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Applications of Drones for Environmental Monitoring of Pollutant-Emitting Facilities

Seung Woo Son[1], Jae Jin Yu[1], Dong Woo Kim[1], Hyun Su Park[2], Jeong Ho Yoon[1]*

[1] Department of Land and Water Environment Research, Korea Environment Institute, Sejong, Korea
[2] Team of Ecosystem Service, National Institute of Ecology, Seocheon, Korea

ABSTRACT

This study aimed to determine the applicability of drones and air quality sensors in environmental monitoring of air pollutant emissions by developing and testing two new methods. The first method used orthoimagery for precise monitoring of pollutant-emitting facilities. The second method used atmospheric sensors for monitoring air pollutants in emissions. Results showed that ground sample distance could be established within 5 cm during the creation of orthoimagery for monitoring emissions, which allowed for detailed examination of facilities with naked eyes. For air quality monitoring, drones were flown on a fixed course and measured the air quality in point units, thus enabling mapping of air quality through spatial analysis. Sensors that could measure various substances were used during this process. Data on particulate matter were compared with data from the National Air Pollution Measurement Network to determine its future potential to leverage. However, technical development and applications for environmental monitoring of pollution-emitting facilities are still in their early stages. They could be limited by meteorological conditions and sensitivity of the sensor technology. This research is expected to provide guidelines for environmental monitoring of pollutant-emitting facilities using drones.

Keywords: Air pollutants, Drones, Environmental Monitoring, Particulate matter, Pollution-emitting facilities

Introduction

Environmental monitoring is important for determining discharge levels of environmental contaminants and illegal operations of pollutant-emitting facilities. Monitoring can prevent environmental contamination, thereby supporting conservation efforts. Pollutant-emitting facilities are sometimes involved in discharge accidents, which can cause property damage and threaten human life. Therefore, it is extremely important to monitor these facilities. However, illegal activities of facilities have evolved diversely, making it challenging to monitor their activities in a timely and effective manner. In addition, manpower and funding required for environmental monitoring are insufficient, leading to enforcement of environmental laws through adoption of "Selection and Concentration" for higher efficiency of environmental monitoring (Son *et al*., 2017).

Environmental monitoring mainly targets corporations and facilities that discharge various media into the environment, including contaminated air and water, waste, and chemicals. The monitoring covers sampling, documentation inspection, and facility and equipment inspections to confirm whether the entity has abided by or disobeyed regulations. Environmental monitoring is mostly conducted by local governments, although the Republic of Korea Ministry of Environment conducts special monitoring when required.

Environmental violations have recently become more discreet and intellectual. They mostly involve corporations, regardless of size, that discharge contaminants beyond confines of legal obligations or standards through abnormal operations of their facilities. In the environmental realm, in which violations occur through complicated causes and processes, it is difficult to expose and prove the crime on time without the support of environ-

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***Corresponding author:** Jeong Ho Yoon
e-mail jhyoon@kei.re.kr
https://orcid.org/0000-0003-2321-2172

mental monitoring by personnel with subject matter expertise and technology.

To constantly monitor evolving environmental pollution activities, it is essential to secure equipment such as drones and sensors that can measure on-site pollutant levels while tracking illegal activities. However, current environmental monitoring groups and local governments only have rudimentary equipment, which limits their ability to identify illicit activities. Some discharging facilities use CCTV to disrupt enforcement and/or continuously discharge contaminants illegally at night, making it challenging to collect physical evidence of their illicit activities.

Drones have recently become more accessible for research and monitoring in several fields. They could also be used to monitor pollutant-emitting facilities. Many more factors should be considered when using drones to detect and collect air pollution contaminants compared to a general flying technique of drones. When setting a flying technique, air quality disturbance and sensing data errors resulting from the rotary-wing movement of the drone need to be considered. Villa *et al*. (2016) have quantified the surrounding atmospheric disturbance from drone propellers to determine the extent of the done propeller's effect in up-down, left-right, and front-rear directions.

