

SPATIOTEMPORAL ANALYSIS OF PM_{2.5} CONCENTRATION IN DHAKA, BANGLADESH (1998–2024)

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Abstract

Air pollution, particularly fine particulate matter (PM_{2.5}), has emerged as a critical environmental and public health concern in rapidly urbanizing regions. This study investigates the spatiotemporal variation of PM_{2.5} concentrations in Dhaka and its surrounding districts in central Bangladesh over the period 1998–2024. Using spatial mapping and comparative analysis, the study reveals a significant increase in PM_{2.5} levels over time, with a transition from relatively low and homogeneous concentrations in the late 1990s to highly concentrated and spatially heterogeneous patterns in recent years. The results identify Dhaka as a persistent pollution hotspot, with surrounding districts increasingly affected due to urban expansion and industrial activities. Temporal analysis indicates phases of gradual increase (1999–2003), accelerated growth (2004–2008), peak pollution (2009–2013), fluctuation (2014–2018), and recent variability with temporary improvements followed by renewed intensification (2019–2023). The findings highlight the urgent need for effective air quality management strategies and sustainable urban planning to mitigate the adverse impacts of PM_{2.5} pollution in Bangladesh.

Keywords: PM_{2.5} , Air Pollution, Spatiotemporal Analysis, Dhaka, Urbanization, GIS Mapping, Environmental Health

Introduction

Air pollution is widely recognized as one of the most pressing environmental challenges globally, with fine particulate matter (PM_{2.5}) posing severe risks to human health and ecosystems. Due to their extremely small size, PM_{2.5} particles can penetrate deep into the lungs and enter the bloodstream, contributing to respiratory illnesses, cardiovascular diseases, and premature mortality (World Health Organization, 2021). The WHO further emphasizes that even low concentrations of PM_{2.5} can have significant adverse health effects, leading to the introduction of stricter global air quality guidelines. Recent studies indicate that long-term exposure to air pollution is associated with an increased global disease burden and reduced life expectancy (Health Effects Institute, 2020). The Health Effects Institute reports that millions of deaths annually are attributable to air pollution exposure, underscoring its global scale and severity. Scientific evidence consistently demonstrates that fine particulate matter is a critical link between environmental pollution and adverse human health outcomes, reinforcing the need for integrated policy responses and mitigation strategies (World Health Organization, 2021; Health Effects Institute, 2020). Additionally, large-scale assessments reveal that outdoor air pollution contributes substantially to global premature mortality, particularly in rapidly urbanizing and industrializing regions (Health Effects Institute, 2020). These findings highlight the urgent need for comprehensive spatiotemporal analyses of PM_{2.5} to better understand pollution dynamics and to support effective environmental management and public health interventions.

