BABEŞ-BOLYAI UNIVERSITY OF CLUJ-NAPOCA
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FACULTY OF ENVIRONMENTAL SCIENCE AND ENGINEERING
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# Ph.D. THESIS SUMMARY

## Quantification of Air Pollutants Emissions Through In-Situ Measurement and Dispersion Modelling in Romania and Rwanda. Risk Assessment

**Keywords:** *Vulnerability, Impacts, Risks, $PM_{2.5}$, $PM_{10}$, $NO_2$, $SO_2$, CO, In-situ Monitoring, Dispersion Modelling, AERMOD, ISCST3, Urban Traffic, Tailings Ponds, Wind Erosion, Kigali, Rwanda, Moldova Nouă, Romania.*

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# Contents

# Abstract

The global air quality crisis intensifies due to emissions from natural causes like volcanic eruptions and human activities such as traffic and industrial operations. These emissions impact environment and human health, with air pollution contributing to seven million deaths annually. While existing literature acknowledges the wide-ranging effects of air pollution, significant gaps remain in understanding air pollutants' dispersion mechanism, especially in complex topographic environments affected by wind erosion. Moreover, studies on urban traffic often lack inclusivity, neglecting factors such as vehicle fuel types, vehicle categories, and the physical characteristics of roads. Currently, there is a lack of consensus on a standard approach to characterizing and mapping out areas of high air pollution (hotspots), which may vary based on factors such as the pollution source, type of pollutant, and time frame. This underscores the need for further investigation and careful evaluation of pollution levels counting both time and space. Therefore, this thesis aimed to address these gaps by conducting an in-depth exploration of air quality dynamics, providing a nuanced analysis of air quality challenges, and attempting to develop a protocol for detecting air pollutant hotspots in urban environments. This was achieved through the use of dispersion modelling and in-situ measurement methods in case studies conducted in Kigali City, the capital of Rwanda, and in Moldova Nouă, located in the south-west of Romania.

The study compared dispersion modelling results from AERMOD and ISCST3 air pollutant dispersion models with simultaneous real-time in-situ measurement of particulate matter with a diameter of 10 micrometers or less ($PM_{10}$), particulate matter with a diameter of 2.5 micrometers or less ($PM_{2.5}$), sulphur dioxide ($SO_2$), nitrogen dioxide ($NO_2$), and carbon monoxide (CO) levels throughout the year 2021. The reliability of the models was evaluated using statistical metrics and Taylor diagrams. Characterization

of additional potential sources was made through three-dimensional bivariate polar plots under dispersion perceptive. The study examined how complex topography affects air pollutant dispersion using various digital elevation models (DEMs) from a modelling standpoint. The study developed a systematic method to assess wind erosion's effect on $PM_{10}$ emissions by quantifying horizontal and vertical fluxes from Moldova Nouă tailings ponds. Additionally, the study implemented the Integrated Impact and Risk Assessment (IIRA) methodology to evaluate vulnerable zones, impacts, risks, and probabilities of personal exposure to hazardous air pollutants.

The spatial-temporal dispersion maps and variation trends of considered air pollutants were identified in both case studies. In Kigali, concentration trends indicate lower emissions during noon hours (11:00-14:00) and an increase during morning (06:00-08:00 AM) and evening hours (16:00–20:00), highlighting the significant contribution of urban traffic. The annual averages of air pollutants were as follows: $PM_{10}$ concentrations ranged from 44 to 56 $\mu$g m$^{-3}$, $PM_{2.5}$ levels varied between 25 and 48 $\mu$g m$^{-3}$, $NO_2$ averaged 20.35 $\mu$g m$^{-3}$, CO ranged from 527.7 to 721.6 $\mu$g m$^{-3}$, and $SO_2$ averaged between 34.8 and 62.0 $\mu$g m$^{-3}$. Dispersion modelling revealed significant concentration levels, with a hotspot identified at a specific roundabout, while their dispersion behaviour is primarily influenced by atmospheric conditions and local topography. The study identified potential vulnerable zones within the city influenced by high population density, traffic, and household emissions, with a high probability of personal exposure ranging from 0.12 to 0.3. The IIRA results indicated that impacts of personal exposure to $PM_{10}$ and $NO_2$ are within permissible limits (100-350), $SO_2$ and CO may cause discomfort (350-500), while $PM_{2.5}$ poses threats to both human health and the ecosystem (700-1000). Risk evaluation concluded that prevention measures are required for $PM_{2.5}$ (200-350), monitoring activities for $SO_2$ and CO (100-200), and negligible risk for $PM_{10}$ and $NO_2$ (less than 100).