As for drone-based air quality measurements, previous studies have measured vertical profiles of air quality concentration changes and effects at different altitudes (Tao *et al*., 2007; Wu *et al*., 2002). Most studies based on air pollutants generated on the ground have found that the air quality profile is decreased when the altitude is increased. Recent studies have also investigated vertical profiles of contaminants such as particulate matter (PM) (Alvarado *et al*., 2017; Lee, 2018; Lu *et al*., 2016) and concentration profiles of contaminants from roads (Villa *et al*., 2017; Weber *et al*., 2017). The aim of this study was to determine the potential for the development and application of an environmental monitoring methodology using drones to monitor pollutant-emitting facilities.

Materials and Methods

The objectives of this study were: 1) to develop an environmental monitoring methodology using drones for effective monitoring of constantly evolving emissions and environmental crimes, and 2) to determine the feasibility of applying the developed methodology. Two methods were tested in this study for atmospheric environmental monitoring using drones: 1) the use of orthoimagery for precise monitoring of pollutant-emitting facilities; and 2) the use of atmospheric sensors for monitoring air pollutants in emissions (Table 1).

Target areas for this study were industrial complexes located in metropolitan cities of Busan and Daejeon, Korea. Industrial Complex A was located in Busan, covering a total area of 885,247 m^2. Industrial Complex B was located in Daejeon, covering a total area of 3,113,699 m^2.

Precise monitoring of pollutant-emitting facilities through orthoimages

Drone-based orthoimagery is a highly suitable environmental monitoring system. One of its greatest strengths is that the flight schedule can be modified depending on the objective. Previously, orthoimages were mostly produced using satellite or aircraft imagery. Although raster data from satellite and aircraft imagery can provide information over a wide area, they are limited in collecting information at a fine temporal and spatial scale and continuously in short time frames. The spatial resolution ranges from 11 cm

Table 1. Areas subjected to drone monitoring

Dates	Area	Method	Dates	Area	Method
Aug. 28-29, 2017	Industrial Complex A (Busan)	High-resolution Orthoimagery	Aug. 28-29, 2017	Industrial Complex A (Busan)	Emission monitoring of air pollutants
Mar.12, 2018	Industrial Complex B (Daejeon)		Jan. 31 – Feb. 1, 2018	Industrial Complex B (Daejeon)	
Apr. 3, 2018			Mar. 13, 2018		
			Apr. 3, 2018		
			Apr.10, 2018		
			Apr. 3 – May 17, 2019		

to 1 m, which limits the ability to decipher objects depending on the task required. Domestic orthoimagery technology has become sophisticated during the shift from analog to digital methods, which have been produced through satellite and aircraft imagery. However, its meteorological constraints and high costs make it challenging to produce spatial information in a timely manner. Therefore, there has been more interest in establishing prompt and precise 3-D spatial information using unmanned aerial systems at an affordable cost.

In this study, a medium-sized DJI Inspire one pro drone and a small-sized Mavic Pro drone were used to produce orthoimages. An optical camera was used to shoot target sites and deliver images. Collected images were then matched and consolidated to form a high-resolution map of industrial complexes.

Air pollutant emission monitoring through air sensors

Air sensors and collectors were attached to drones to detect and collect air contaminants. These sensors were examined prior to flight to ensure their reliability. They were installed in the vicinity of the NAPMN to compare data. Additionally, portable PM measuring instruments (TSI instruments) with a similar level of accuracy to the NAPMN were used indoors and outdoors for comparison. The module with a PM sensor was initially tested. This is because PM has become a major issue recently. Drones equipped with these sensors and air sample collectors were specifically designed for this study. These drones then automatically flew a preset flight route within industrial complexes and factory-concentrated areas expected to emit air contaminants for monitoring contaminants in the air above study sites. A flight controller (FC) with autopilot capability was attached. Flight path was set prior to taking off. Air contaminants could be detected by sensors during flight. Readings were relayed to a ground control system (GCS) for real-time verification.

Collection of air contaminants was also possible with air sensors. When air samples were collected at particular points, they were brought back to the ground for analysis to determine the precise concentration or level. Air sample collection points were automatically geotagged by the FC, which saved its coordinates to determine its precise location. The air contaminant concentration could also be determined from orthoimages in centimeters together with overlap analysis. A DJI's M600 drone and an air sensor DR1000 (Sentroid) were used for this operation. Air sensor collection by DR1000 was divided into enclosures A and B within each industrial complex. Enclosure A was used to measure NO2, VOCs, PM, SO2, and CH20. Enclosure B was used to measure CO, CO2, H2S, HCL, and NH3. It could be used for about 3 hours on a single charge. A high-frequency antenna and a Wi-Fi module were installed in the GCS.