Study Area

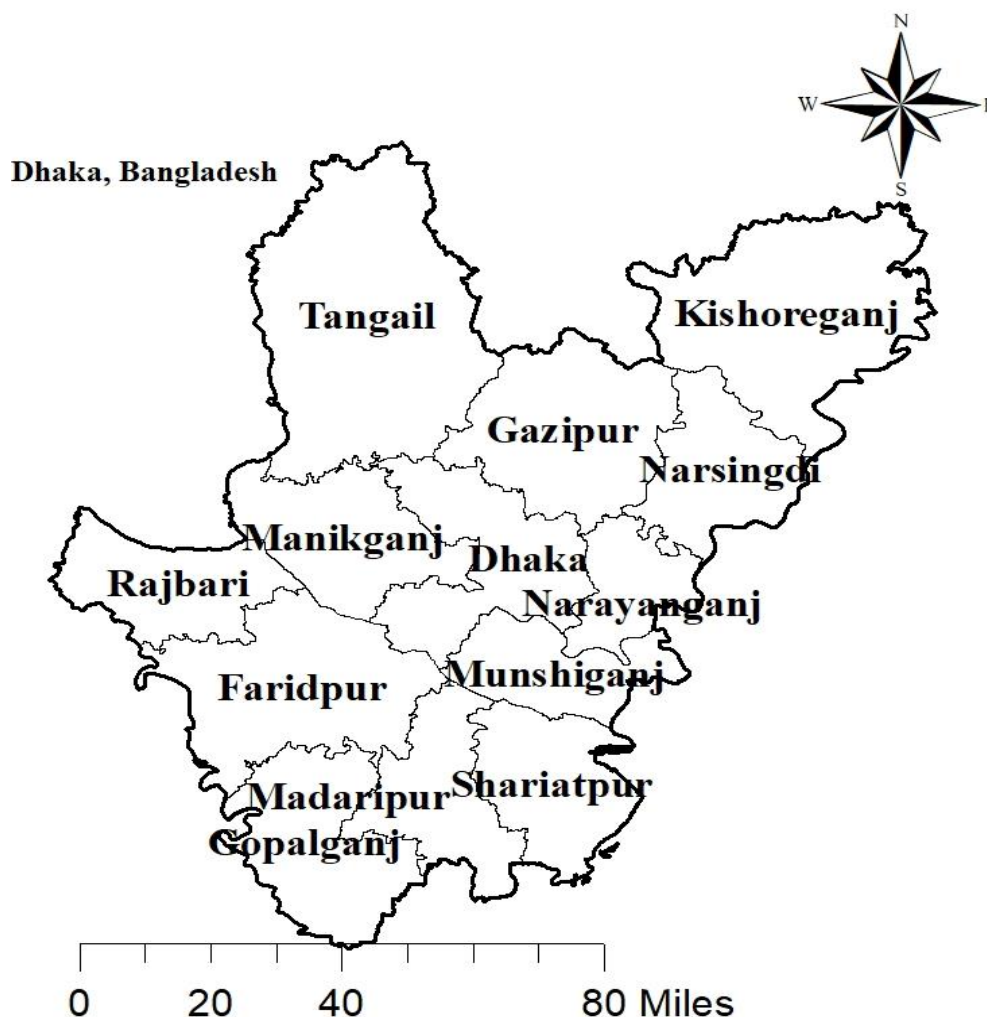


Figure 1. Study area map showing Dhaka and its surrounding districts in central Bangladesh

The study area is centered on Dhaka and encompasses its surrounding districts in central Bangladesh, including Tangail, Gazipur, Kishoreganj, Narayanganj, Munshiganj, Manikganj, Rajbari, Faridpur, Madaripur, Shariatpur, and Gopalganj. This region represents one of the most densely populated and rapidly urbanizing zones in the country, characterized by a mix of urban, peri-urban, and rural landscapes. Dhaka, as the economic and administrative hub, exerts significant influence on adjacent districts through industrial expansion, transportation networks, and population growth. The presence of major industries, brick kilns, and extensive road traffic contributes to increasing environmental pressures, particularly air pollution. Additionally, the area's flat topography and seasonal climatic conditions can influence pollutant dispersion and accumulation. Due to its strategic importance and escalating environmental challenges, this study area provides a critical setting for analyzing spatial and temporal variations in $PM_{2.5}$ concentrations and their implications for public health and sustainable urban development.

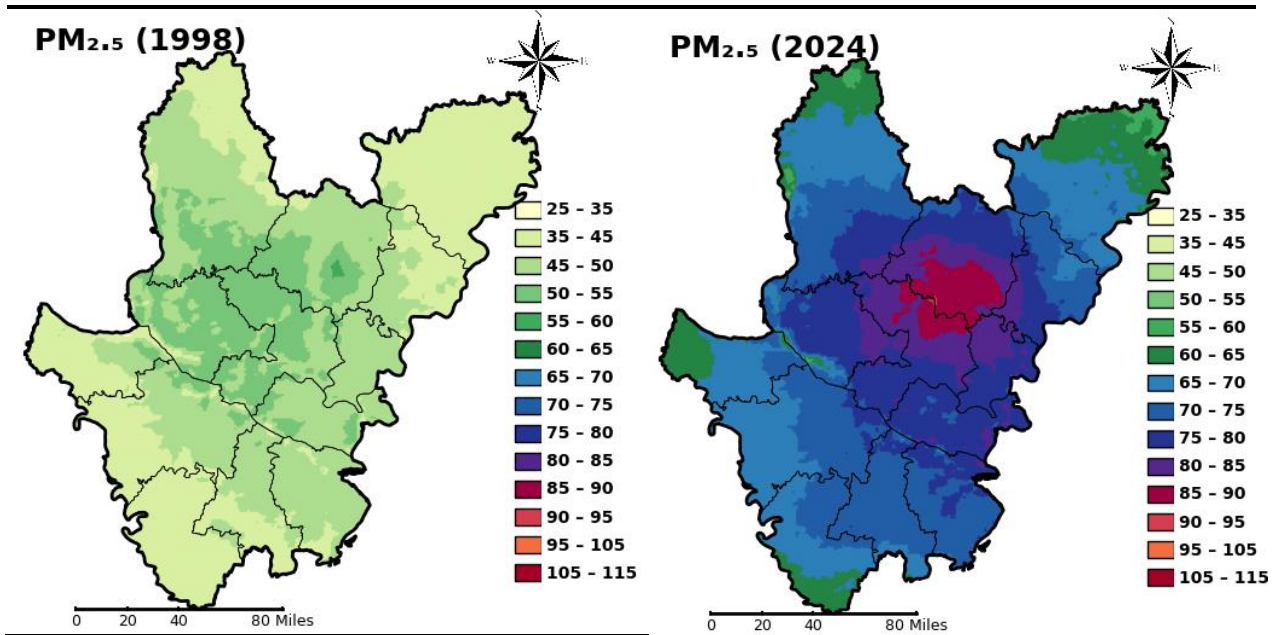


Figure 2. Spatial distribution of PM_{2.5} concentrations in the study area for 1998 and 2024, illustrating a significant increase in pollution levels and the emergence of a high-concentration hotspot in Dhaka and its surrounding regions.