In Moldova Nouă, $PM_{10}$ concentrations exhibited hourly fluctuations, with rises during the early morning hours (00:00-06:00 AM) and evening hours (18:00-23:00), and a decline during the midday hours (12:00-17:00). The annual average concentration was recorded as 29.3 $\mu$g m$^{-3}$ at the CS5 station and 20.9 $\mu$g m$^{-3}$ at the CS3 station. Wind direction and speed significantly affect concentration level, with south-easterly winds contributing to higher levels near tailings ponds and north-western winds associated with

urban emissions from Moldova Veche city. Through dispersion modelling perceptive, Moldova Nouă experience a significant $PM_{10}$ concentration with hotspot in the vicinity of tailings ponds. Analysis suggested tailings ponds as potential emission source, particularly during south-easterly winds accumulation. Its dispersion extending into Moldova Nouă city and bordering Serbia. Key hotspot values include a 63 $\mu$g m$^{-2}$ s$^{-1}$ annual horizontal flux, and a 3 $\mu$g m$^{-2}$ s$^{-1}$ annual vertical flux, while AERMOD estimated daily and annual average concentrations of 563.7 $\mu$g m$^{-3}$ and 115.5 $\mu$g m$^{-3}$, respectively.

Statistical metrics and Taylor diagrams results indicated that both AERMOD and ISCST3 models accurately predict pollutant concentrations, with AERMOD generally showing slightly superior performance. Additionally, the assessment informed the choice of DEMs, influencing model accuracy. The study underscores the significant impact of complex terrain on air pollutant dispersion, with high-resolution DEMs like Shuttle Radar Topography Mission (SRTM3) and Global 30 Arc-Second Elevation (GTOPO30) exhibiting superior accuracy in modelling. Dispersion patterns highlighted the role of elevated or hilly terrain features in impeding airflow, leading to the accumulation of air pollutants in lower-lying areas. The study identified uncertainties during the evaluation of models. These uncertainties stem from variations in pollutant concentrations across space and time, potential discrepancies in emission factor calculations, limitations in capturing all local pollution sources by the models, uncertainties in meteorological data, and disparities between AERMOD and ISCST3 highlight their differing capabilities and algorithms in computing.

The overall findings emphasized the importance of comprehensive modelling frameworks, utilizing air pollutant dispersion models, particularly in regions where in-situ monitoring is challenging or simply impossible. These insights are invaluable for informing policymaking in similar regions facing environmental challenges from urban and mining backgrounds, facilitating informed decisions by officials, urban planners, and public health stakeholders to safeguard public health and mitigate the adverse impacts of air pollution.

**Keywords:** *Vulnerability, Impacts, Risks, $PM_{2.5}$, $PM_{10}$, $NO_2$, $SO_2$, CO, In-situ Monitoring, Dispersion Modelling, AERMOD, ISCST3, Urban Traffic, Tailings Ponds, Wind Erosion, Kigali, Rwanda, Moldova Nouă, Romania.*

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# Chapter 1

# General Introduction and Thesis Framework

## 1.1 Background and Thesis Description

For numerous years, global air pollution has remained a significant environmental concern. According to the World Health Organization (WHO), over seven million deaths occur annually worldwide due to air pollution. Specifically, approximately 4.2 million deaths result from exposure to outdoor air pollution, while 3.8 million deaths are attributed to indoor air pollution (WHO, 2016). As indicated by WHO (2021), approximately 92% of the world's population resides in areas where air pollution levels surpass the international limits as guidelines set by WHO for air quality, and whereby about 99% of the worldwide population breathes polluted air.

