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Campus countermeasures to deal with atmospheric pollution using engineered water features as based on the simulations of the AERMOD model

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Abstract. This paper proposes an innovative dual strategy for campus water landscape engineering combining environmental construction and regulation of pollutant concentration to counteract atmospheric pollution, as simulated by the AERMOD model. By integrating elements of fountains, falling water and mist, the campus can create a comfortable microclimate environment for students during regular atmospheric conditions. During pollution events, these features can ameliorate atmospheric pollution resulting from prevailing winds and specific wind speeds to ensure the ecological safety of the campus.

1. Research background

The island of Donghai of Guangdong Zhanjiang is an important base for heavy chemical industry (petrochemical, steel), and is situated within the Pearl River delta of Guangdong. Also situated here is a petrochemical industrial park that has received heavy investment (\$10 billion) from BASF, a well-known German enterprise. It is very likely that the heavy chemical industry will result in air pollution impacting the downwind area. The results show that artificial landscape facilities such as water fountains can improve the local microclimate environment [1].

2. Analysis of the air pollution relationship

2.1. Introduction to pollution sources and their targets

The island of Donghai is located in the southeast of Zhanjiang City. A petrochemical and steel industry is planned for the area, with production starting in 2019. The area will also contain a crude oil processing plant with a capacity of 15 million tons year⁻¹, producing 10,000 tons of ethylene [2]. The Zhanjiang Environmental Protection Bureau has confirmed that the total emission control index of SO₂ is 4,800 tons year⁻¹ [3].

The main campus of Guangdong Ocean University, located approximately 10 km from the planned industrial area on the northwestern part of the island, is located close to the national 4A level geopark - Huguang Lake Global Geopark (the SO₂ concentration limit should meet the national level 1 standard of 0.2 mg m⁻³). The total area of the university is 3.26 km², and the campus has an enrollment of approximately 40,000 students. The campus includes a large green area, with water features including two artificial lakes and a few artificial water scenes (fountains).



2.2. Analysis of pollution model simulation

The prediction of atmospheric pollution concentration generally follows the laws of diffusion under steady-state conditions. The AERMOD model is adopted to establish the Aermosystem model. The AERMOD model is based on the theory of diffusion and follows a Gaussian distribution. The model, is suitable for application to various pollution scenarios, such as point sources, non-point sources, volume sources, rural or urban areas, simple or complex topography, ground sources and elevated sources [4].

2.2.1. Parameter setting. The present study refers to the indicators of Sinopec's existing projects, and the following parameters are set in the model [5]:

(1) The strength of pollution sources. The pollution source is set as a single pollutant SO₂ point source. The settings included a chimney height of 120 m, flue gas speed of 15 m s⁻¹, SO₂ emission rate of 548 kg h⁻¹ and the smoke temperature of 100 °C.

(2) Surface parameters. These are mainly set for surface albedo, Bowen ratio and surface roughness parameters.

(3) Terrain data. Taking the East Island petrochemical industry area as the center, the range is N20°55'2.38" to N21°12'24.60" North, E110°15'38.57" to E110°35'49.86" East. Data are obtained by importing digital elevation model (DEM) data files.

(4) Meteorological data. These data originate from the Zhanjiang Meteorological Bureau and the China Meteorological Data Network. The surface meteorological data include total cloud cover, low cloud cover, dry bulb temperature, relative humidity, wind direction, and wind speed. High altitude air image data include air pressure, ground clearance height, dry bulb temperature, dew point temperature, wind direction and wind speed.

(5) Forecast content. These data include the hourly point of interest and grid point SO₂ maximum ground concentration, daily average maximum ground concentration and average maximum ground concentration during the period.

2.2.2. Simulation results. The simulation results shown in Figure 1–2 illustrate that after the model simulation results are superimposed on the annual wind direction frequency of Zhanjiang, the concentration of SO₂ pollutants in the campus from April to June in summer is below 0.2–0.3 mg m⁻³ (beyond the national first-class standard); therefore, the campus will be exposed to SO₂ gas pollution. From October to December, the SO₂ pollutant concentration reaches 0.1–0.2 mg m⁻³ (below the national first-class standard); therefore, the campus does not experience pollution during this time.