Results and Discussion

Precise monitoring of pollutant-emitting facilities through orthoimages

Flight altitude, image overlap, ground sample distance (GSD), and so on were identified through high-resolution orthoimages of industrial complexes and pollutant-emitting facilities. This enabled the development of an optimal drone flight to conduct environmental monitoring within an industrial complex. The accuracy of the orthoimage was based on its flight.

Environmental monitoring through orthoimages involves the analysis of orthoimages based on time series data and detection of sites confirmed or suspected to cause environmental pollution. An efficient environmental monitoring system can reduce the spatial range of environmental

Table 2. Variables derived from orthoimages of Industrial Complexes A and B

Location	Industrial Complex A (Busan)		Industrial Complex B (Daejeon)		
Drone	Mavic Pro	Inpire 1	Inpire 1	Inpire 1	Inpire 1
Camera		Zenmuse X5	Zenmuse X5	Zenmuse X5	Zenmuse X5
Flight Distance	3608m	5709m	1757m	1423m	3297m
Flight Time	9’ 42”	15’ 20”	5’ 4”	4’ 50”	9’ 10”
Altitude	100m	100m	70m	70m	70m
Imagery Overlap	80%	80%	80%	80%	80%
Imageries	178	228	131	71	232
GSD	4cm	4cm	4cm	4cm	4cm

enforcement and investigations.

All orthoimages from target sites were accurate enough to provide naked eye confirmation of specific facilities within industrial complexes. This was possible because the GSD of most orthoimages was lower than 5 cm. For Industrial Complex A in Busan, the flight time of a small-sized drone was approximately 9 min at an altitude of 100 m. The flight variable of imagery overlapping at 80% was attained with a total of 178 images and a GSD of 4 cm. In other words, it took approximately 10 min to fly above an industrial complex with an 885,247m^2 area to collect enough images for producing an orthoimage. After which, an overall and specific map of the area could be drawn up in 20 min. In the case of Industrial Complex B in Daejeon, safety and security constraints only allowed imagery and analysis of 10% of the overall complex. Overall orthoimagery results for the two study sites are listed in Table 2.

Air contaminant emission monitoring through air sensors and collection devices

Air quality analysis utilizing drone-mounted sensors involved drone and sensor selection, sensor calibration and validation, air contaminant measurement through flight, and data analysis. Study results revealed that PM10 and PM2.5 measured with air sensors tended to be lower than those measured with the NAPMN sensor installed on the roof of the Daejeon Institute of Health and Environment located in Gooseong-dong, Korea. This might be because approximately a meter-long inlet was connected to a pump when conducting outdoor measurements or attaching to a drone. For this particular research, an indoor sensor and a hose over two mas an inlet were used, which might have lowered PM10 and PM2.5 values.

After comparing values collected by the drone with those measured with the NAPMN, a comparative experiment was conducted in the Korea Environment Institute (KEI) for indoor and outdoor environments to compare drone, NAPMN, and a TSI Aerosol Monitor equipment. TSI measures PM through light scattering, similar to the

Fig. 1. Comparison of drone and air sensor.