Personal exposure to long-term or high concentration levels of air pollutants shocks health in various ways (Brunekreef & Holgate, 2002; Wong et al., 2001) but much more as a burden to individuals who are particularly susceptible to the effects of air pollution include children, pregnant-women, and individuals with chronic respiratory illnesses (WHO, 2016). Human health studies showed that air pollutants increase respiratory illness, mortality, and morbidity (Backes et al., 2013; Bavaria et al., 2014; Gibson et al., 2013; Tecer, 2009). Personal exposure to air pollutants were identified to be responsible for premature deaths caused by lung-cancer (Cohen et al., 2017), lung diseases, and heart infections (Samet et al., 2000), and raise the frequency of diseases like heart attacks, strokes, asthma, and chronic bronchitis (Cropper et al., 2012). Furthermore, studies showed that pollutants contribute enormously to the atmospheric processes leading to environmental impacts. These include acid precipitation, known as acid rain (Terán et al., 2021), global warming (Kaplan & Vidyashankar, 2012), climate change (Collins et al., 2013), and weather variabilities incident to visibility reduction (Peters et al., 2013; Raupach et al., 2007).

Global and European international bodies, including the World Health Organization (WHO), the United States Environmental Protection Agency (US-EPA), the United Nations Economic Commission for Europe (UNECE), the European Union (EU), the European Environment Agency (EEA), the United Nations Environment Programme (UNEP), and various others, are actively engaged in tackling environmental challenges related to air pollution by making environmental policies for better air quality. This later, in Europe is grounded on the 2008/1/EC Directive of the European Parliament targeting the integration of air pollution prevention and control (Directive, 2008). According to the European Air Pollution Data Center (EEA, 2020), air pollutant emissions have diminished many years ago, leading to considerable improvement among member states. But, air contaminant levels are too high, and their effects continue due to the rapid growth rate in transportation, residential heating, and industrialization. Critical air contaminants, including particulate matter ($PM_{2.5}$ and $PM_{10}$), nitrogen dioxide ($NO_2$), Ozone ($O_3$), are the most worrying pollutants in Europe and continue to have a significant impact on Europeans' health. (EEA, 2020).

Factors like: local climatology, meteorological conditions (mostly incoming solar radiation and humidity), topographic features, geographical and further local scare conditions, and characteristics of air pollutant source (like: stack height, plume size, and emission rate, among others) contribute to the air quality status of a particular place (Rouhi et al., 2013). Pollutants can be elevated over a long distance, even Hundreds of Kilometers from the source, dispersed in the air, and then dropped to the ground or undergo chemical transformation scenarios which rise to the development of second atmospheric pollutants (Ajtai et al., 2012; Gibson et al., 2013a; Macdonald, 2003). In-situ monitoring methodology can quantify air pollutant concentration in a particular study case as sufficient. But when the targeted zones are not manageable for in-situ monitoring instruments or when air pollutants from various sources are not technically easy to sample by site or near-site monitoring method, air pollutants dispersion modelling can be used as an alternative method (EPA, 2009; O'Shaughnessy & Altmaier, 2011).