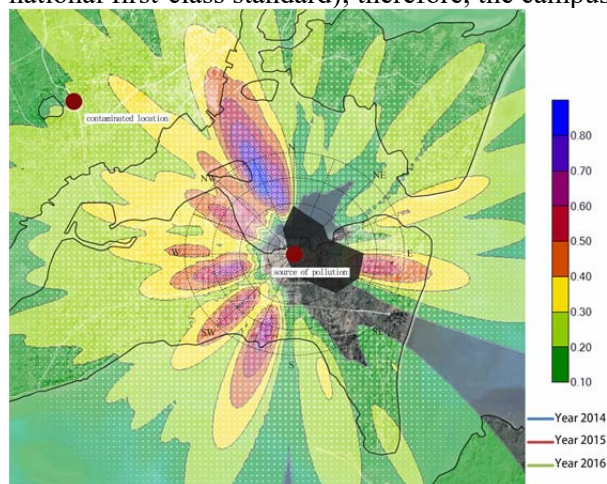


Figure 1. Simulation of SO₂ pollution affecting the island of Donghai from April to June.

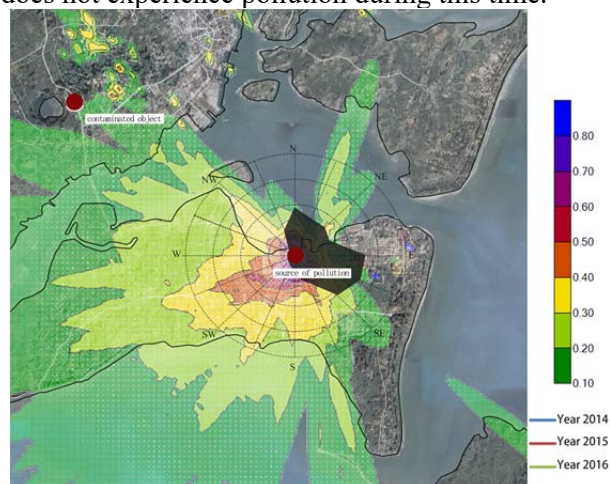


Figure 2. Simulation of SO₂ pollution affecting the island of Donghai from October to December.

2.3. Wind impact analysis

Wind acts to transport and dilute airborne pollutants. According to the study results, meteorological factors other than wind (such as atmospheric stability) indirectly affect the diffusion of atmospheric pollutants through wind and turbulence [5]; therefore, it is necessary to take into consideration the diffusion law of pollutants by analyzing wind direction and speed.

2.3.1. Wind direction analysis. Based on the model analysis, and further determining the influence of wind direction, the wind direction frequency statistics for 16 wind directions are generated for Zhanjiang from 2014 to 2016. Figure 3 shows that the prevailing wind directions in Zhanjiang are southeast (SE 135°), east-southeast (ESE 112.5°), east (E 90°) and north (N 360°). The campus is located between ESE 112.5°–SE 135° and is affected by the prevailing SE and ESE winds.

The statistics properties of the ESE and SE winds during 2014–2016 are generated. The result shown in Figure 4 indicates that SE and ESE winds are prevalent during April–August (10% as the standard and contaminated from April to June).

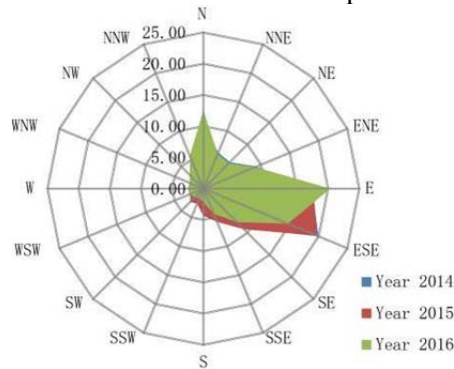


Figure 3. Statistics of wind direction frequency during 2014-2016.

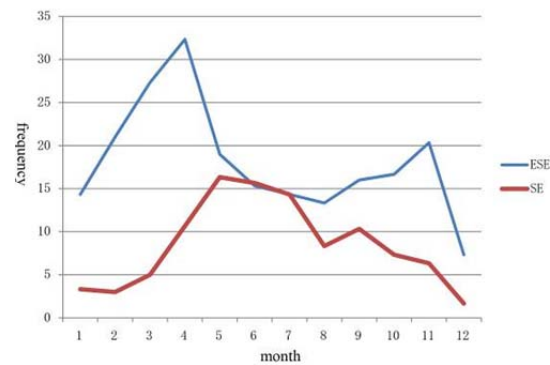


Figure 4. Statistics showing the concentrated months for ESE and SE wind directions during 2014-2016.