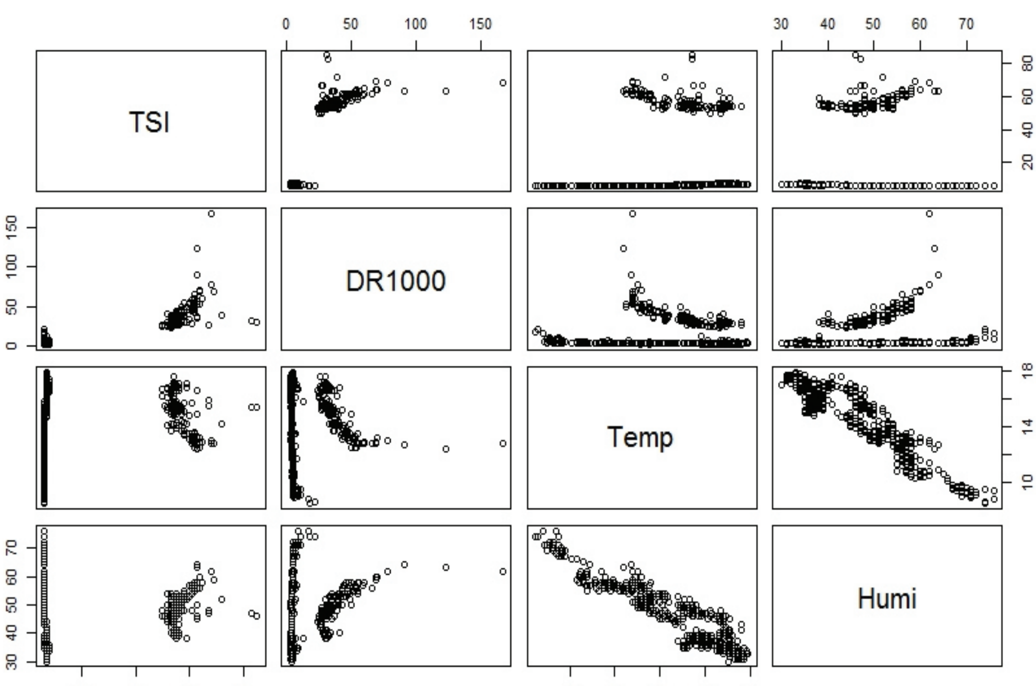

Fig. 2. Comparison of results of drone air monitoring sensors in indoor and outdoor environments.

drone's air monitoring sensors. Although the accuracy of a TSI is lower than that of the NAPMN, it is in accordance with the beta-ray measurement. Thus, it was selected as a comparative test equipment. The comparison of indoor and outdoor environments was conducted at the KEI rooftop (outdoors) and its conference room (indoors). PM was periodically and artificially generated by burning incense to confirm detection by the sensor. The conference room was vented (Fig. 1).

Comparative results for drone air monitoring sensors and the TSI equipment showed a correlation of 1:0.88 between the two devices. They also showed strong negative correlations with temperature and humidity. However, humidity showed low correlations with the air monitoring TSI equipment and drone air monitoring sensors. On the other hand, the air monitoring TSI equipment and drone air monitoring sensors showed almost no correlation with temperature (Fig. 2).