Given the current potential emission of air pollutants in urban residential areas, socio-economically exposed populations and regions with limited data, particularly in low/middle income countries, it becomes clear that air quality studies are essential for assessing mitigation policies. This thesis investigates the effect of traffic emissions on the quality of air in Kigali, Rwanda. Additionally, it examines the impact of emissions from tailing ponds rising from industrial mining activities developed back in the south-western part of Romania, on the air quality of Moldova Nouă city. The study involves quantifying air pollutant emissions through in-situ monitoring and dispersion modelling methodologies. It further compares in-situ measurement data with dispersion modelling results using statistical metrics and Taylor diagram for model performance evaluation. The study characterized further potential emission inventories using three-dimensional bivariate polar-plot from a dispersion prospect. It investigated influence of complex topographic features on air pollutant dispersion under different digital elevation models (DEMs). The research implemented a systematic approach to analyze and quantify the influence of wind erosion on $PM_{10}$ emission rates in the tailings ponds of Moldova Nouă. This analysis encompassed both horizontal and vertical fluxes, with a focus on those emissions from the Moldova Nouă tailings ponds. Finally, the study employed the Integrated Impact and Risk Assessment (IIRA) methodology to evaluate vulnerable zones and probabilities, impacts, and risks of personal exposure to hazardous air contaminants.

## 1.2 Definition of the Problem

### 1.2.1 Situation at International Level

The effect of anthropogenic activities on ongoing environmental changes, with harmful impacts on both human-health and the ecosystem, remains a pressing scientific concern. This complex effects pose substantial challenges for public awareness, environmental scientists, and policymakers. Additionally, the correlation between air contaminants and broader topics like climate change and global warming continues to be a subject of international debate, with many aspects still requiring comprehensive understanding. According to WHO (2021), the global burden of diseases associated with human exposure to atmospheric contaminants is evaluated to cause approximately seven million mortalities annually. The WHO has provided air quality limits as international guidelines to help nationals and health stakeholders to decrease social exposure to contaminants and their effects since 1987, which has resulted in currently a considerable improvement but still PM, $O_3$, $SO_2$, and $NO_2$ are still at the top of affecting human health (WHO, 2016).

Many decades ago, the environmental problem in Europe originated from energy consumption growth, rapid economic development, and urbanization. Since the 1970s, the air pollution problem in Europe has been a burden issue. But in 1996, The EU implemented a new impressive plan to reduce pollutants releases across almost the continent by setting air quality limiting targets and its implementations through field monitoring activities together by reporting and managing air quality across all EU state members (Bagayev & Lochard, 2017; Năstase et al., 2018). The EU has initiated the cleaner society program by monitoring air pollutants within industrial, urban transport, and residential sectors (Korkmaz et al., 2020) across its member states, where air pollution control and emissions tracking are managed and controlled by EEA. According to EEA (2020), in Europe, air pollution levels have diminished over many decades ago, resulting in a considerable improvement in air quality across the region. However, the concentration is still too high for PM, $NO_2$, and $O_3$, and their effects persist. Although a considerable effort has been made in Europe, Guttikunda et al. (2014) indicated that by 2030 the expected growth rate in sectors like industry, transport, residential, construction, and power generation would increase pollution resulting in human health effects across state cities of the EU.

Rapid urbanization and population growth are among the main factors accelerating air pollutants emissions into the atmosphere through human activities. Schwela (2012) indicated the statistical projection of the urban population growth rate from 1940 to 2040 for each continent compared to the worldwide urban population growth rate as shown in Figure 1.1. The results indicate Africa's urban population growth rate would be higher than other continents. According to the United Nations (UN), the same results were found. Africa is experiencing the fastest population growth in the world. It is expected to double from 2017 to 2050 (UN, 2017). Rapid population growth in Africa is linked to faster industrialization and urbanization, worsening air quality (UN, 2017).