2.3.2. Wind speed analysis. (1) According to the current research results, the Gaussian diffusion model of atmospheric pollutants is used to calculate the wind speed interval of the polluted atmosphere. The calculation process is as follows: [6]

- 1) Gaussian diffusion model hypothesis:
 - a. A system: right hand coordinate system with y as the cross wind direction and z as the vertical direction;
 - b. Assume that the concentration of pollutants is normally distributed in the y and z winds;
 - c. All heights are uniform and constant;
 - d. The source strength is continuously uniform and stable;
 - e. Contaminants are conserved during diffusion (regardless of conversion).
- 2) Use the ground axis pollutant concentration model for pollutant estimation with the Zhanjiang atmospheric stability assumed mainly neutral (Class D) [7]:

$$C(x, 0, 0, H) = \frac{2q}{\pi \bar{u} \sigma_y \sigma_z} \cdot \exp\left(-\frac{H^2}{2\sigma_z^2}\right) \quad (1)$$

Displayed in the formula: q is the source strength, $\bar{u}$ is the average wind speed, H is the effective chimney height, σ_y and σ_z are diffusion coefficients

- 3) Effective source height calculation:

$$H = \Delta H + H_s, \quad \Delta H = \frac{V_s D}{\bar{u}} \left(1.5 + 2.7 \frac{T_s - T_a}{T_s} D\right) \quad (2)$$

Where ΔH is the smoke lift height, H_s is the chimney geometric height, V_s is the chimney mouth smoke speed, D is exhaust pipe outlet diameter (set to 3.6 m), T_s is flue gas outlet temperature (423 K) and T_a is the average ambient atmospheric temperature (302 K)

- 4) Use the P-G curve method to determine the diffusion parameters. As shown in Figure 5, when x is 10 km, σ_z is 150 m while σ_y is 500 m.

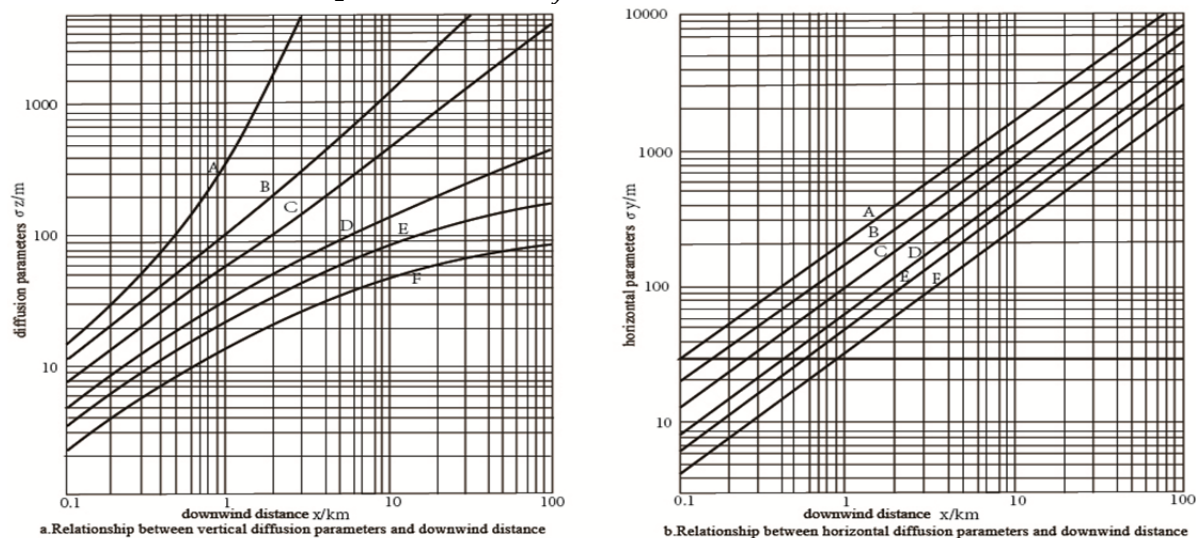


Figure 5. Diagram showing the relationship between downwind distance and diffusion parameters.

- 5) Let $\bar{u}$ be 0.3 m s^{-1} , 1.6 m s^{-1} , 3.4 m s^{-1} and 5.4 m s^{-1} , and calculate the critical value of the wind speed.