Figure 2 demonstrates a substantial increase in PM_{2.5} concentrations across the Dhaka between 1998 and 2024, along with a notable shift in spatial patterns. In 1998, PM_{2.5} levels were generally low to moderate and exhibited a relatively uniform distribution, indicating limited localized pollution sources. However, by 2024, a pronounced hotspot has developed in the central region, particularly in Dhaka, where concentrations exceed the highest classified ranges. Surrounding districts such as Gazipur, Narayanganj, and Manikganj also show elevated levels, suggesting the outward spread of pollution from the urban core into peri-urban areas. This transformation reflects the cumulative impacts of rapid urbanization, industrial expansion, increased vehicular emissions, and construction activities over time. Additionally, regional atmospheric conditions and transboundary pollution may further intensify concentration levels. The observed pattern highlights a transition from diffuse pollution to a highly concentrated and spatially heterogeneous distribution, raising significant concerns for air quality management and public health in the region.

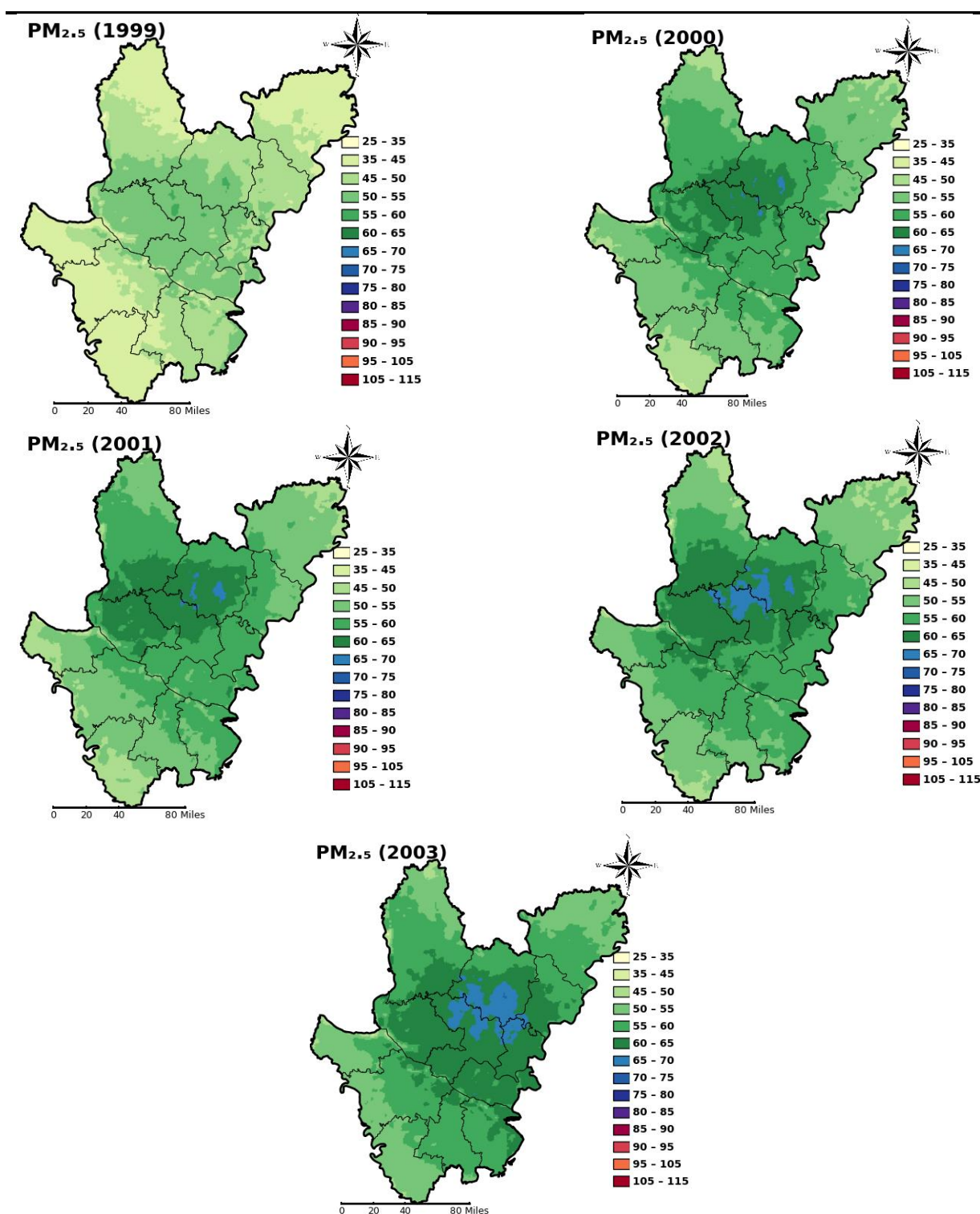


Figure 3. Spatial distribution of PM_{2.5} concentrations in the study area from 1999 to 2003, showing gradual changes in pollution levels and emerging spatial variability across central Bangladesh.