Air pollutant dispersion models in Europe have been increasingly used to simulate air pollutants concentrations, but in the past, air quality assessment was only based on field

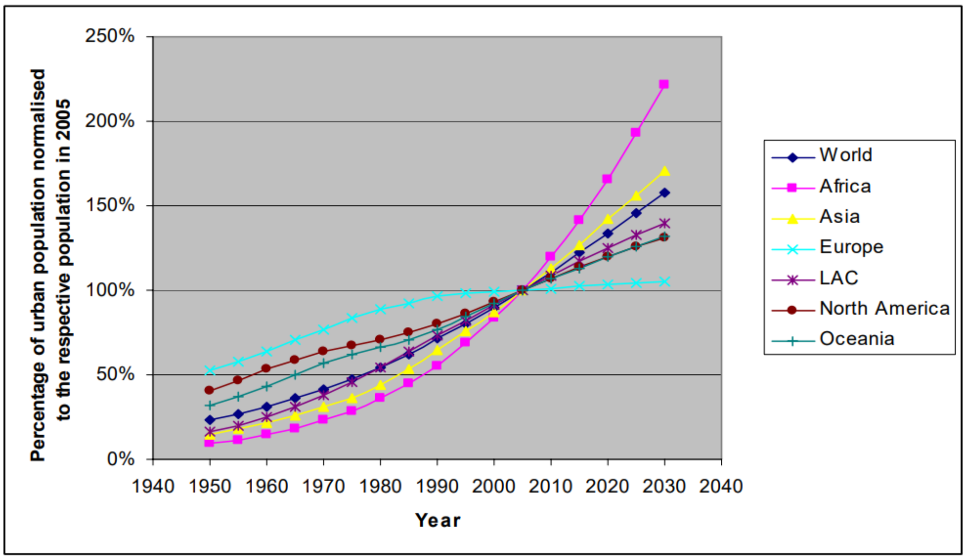


**Figure 1.1:** Rate of urban population growth worldwide from the year 1940 till 2040. (Schwela, 2012)

measurements. Still, more emphasis was recently added to air quality models to validate the existing field monitoring datasets. The air pollutant dispersion model application for tasks related to managing air quality, including air quality assessments, planning, and even forecasting, was strongly recommended by European legislation regarding ambient air quality and clean air, established in 2008. (Thunis et al., 2015). Apart from in-situ monitoring methodology, research gaps have been identified in air quality modelling worldwide. Therefore, Table 1.1 summarizes literature reviews on dispersion models, including ISCST3, AERMOD, and others) to simulate the concentration level of air pollutants in particular locations worldwide.

**Table 1.1:** Sample summary of consulted literature reviews using the Gaussian plume dispersion model, AERMOD, in Europe, Africa, Asia, and America.

| **References** | **Country** | **Location** | **Pollutants** | **AERMOD Application** |
|---|---|---|---|---|
| Matacchiera et al. (2019) | U.K. | Landfill | $CH_4$ | Run and determine the influences of meteorological conditions on greenhouse gases. |

| | | | | |
|---|---|---|---|---|
| Tripathy et al. (2019) | U.S./ Allegheny | Industrial | $PM_{2.5}$, BC | Predicting pollutant concentration level |
| Dinçer et al. (2020) | Turkey | Industrial | Odour pollution | Predicting odour level |
| Teggi et al. (2018) | Italy | Complex source | Pesticides | Simulating ground-level pollutant concentration and deposition flux |
| Tezel-Oguz et al. (2020) | Turkey | Traffic emission | $NO_x$ | Predicting and validating the field monitoring datasets. |
| Adeniran et al. (2019) | Nigeria | Industrial | $SO_2$, $PM_{2.5}$, $PM_{10}$, $NO_2$ | To model the effects of industrial activities on air quality |
| Liu-Cong et al. (2019) | Atlanta | Traffic emission | $PM_{2.5}$ | Spatial distribution and the effects of urban traffic pollution on air quality |
| Tyovenda et al. (2021) | Nigeria | Industrial | $NO_2$, CO | Modelling pollutant concentration level |
| Gibson et al. (2013) | Canada | Line source | $SO_2$, $PM_{2.5}$, $NO_x$ | Model evaluation by comparing output with the existing datasets. |
| Mentese et al. (2020) | Turkey | Urban area | VOCs, CO, CO2, $PM_{2.5}$ | Predicting the annual concentration levels |
| Langner & Klemm (2011) | German | Urban and rural | $SO_2$, $SF_6$, NO, $NO_2$ | Prediction of the concentration level and model validation |
| Haq et al. (2019) | Pakistan | Point source | $SF_6$ | Predicting pollutants concentration level and model validation |