Table 1. The relationship between the concentration of pollutants on the ground axis and the average wind speed.

$\bar{u}(\text{m s}^{-1})$	$\Delta H(\text{m})$	$H(\text{m})$	$c_{\text{SO}_2}(\text{mg m}^{-3})$
0.3	362.5	482.5	0.01
1.0	108	228	0.09
1.6	67.5	187.5	0.24
2.5	43.2	163.2	0.14
3.4	31.8	151.8	0.11
5.4	10	130	0.08

As is evident in Table 1, when the wind speed is approximately 1.6 m s^{-1} , the campus experiences atmospheric pollution. According to the wind speed table, when the wind speed interval is between 0.3 m s^{-1} – 3.4 m s^{-1} and the wind speed is close to 1.6 m s^{-1} , the campus faces atmospheric pollution threats.

(2) According to the statistics of the daily average wind speed of ESE and SE during April–June 2014–2016, as shown in Figure 6, light winds (1.6 m s^{-1} – 3.4 m s^{-1}) occur more frequently in the 4–6 months under the influence of ESE and SE winds, followed by gentle wind (0.3 m s^{-1} – 1.6 m s^{-1}).

(3) After deriving statistics on the hourly average ESE and SE wind speeds during April–June 2014–2016 (ignoring the impact of typhoon weather), combined with the travel rate of students within one day, as shown in Figure 7, the period of atmospheric contamination is from 3:00 pm–9:00 pm in summer every day, with the peak period of pollution between 6:00 pm–9:00 pm. Due to the hot summer weather, student outdoor activities mostly occur in the evening.

2.4. Conclusions

From the simulation results of the Aeromodsystem model and wind analysis, it is known that during April–June every year, under the prevailing downwind direction (ESE, SE) and specific wind speed

(close to 1.6 m s^{-1}), SO_2 exceeding the first-class standard limit is transported in the atmosphere. The impact is more serious during 6:00 pm–9:00 pm, coinciding with the period of highest student outdoor activities. In this regard, the campus should adopt relevant countermeasures to respond positively.

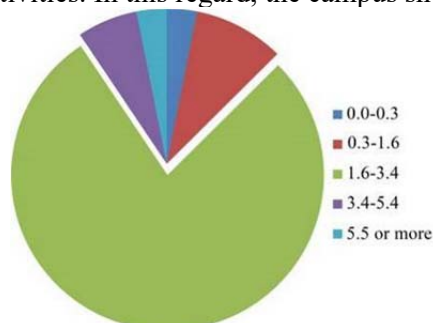


Figure 6. Daily average speeds of ESE and SE winds during April-June.

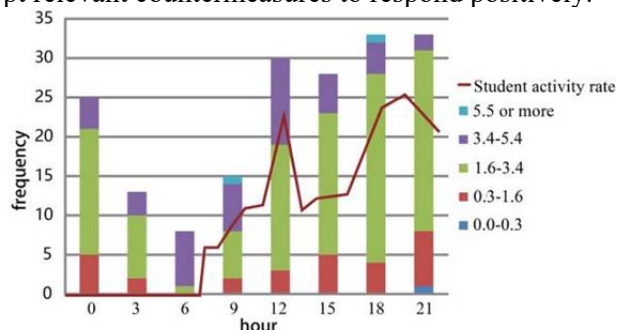


Figure 7. Hourly average speeds of ESE and SE winds during April-June.

3. Countermeasures and safeguards

Given the context of the study results and the current situation on campus, it is recommended that the overall countermeasures start from the construction of a local microclimate, with waterscapes being a particularly important design component. In addition to their beneficial effects of cooling, humidification and dust removal, waterscapes can also remove sulfide from the atmosphere. Therefore, it is possible to form the pollution prevention and control strategy water landscape project, and to construct associated monitoring measures to test its effectiveness.

3.1. Water landscape engineering and its principle

3.1.1 Water landscape engineering. The suggested waterscape form is mainly based on dynamic water design. Flowing water produces a large amount of small water droplets and water mist, which not only dissolve the sulfide in the air (purifying the air), but can also improve the humidity of the air and plays a certain role in dust removal and cooling [8].

3.1.2 Principle exploration. The principle of action of water and air is as follows:

(1) The exchange principle of heat and humidity between the air and the water: When the air is in direct contact with water, the boundary layer of saturated air formed on the surface of the water diffuses with the bulk air through molecular diffusion and turbulence. This results in the saturated air of the boundary layer being continuously mixed with the surrounding atmosphere, thereby changing the state of the surrounding atmosphere [9].

