynamic model using the SD method based on the data of Wuhan city's economical, meteorological, energy and environmental statistical data in 2014. An SD model does not require simulation of the complicated physicochemical processes of atmospheric transmission and diffusion; instead it exploits the pollutants' proportionality factors and conversion rates to establish quantitative connections among different kinds of variables such as GDP, annual $PM_{2.5}$ concentration and six air pollutant emissions (SO_2, NO_x, VOCs, NH_3, primary PM_{10} and primary $PM_{2.5}$). Assuming a stable climatic environment over the next several years, changing the control variables of economy, energy and emission reduction enables us to forecast GDP, pollutant emissions and annual concentrations of $PM_{2.5}$ and PM_{10} from the year 2015 to 2030 in four scenarios. This was then used to calculate AEC and AECC thresholds (PM_{10} is also particulate matter whose diameter is less than 10 μm and having a tight relationship with $PM_{2.5}$).

2. Background, concepts and technology roadmap

The concepts of environmental capacity and environmental carrying capacity are different between Western countries and China; because different countries are at different stages in their environmental protection plans. Developed countries have progressed from the contradictory period of economic development and environmental protection towards a period that contains environmental quality protection. These countries have no need for a considerable emission reduction scheme and maintain their environmental status through supervision and regulation. With reference to the two concepts of environmental capacity and environmental carrying capacity, the majority of researchers from Western countries do not differentiate between them. Instead, they generally study the capacity of ecological and urban resources from the perspective of the ecological or environmental system itself, such as forests, land use, marine, mineral and transportation capacity (Zeng and Yang, 1991; Arrow et al., 1995; Saveriades, 2000; Furuya, 2004; Mondino et al., 2014; Martire et al., 2015).

However, these two concepts in China are very different. Several Chinese researchers study them from the perspective of environmental carrying variables such as social, economic, technological development and the accompanying pollution. Developing countries, including China, are still located in the climb portion of the Environment–Economy Kuznets curve ('Inverted-U' curve), where a number of environmental indicators fail to reach the established standards. It is therefore necessary to distinguish the bottom line that the environment can bear, i.e. the environmental capacity, as well as determine the scale of social and economic activities within a reasonable scope of lower effect to the environmental quality, i.e. environmental carrying capacity, for China and other developing countries. Additionally, the Chinese government has powerful macro-control, and is capable of regulating the social and economic activity to ensure better development.

Thus, environmental capacity is generally defined as the maximum total pollutant load that the environment can receive according to the environmental quality standard in a certain geographical range. This is a prototype of the concept of environmental carrying capacity theory (Wang et al., 2005; Li, 2007). However, environmental issues are complex, and have close relationships with social and economic development. This means that merely discussing the assimilative capacity of the environment itself cannot meet China's future developmental needs. Conceptually, on the basis of the environmental capacity, the environmental carrying capacity needs to be extended to include not only capacity, but also

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