| | | | | |
|---|---|---|---|---|
| Askariyeh et al. (2017) | US/Texas | Near road | $SF_6$ | Predicting pollutant concentration levels and model validation across the roadside |
| Mutlu (2020) | Turkey | Industrial | $PM_{10}$ | Predicting air pollutant concentration level and validation of the model |
| Abdel-Rahman (2008) | Egypt | Industrial | Dust plume | Theoretical approach for stack height emissions |
| Al-Fadhli et al. (2019) | Kuwait | Industrial | $NO_2$, $SO_2$ | Predicting pollutants concentration level |
| X. Zou et al. (2020) | Togo | Traffic emission | $SO_2$, PM, $NO_x$ | Simulation of pollutants concentration levels |
| Ma et al. (2013) | China | Industrial/Urban | $PM_{10}$ | Predicting air pollutant concentration level and validation of the model |

### 1.2.2 Situation at National Level, Romania

In Romania, a considerable effort in air pollution reduction is remarkable since Romania joined UNECE on December 14, 1955, and the EU on January 1, 2007, as a state member. According to Năstase et al. (2018), since Romania joined the EU a considerable improvements in air quality have been remarkable, whereby from 1990 to 2014 the annual concentration of CO decreased by 76%, $So_x$ by 60%, $NO_x$ by 87%; and $CO_2$ reduced out 41% from 2007 to 2014. According to Romanian Statistical Year Book-2019 (INS, 2019), different air quality projects, atmospheric observatory laboratories, construction and reconstruction of environmental institutions, and modernization have been implemented for excellent ecological and environmental purposes, including clean air. However, these oppose the increasing urban population as shown in Figure 1.2 (INS, 2019). Table 1.2 indicates the statistical outcomes of the urban population with elderly ratio for some earlier years in Romania (INS, 2021).

The information given in Figure 1.2 was also confirmed through air quality research conducted by Roba et al. (2014), mentioning that in populated cities of Romania, particulate matter (PM) concentration levels were more significant than rural areas. An air pollution study in Iași city located in the North-east of Romania confirmed that air pollution remains a foremost environmental problem in Romania cities where traffic emission is the main contributor to air quality degradation (Banica et al., 2017). The study concludes that air dispersion within buildings and streets environment causes an increase in pollutant concentration in Iași (Banica et al., 2017). A study conducted over metropolitan regions of Romania by Rosu & Banica (2018) concluded that the increase in urban areas in Romania had mentioned similar trends within all major cities in Eastern Europe, where traffic and household emissions are the main contributors to air pollution. Banica et al. (2017) continue to state that traffic congestion and urban air pollution have become a common outlook of urban life, as most big European cities were not yet prepared for the linked environmental problem.