(2) The dissolution mechanism of gas in water: Because of gap filling and hydration, gas is soluble in water. Gas molecules are able to fill in the gaps existing between water molecules, and an interaction exists between gas and water molecules [10].

(3) The chemical properties of SO_2 produced by petrochemicals are extremely unstable and often combine with water to form sulfurous acid. The reaction equation is: $\text{SO}_2 + \text{H}_2\text{O} \rightarrow \text{H}_2\text{SO}_3$.

Based on the above principle, the gas dissolved in water through water landscape engineering is as shown in Figure 8:

3.2. Safeguards

3.2.1. Monitoring equipment. To facilitate monitoring of the concentration trend of SO_2 in real time and to allow a response to high concentration pollution, SO_2 monitoring equipment should be installed on campus.

3.2.2. Indicator plants. According to research, indicator plants are able to detect air pollution earlier and respond to atmospheric pollution more sensitively than humans [11]. The plants able to indicate the presence of SO_2 in the subtropical region include *Heteropanax fragrans* (Roxb.) Seem., *Ormosia pinnata* (Lour.) Merr., *Fagraea ceilanica* Thunb., *Dillenia indica* L., *Liquidambar formosana* Hance, *Elaeocarpus hainanensis* Oliver, *Dianthus chinensis* L., *Zinnia elegans* Jacq., *Rosa chinensis* Jacq., *Dianthus chinensis* L. and *Albizia julibrissin* Durazz.

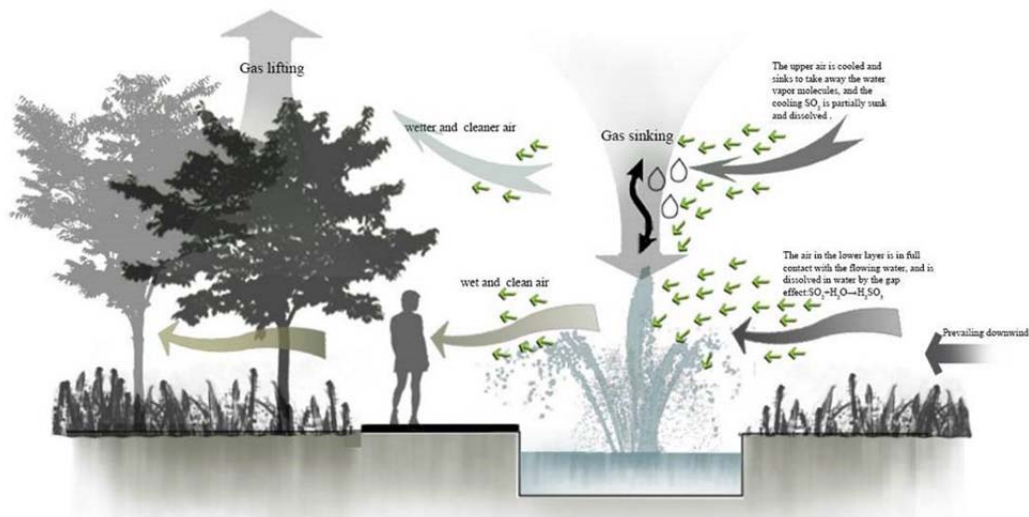


Figure 8. Principle of the interaction between water and gas within water landscape engineering.

4. Water landscape engineering project design

4.1. Section point for microclimate simulation

ENVI-met is a microclimate simulation tool that simulates a local microscale wind environment, eddy currents and water bodies over a short period [12]. ENVI-met is selected for the implementation of water landscape engineering.

According to the ENVI-met simulation, it can be seen from Figure 9 that the wind speed between buildings with uniform layout is larger, and the closer the distance, the higher the wind speed. Buildings with an uneven layout form a low-speed zone near the building and a high-speed zone in the outer periphery. The concentrations of pollutants gather on the back side of the windward building.