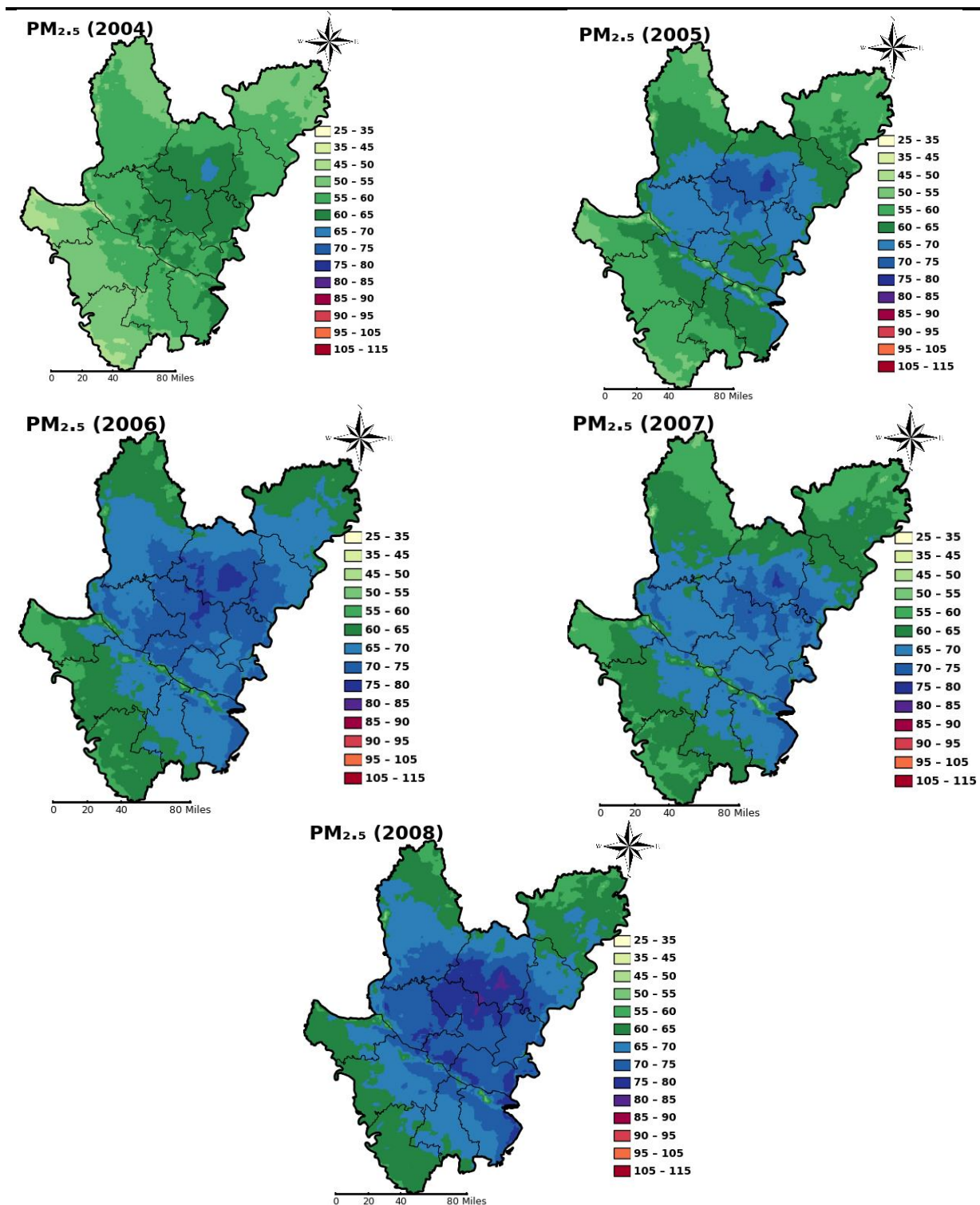


Figure 4. Spatial distribution of $PM_{2.5}$ concentrations in the study area from 2004 to 2008, illustrating a progressive increase in pollution intensity and the expansion of high-concentration zones across central Bangladesh.