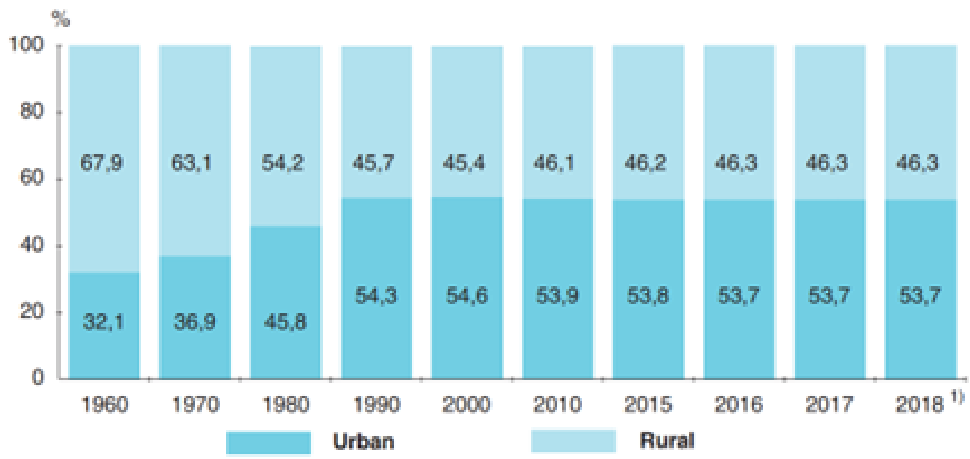


**Figure 1.2:** Classification population by area from 1960 to 2018 in Romania ( 2018[1]: provisional data set in the year 2018) (INS, 2019)

The trajectory analysis of air pollutants in the Transylvanian basin of Romania by Bodor et al. (2020) concluded that pollutants like $PM_{10}$, $SO_2$, $NO_x$, CO, and $O_3$ are associated with slow-moving air mass in the southerly and northwesterly of Transylvania region, and their dispersion is mainly affected by the local scale conditions. According to Sechel & Mariasiu (2022), Romania has enforced the use of electric vehicles due to traffic emission reduction, whereby electrical usage vehicles is increase exponentially in the country. The European Commission emphasizes the use of electric vehicles and alternative means of lower emission levels but stacked with secondhand vehicle sales, which is increasing in the member states, including Romania, whereby the number of registered vehicles in Romania, the majority are hybrid vehicles (Sechel & Mariasiu, 2022). According to INS (Romanian National Institute of Statistics), press release

**Table 1.2:** Statistical structure of the elderly (65 years and over), age group, and urban population in Romania (INS, 2021).

| **Year of Census** | **Urban Population (%)** | **Increase of Elderly (%)** |
|---|---|---|
| 2021 | 56.3 | 0.4 |
| 2020 | 56.4 | 0.4 |
| 2019 | 56.4 | 0.3 |
| 2018 | 56.4 | 0.3 |

No.104/27 April 2021, the number of elderly (65 years and above) in 2021 has increased by 0.4% compared to the previous year, 2020. In 2021, INS concluded that 56.3% of the Romanian population stays in urban areas. Therefore, several air pollution measures have been introduced in urban areas for the safety of residents attempting to reduce urban air pollution, including street washing, planting trees near roadsides for minimizing PM and carbon monoxide emitted from urban traffic emissions.

The Romanian National Air Quality Monitoring Network (RNMCA) has established over 100 air quality monitoring stations (Năstase et al., 2018) for good air quality purposes where monitoring point selections, calibrations, and data validations conform to the EEA protocol (www.eea.europa.eu). The monitoring point includes urban (traffic), industrial, suburban, and regional air quality stations. All air quality data sets monitored across the country are released to the community, researchers, or stakeholders after being certified by the National Reference Laboratory for Air Quality (LNRCA) of the Romanian National Environment Protection Agency. The above air quality system and air quality related studies conclude the availability of data and air quality index (AQI) in Romania AQI (2022). Few studies assessing air pollutant dispersion in Romania's urban areas were identified as research gaps. Table 1.3 summarizes the consulted literature that used AERMOD to validate Romania's existing field monitoring data.

**Table 1.3:** Sample summary of literature reviews using Gaussian plume dispersion model, AERMOD, for various pollutants and sites in Romania.

| **References** | **Country** | **Location** | **Pollutants** | **AERMOD Application** |
|---|---|---|---|---|
| Mihăiescu et al. (2011) | Romania | Industrial | $PM_{10}$, $NO_X$ | Simulating pollutants concentration levels |