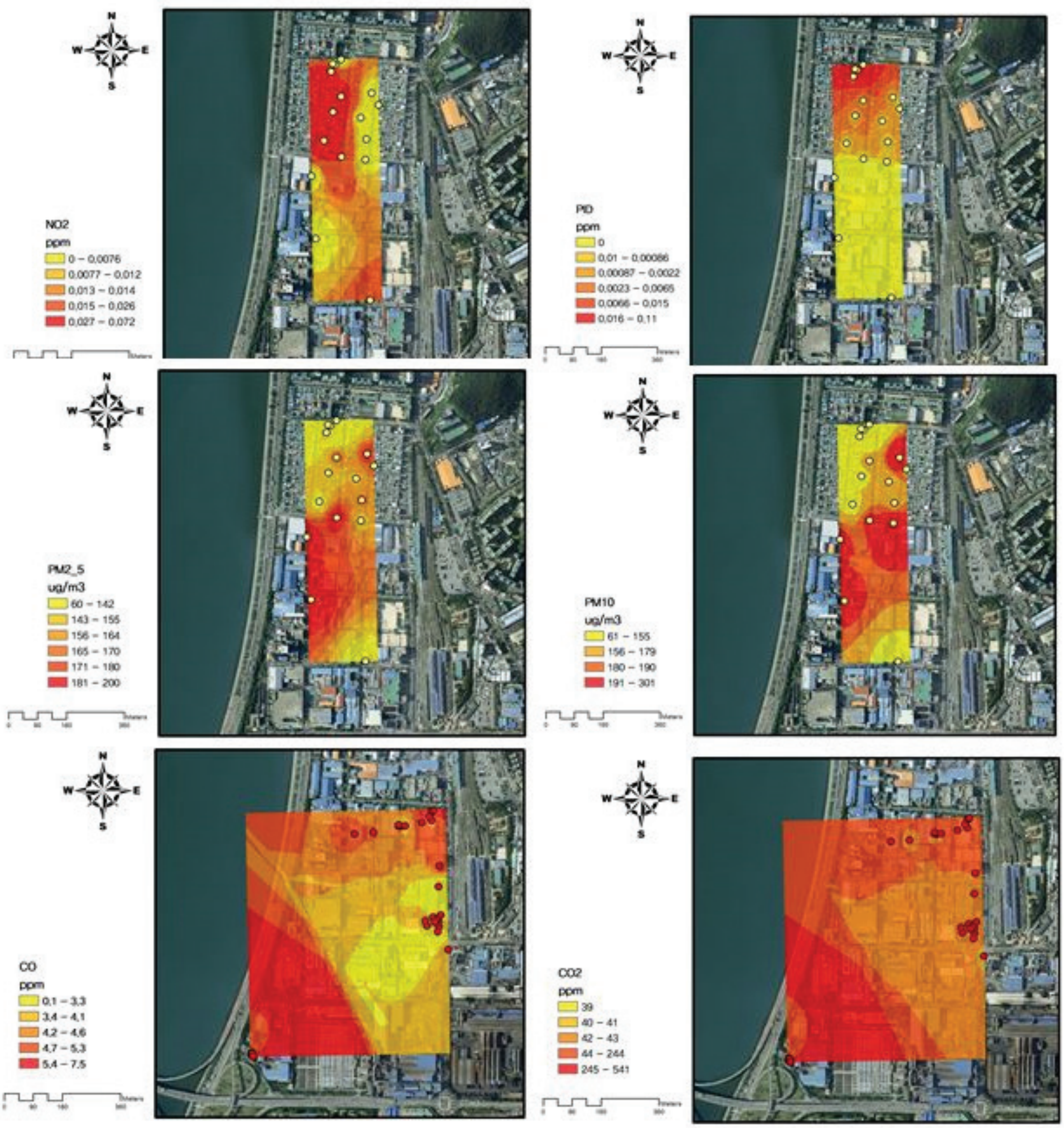

Fig. 3. Air quality and mapping for Industrial Complex A (Busan).

Air contaminant emission monitoring for Industrial Complex A in Busan was conducted in two areas (Fig. 3). Residential areas were covered by Enclosure A, with a total of 15 different points. Nitrogen dioxide and volatile organic compounds (VOCs) showed unreliable values due to flight execution prior to sensor stabilization. Sulfur dioxide was not detected because of sensor errors, although its presence was known. Average values of PM2.5 and PM10 were 160.153μg/m^3. PM2.5 and PM10 values were higher while nitrogen dioxide values were lower using air sensors than those measured with the NAPMN closest to the target ai r contaminant emission area being monitored. VOCs could not be compared because they were not monitored by NAPMN.

The drone was flown through Enclosure B. A total of 50 different points were monitored. Ammonia was not detected This could be due to sensor errors. Average concentrations of carbon monoxide, carbon dioxide, and hydrogen chloride were 4.57488, 52.22026, and 0.40584 ppm, respectively.

Some areas within Industrial Complex B in Daejeon were subjected to testing for PM within sensor A at altitudes of 50 and 100 m (Fig. 4). Batteries of a drone and the sensor module limited the time for deployment. Therefore, monitoring was conducted over two days. The distance between Industrial Complex A in Busan and the local NAPMN was large, making it unfeasible to compare data collected by the drone with those collected by the NAPMN. However, in the case of Complex B in Daejeon, a local NAPMN was installed nearby (5 km), making it easier to confirm the accuracy of the sensor.

Monitoring results revealed that average PM2.5 and PM10 levels at an altitude of 50 m were 5.42μg/m^3 and 6.19μg/m^3, respectively. These average values at an altitude of 100 m were 6.19m^3 and 10.41μg/m^3, respectively. PM2.5 and PM10 concentrations at both altitudes were lower than those measured by the NAPMN. According to altitude, PM2.5 showed a tendency to increase in concentration as altitude increased, while PM10 showed a decrease in concentration as altitude increased.