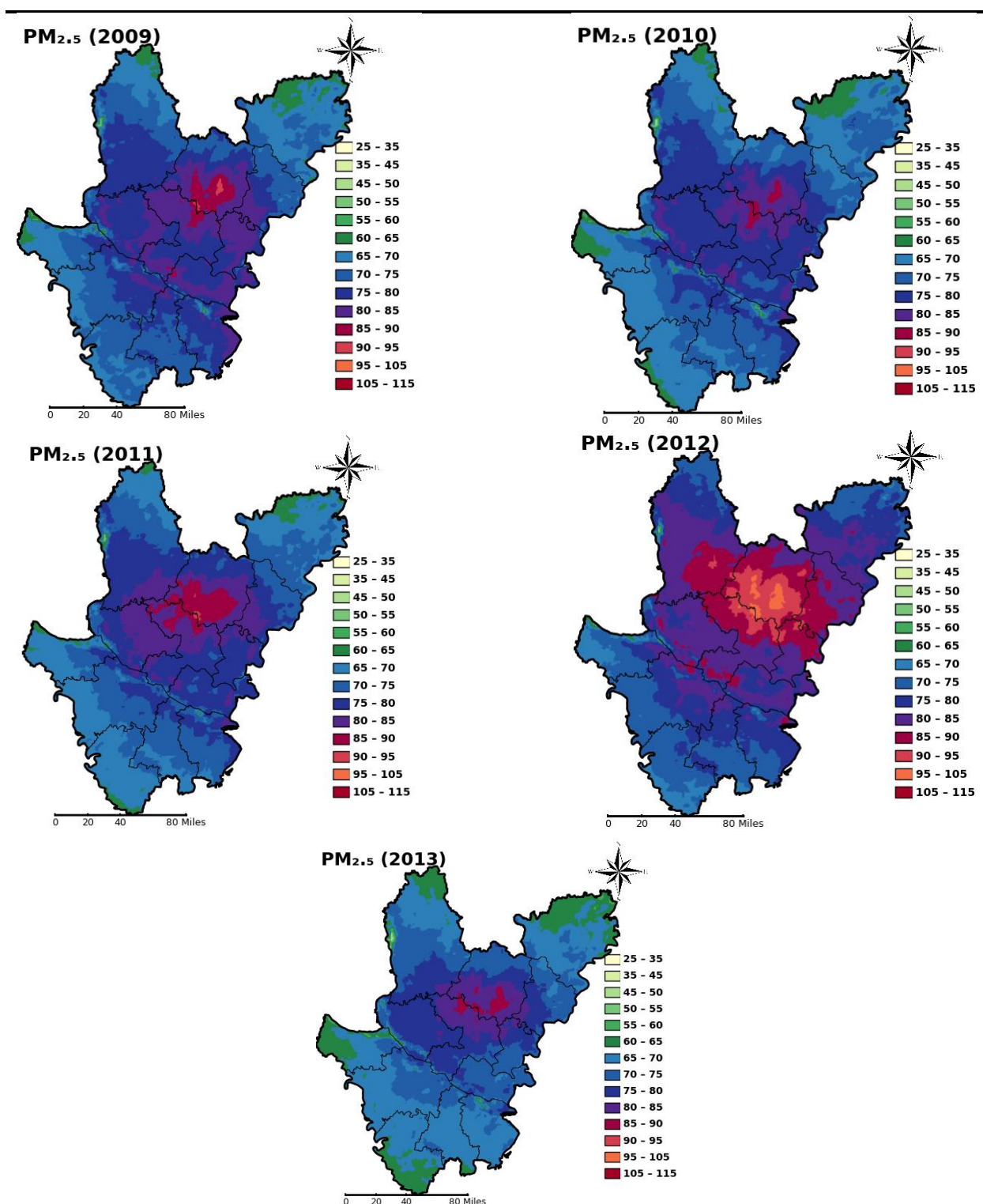


Figure 5. Spatial distribution of $PM_{2.5}$ concentrations in the study area from 2009 to 2013, showing the emergence of severe pollution hotspots and peak concentration levels in central Bangladesh.