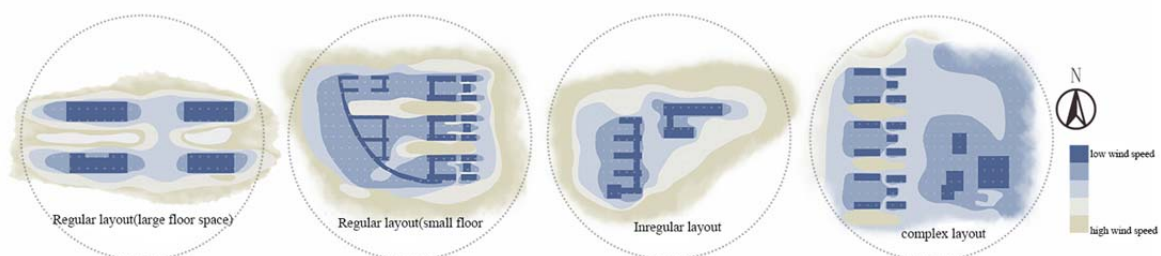


Figure 9. ENVI-met simulation.

Based on the simulation results and a comprehensive consideration of the needs of student activities, it is advisable to set the waterscape engineering implementation point in the green space between Butterfly Lake, Ocean Square, Central Square, Zhonghai Building and Haixuan Dormitory Building.

4.2. Water landscape engineering design

According to the frequency and method in which students use the above-mentioned venues from April to June, combined with the above conclusions, it is proposed that the campus air purification design be conducted using the three types of water landscape projects. The design and effects are shown in Figure 10 and Figure 11.

4.2.1. The key points for the design of water fountain features. Combined with the existing water landscape research results [13] and site characteristics, the campus fountain landscape design points are described: change the nozzle performance to reduce the particle size, control the height of the fountain to approximately 3.5 m, arrange the nozzles side by side to increase the length of the vertical wind direction, reduce the number of nozzles arranged along the direction of the wind and increase the nozzle spacing to maintain the desired wind speed.

Considering the characteristics of student activities and wind speed characteristics within the design of different fountains on campus, and to maximise energy savings and efficiency, it is recommended that the frequency of fountain use be increased after 4:00 pm from April to June, and used appropriately the rest of the time.

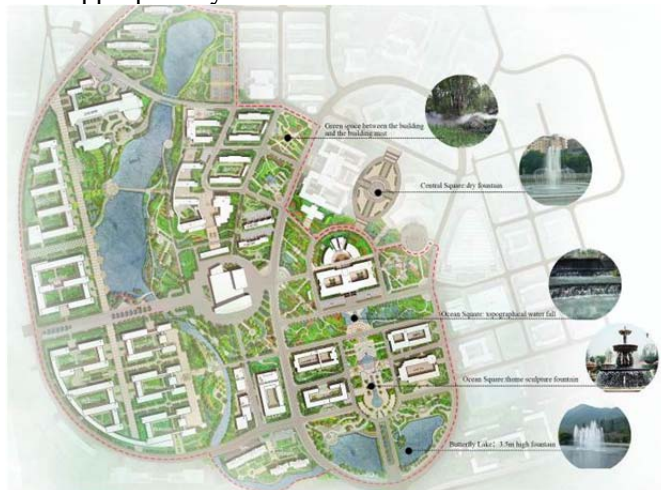


Figure 10. Design plan and intention.



Figure 11. Landscape renderings.

4.2.2. The key points for the design of falling water features. The distance between the water feature and the main student activity spaces should be shortened to within 1 m–1.5 m. The design is mainly based on the campus terrain.

4.2.3. The key points for the design of mist-creating water features. Mist consists of tiny water particles formed by mechanical pressure to promote high-speed injection of liquid water into the atmosphere [14]. Due to the complicated structure and high construction and maintenance costs of these water features, it is necessary to strictly control the running time of the operation to avoid wasting of resources. It is the best to control the time of operation to around 1 h–1.5 h during the evenings between April–June.

5. Summary

The proposed water landscape engineering design is focused on meeting the physical and psychological needs of people and environmental climate regulation requirements. However, water landscape engineering has rarely been applied for specific scenarios and targets. The water landscape engineering design proposed in the current study is based on the results of Aermosystem model simulations. The present study focusses on a small-scale site on the campus and connects atmospheric pollution with the campus water landscape, thereby using the principle of diffusion between water and

gas to design water features incorporating fountain, falling water and mist elements. Under the premise of satisfying the characteristic landscape design of the campus environment, these measures are beneficial to ameliorate SO₂ pollution, thereby optimizing the campus microclimate environment and maintaining the ecological environment of the campus. The study can be improved and extended in practice in the future to further play a role in air pollution response measures.

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