Conclusions

This study was conducted to determine the poten-

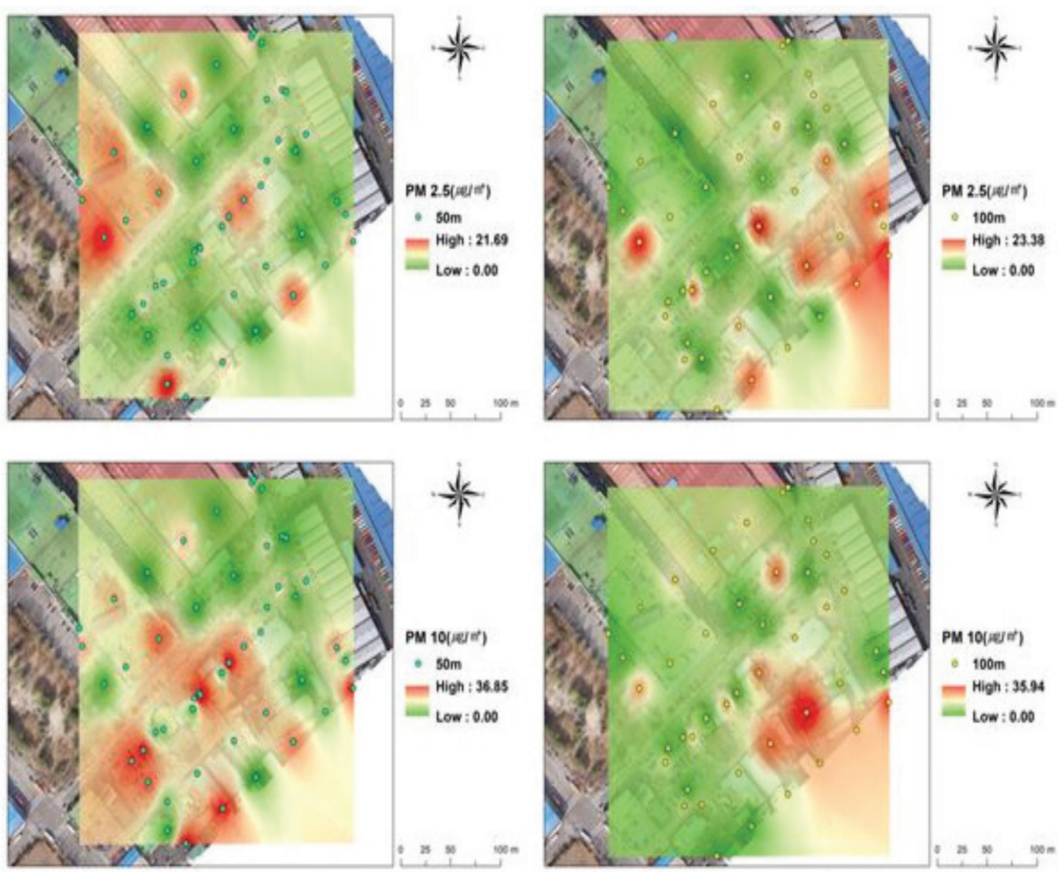

Fig. 4. Air quality and mapping for Industrial Complex B (Daejeon).

tial of utilizing drones and air monitoring sensors to facilitate environmental monitoring of pollutant-emitting facilities. Results showed that environmental monitoring through orthoimagery enabled monitoring with naked eyes. In addition, the condition and status of facilities could be determined and air qualities within and surrounding pollutant-emitting facilities could be measured in real-time. This study also identified some positive and negative implications for drone-based monitoring of emission facilities. Utilizing drones allows for flexible atmospheric environment monitoring. It can eliminate temporal and spatial constraints of satellite and aerial images. For example, a smokestack from a pollutant-emitting facility is difficult for a person to approach and emission timeframes cannot be set. However, the use of drones can help mitigate this issue by monitoring air pollutant emissions at a particular time and location. In addition, using drones enables mapping of the atmospheric environment which can play an important role in conservation and spatial decision-making, such as local planning and urban planning. Drones also allow for mapping in 2-D and 3-D at the required point and space. The precise data collected through drones can also facilitate modeling with a higher precision through machine learning and high-level data analysis.

Athough utilizing drones for environmental monitoring of emission facilities has shown much promise, it is still in its infancy. Meteorological conditions still limit drone use. Sensor technology centered on PM can also be a limiting factor. The establishment ofalegal and institutional foundation, along with further technological development of sensors, will facilitate the active employment of drones in the field of environmental monitoring.

Conflict of Interest

The authors declare that they have no competing interests.

Acknowledgments

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