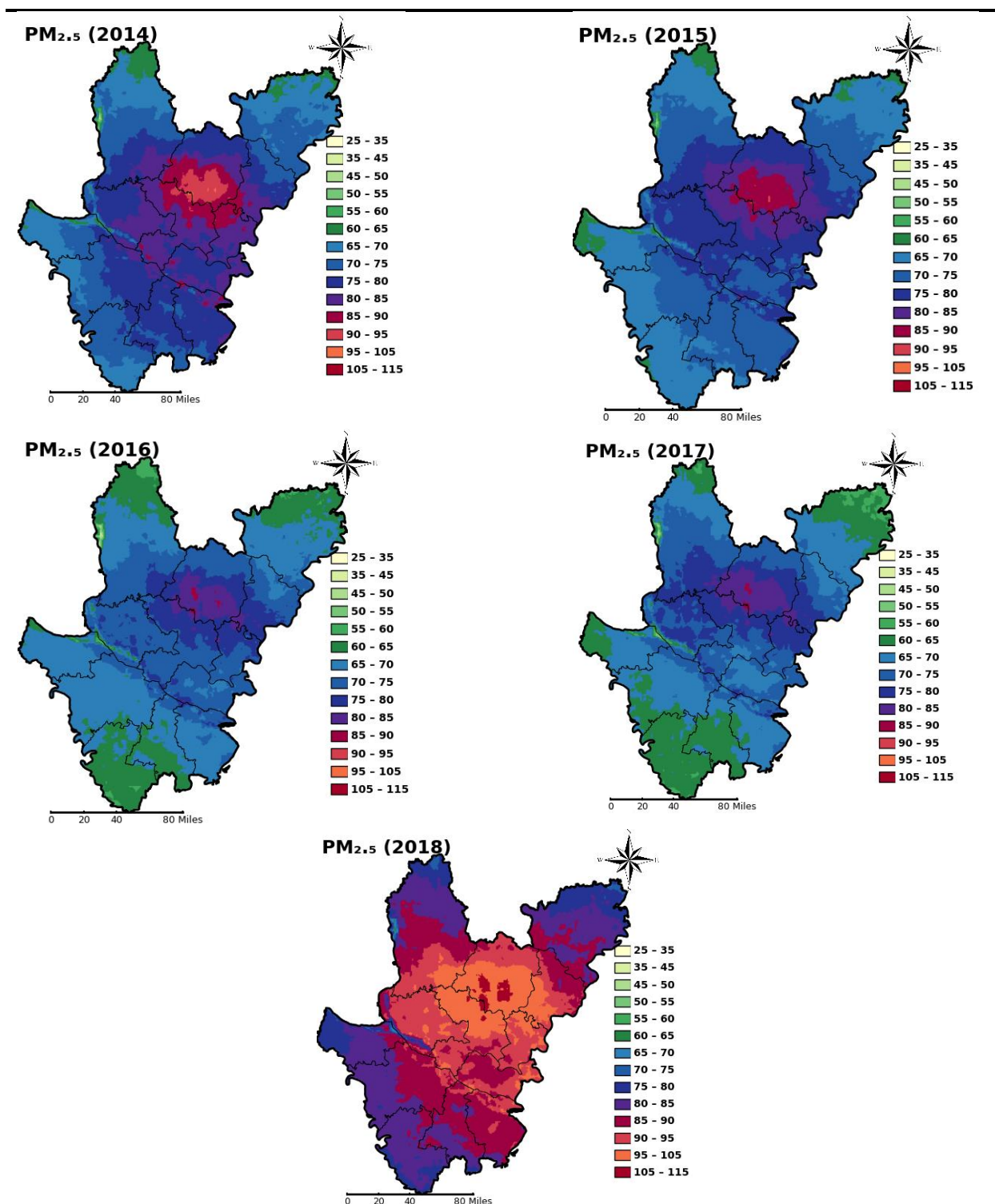


Figure 6. Spatial distribution of $PM_{2.5}$ concentrations in the study area from 2014 to 2018, highlighting fluctuations in pollution levels and a sharp increase culminating in widespread high concentrations in 2018.

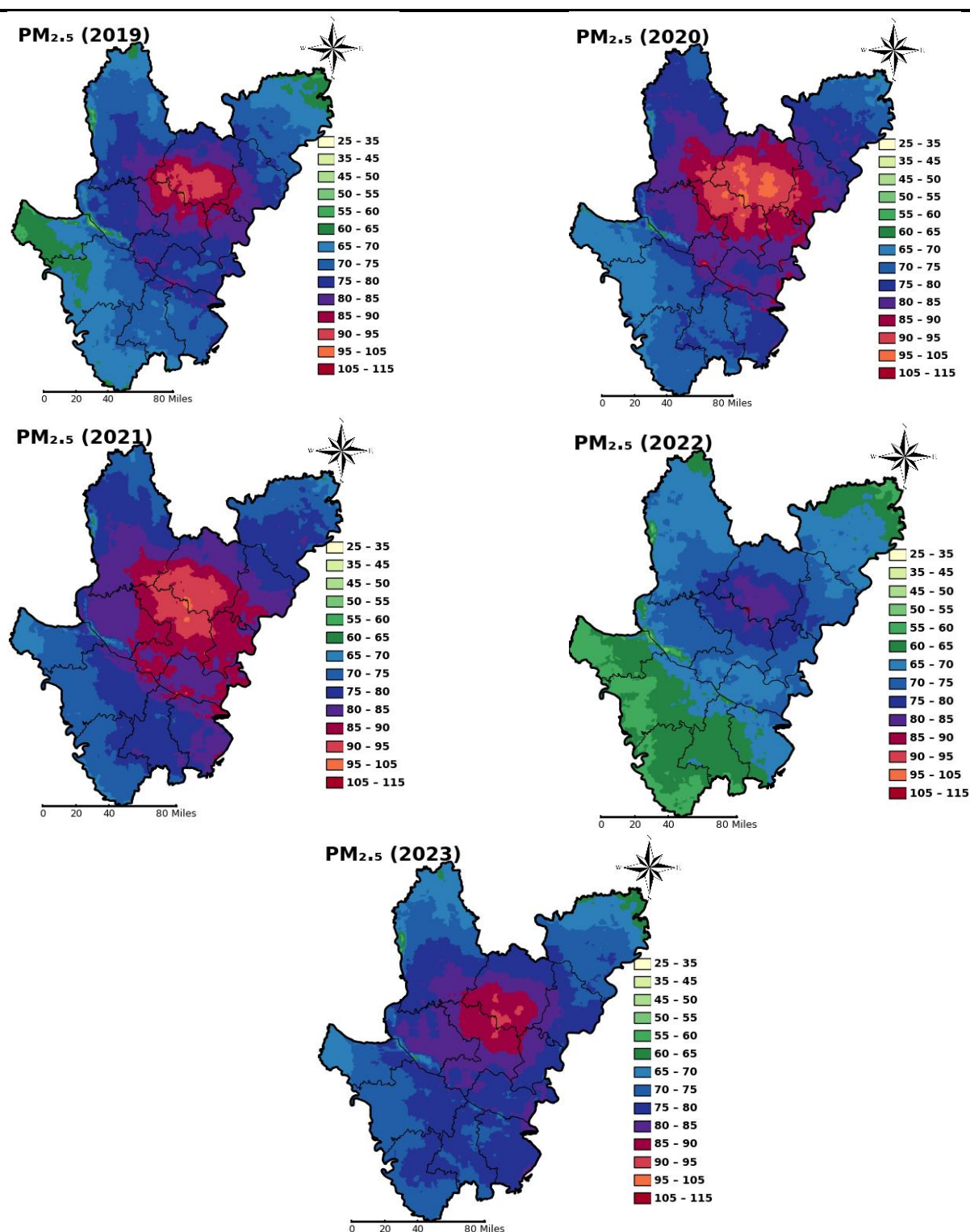


Figure 7. Spatial distribution of PM_{2.5} concentrations in the Dhaka from 2019 to 2023, showing continued high pollution levels, temporal fluctuations, and a temporary decline followed by renewed intensification.

Figure 3 illustrates the temporal evolution of PM_{2.5} concentrations in the study area over the period 1999 to 2003, revealing gradual changes in both magnitude and spatial distribution. In 1999, PM_{2.5} levels were relatively low and evenly distributed across the region. However, from 2000 onward, a steady increase in concentration is observed, particularly in the central and northern parts of the study area. By 2001 and 2002, localized zones of higher concentration begin to emerge, indicating the early formation of pollution hotspots. This trend continues into 2003, where elevated PM_{2.5} levels become more pronounced and spatially heterogeneous. The gradual intensification of pollution during this period may be associated with increasing urban activities, expansion of transportation networks, and the early stages of industrial growth in and around Dhaka. Overall, the figure highlights a transition phase in which air pollution begins to intensify and shift from a relatively uniform distribution to a more structured and regionally differentiated pattern.

Figure 4 presents the spatial and temporal progression of PM_{2.5} concentrations between 2004 and 2008, highlighting a clear intensification of air pollution across the study area. In 2004, PM_{2.5} levels remain moderate, with relatively limited areas of elevated concentration. However, from 2005 onward, there is a noticeable increase in pollution levels, particularly in the central region, where concentrations shift into higher ranges (above 65 µg/m³). By 2006 and 2007, high-concentration zones expand significantly, covering much of the study area and indicating a transition toward widespread pollution rather than localized hotspots. This trend culminates in 2008, where PM_{2.5} levels reach their highest intensity within this period, with a pronounced central core of elevated concentrations and broader regional spread. The observed pattern suggests rapid urban and industrial growth, increased vehicular emissions, and intensified anthropogenic activities during this period. Overall, the figure reflects a critical phase of environmental degradation, where air pollution becomes more severe and spatially extensive, setting the stage for the extreme conditions observed in later years.

Figure 5 illustrates a critical phase in the evolution of PM_{2.5} pollution from 2009 to 2013, marked by a sharp intensification and the formation of pronounced high-concentration hotspots. In 2009, elevated PM_{2.5} levels are already evident, with a distinct hotspot emerging in the central region, particularly around Dhaka. This pattern persists and strengthens in 2010 and 2011, where high concentrations expand spatially and intensify in magnitude. The situation reaches a peak in 2012, when PM_{2.5} levels exceed 100 µg/m³ in the central core, representing the highest pollution intensity observed across all study years. This extreme concentration suggests a combination of rapid urban expansion, increased industrial emissions, dense traffic, and possibly unfavorable meteorological conditions that limit pollutant dispersion. In 2013, although concentrations slightly decline compared to the 2012 peak, pollution levels remain high and spatially concentrated. Overall, this period represents the peak pollution phase, characterized by severe air quality degradation and strong spatial clustering of PM_{2.5}, particularly in and around the metropolitan center.

Figure 6 illustrates the temporal variability of PM_{2.5} concentrations from 2014 to 2018, revealing a pattern of fluctuation followed by a dramatic escalation. In 2014 and 2015, high concentrations persist in the central region, particularly around Dhaka, indicating the continuation of severe pollution conditions observed in earlier years. However, a relative decline is observed in 2016 and 2017, where PM_{2.5} levels decrease and become more spatially dispersed, suggesting temporary improvements in air quality or variations in meteorological conditions. This declining trend is abruptly reversed in 2018, when PM_{2.5} concentrations surge across nearly the entire study area, with extensive regions exceeding 90 µg/m³ and a dominant central hotspot. The widespread and intensified pollution in 2018 indicates a significant deterioration in air quality, likely driven by increased industrial activities, vehicular emissions, construction, and unfavorable atmospheric conditions. Overall, this period reflects a phase of instability, where short-term improvements are followed by a substantial and widespread escalation in PM_{2.5} levels.

Figure 7 presents the recent trends in PM_{2.5} concentrations from 2019 to 2023, highlighting continued high pollution levels with notable temporal fluctuations. In 2019, a strong hotspot is evident around Dhaka, with elevated concentrations extending into adjacent districts. This pattern intensifies in 2020 and 2021, where PM_{2.5} levels remain high and widespread, indicating persistent and severe air pollution conditions. However, a marked decline is observed in 2022, with lower concentrations and a more dispersed spatial pattern, likely reflecting reduced anthropogenic activities or improved atmospheric conditions during that period. This improvement is short-lived, as 2023 shows a renewed increase in PM_{2.5} levels, with the re-emergence of a concentrated hotspot in the central region. Overall, the figure demonstrates that while short-term reductions in pollution are possible, the general trend remains one of persistently high and spatially concentrated PM_{2.5} levels, driven by ongoing urbanization, industrial activities, and vehicular emissions in and around Dhaka.

Discussion

The spatiotemporal analysis of PM_{2.5} concentrations from 1998 to 2024 reveals a clear and progressive deterioration of air quality in the study area. In the initial phase (1999–2003), PM_{2.5} levels were relatively low and spatially uniform, indicating limited anthropogenic pressure. This was followed by a growth phase (2004–2008), where concentrations increased steadily and began to show spatial variability, particularly in central regions. The period from 2009 to 2013 represents the peak pollution phase, characterized by the emergence of intense hotspots centered around Dhaka, with concentrations exceeding critical thresholds. This phase reflects the cumulative impact of rapid urbanization, industrial expansion, and increased vehicular emissions. In the subsequent period (2014–2018), PM_{2.5} levels exhibited fluctuations, with temporary declines likely influenced by meteorological conditions or short-term interventions, followed by a sharp increase in 2018 indicating widespread pollution. Recent years (2019–2023) demonstrate continued high pollution levels with intermittent reductions, such as the observed decline in 2022, followed by renewed intensification in 2023. These fluctuations suggest that while short-term improvements are possible, the overall trend remains upward due to persistent anthropogenic activities. By 2024, PM_{2.5} concentrations reach critical levels, with a pronounced and persistent hotspot in Dhaka and expanding pollution into surrounding districts. Overall, the study highlights a transition from diffuse and low-level pollution to highly concentrated and spatially heterogeneous patterns, emphasizing the urgent need for long-term air quality management strategies.

Conclusion

This study demonstrates a significant increase in PM_{2.5} concentrations in Dhaka and its surrounding regions over the period 1998–2024, accompanied by a clear shift in spatial patterns. The findings reveal the development of persistent pollution hotspots, particularly in urban centers, and the gradual expansion of pollution into peri-urban areas. While short-term fluctuations and temporary improvements are observed, the overall trend indicates a steady deterioration of air quality driven by rapid urbanization, industrial growth, and increased emissions. The results underscore the urgent need for effective policy interventions, including stricter emission controls, improved urban planning, sustainable transportation systems, and enhanced monitoring frameworks. Addressing PM_{2.5} pollution is critical not only for environmental sustainability but also for protecting public health and ensuring long-term livability in rapidly growing urban regions like Dhaka.

References

- World Health Organization (2021), *WHO global air quality guidelines: particulate matter (PM_{2.5} and PM₁₀), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide*.
<https://www.who.int/publications/i/item/9789240034228>
- Burnett, R., et al. (2021), *Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter*. <https://doi.org/10.1016/j.envint.2021.106515>
- Health Effects Institute (2020), *State of Global Air 2020*. <https://www.stateofglobalair.org>
- Pope, C. A. III, & Dockery, D. W. (2006), *Health effects of fine particulate air pollution: lines that connect*. <https://doi.org/10.1080/10473289.2006.10464485>
- Lelieveld, J., et al. (2015), *The contribution of outdoor air pollution sources to premature mortality on a global scale*. <https://doi.org/10.1038/nature15371>