| | | | | |
|---|---|---|---|---|
| Ajtai et al. (2012) | Romania | Plant | $SO_2$ | Simulating pollutants concentration levels |
| Simona et al. (2019) | Romania | Tailings ponds | $PM_{10}$ | Predicting pollutant concentration around tailings ponds of Moldovan Nouă. |
| Raischi et al. (2017) | Romania | Tailings ponds | $PM_{10}$ | Predicting pollutant concentration around tailings ponds of Moldovan Nouă. |
| Barbulescu & Barbes (2017) | Romania | Buildings | CO | Validation and prediction of pollutant concentration level |
| Corches & Popa (2013) | Romania | Industrial | CO, $NO_X$ | An impact assessment by predicting pollutant concentration levels |
| Dunea et al. (2017) | Romania | Urban area | $PM_{2.5}$ | Predicting air pollutant levels and model validation |
| Vujic et al. (2019) | Romania | Industrial | $SO_2$ | Model validation and prediction of air pollutants |

### 1.2.3 Situation at National Level, Rwanda

According to Schwela (2012), Africa has a rapid population growth worldwide, projected to increase to more than 200% between 2012 and 2050, with 3.3 to 3.7 per cent annually. Africa's rapid population growth rate has been and It is expected to remain the highest globally (Schwela, 2012). Study by Sigman et al. (2012) indicated that in Africa, in the next 40 years, the increased mortality rate, overuse of polluted water, and poor sanitation(Sigman et al., 2012) due to atmospheric contamination increases (Lacey et al., 2017) and climate and weather variabilities (Silva et al., 2017) are questionable and raises further concerns by researchers. In 2015, a study in Sub-Saharan Africa, as per Heft-Neal et al. (2018), found that exposure to particulate matter (PM) led to roughly 400,000 deaths in the specified region. Taghian et al. (2024), indicated that approximately 3,477 deaths (with a 95% Uncertainty Interval (UI) between 2,500 and 4,600) occurred in Rwanda in 2019 due to cardiovascular disease (CVD) linked to air pollution. Among these fatalities, about 689 (UI: 283–1,300) were attributed to CVD associated with ambient air pollution, while approximately 2,788 (UI: 1,800–3,800) deaths were linked to CVD caused by household air pollution (Taghian et al., 2024). In Rwanda, air pollution stands as the second most significant risk factor for premature death following malnutrition, contributing to over 8% of deaths in 2017 (Taghian et al., 2024). In Rwanda, recent study highlighted that the economic impact of poor air-related health issues back in 2019, equivalent to 1.9% of the nation's GDP (Taghian et al., 2024). Additionally, $PM_{2.5}$ pollution significantly impairs cognitive abilities, resulting in an approximate loss of 18.5 million intelligence quotient (IQ) points among children under the age of 10 in 2019 (Taghian et al., 2024).

In Africa, air quality projects encounter persistent challenges beyond the realms of air quality and health risk assessments. Insufficient air quality data remains a primary hurdle, primarily stemming from insufficient funds to establish and maintain long term site monitoring networks, compounded by a scarcity of knowledge about air pollution (WHO, 2019). The few sparsed air quality data in Figure 1.3 indicate that ambient air pollution exceeds the WHO limit guideline, specifically for $PM_{10}$ and $PM_{2.5}$ pollutants (WHO, 2019). Rwanda, a landlocked nation in East Africa, spans across 26,338 square kilometers and is currently experiencing swift urbanization and rapid population growth, reaching 12.6 million in 2020 (Kalisa et al., 2018). Regarding air quality, the primary issue lies in the scarcity of air quality data, coupled with a deficiency in air quality monitoring stations and standards. This inadequacy forms the core problem in Rwanda's demographic and air quality studies. WHO (2018) and Brauer et al. (2012), satellite datasets have identified approximately 3000 deaths associated with ambient air pollution. Therefore, there is a notable absence of studies validating these estimated datasets through ground observations. According to O'Shaughnessy & Altmaier (2011) and EPA (2009), when air pollutants from various sources are not technically easy to sample by site or near-site monitoring method, air pollutants dispersion models can be used as an alternative method. Therefore, apart from air quality monitoring stations and data problems, in Rwanda, to date, no study has conducted quantification of air pollutant concentrations through dispersion modeling or their corresponding risk assessment.

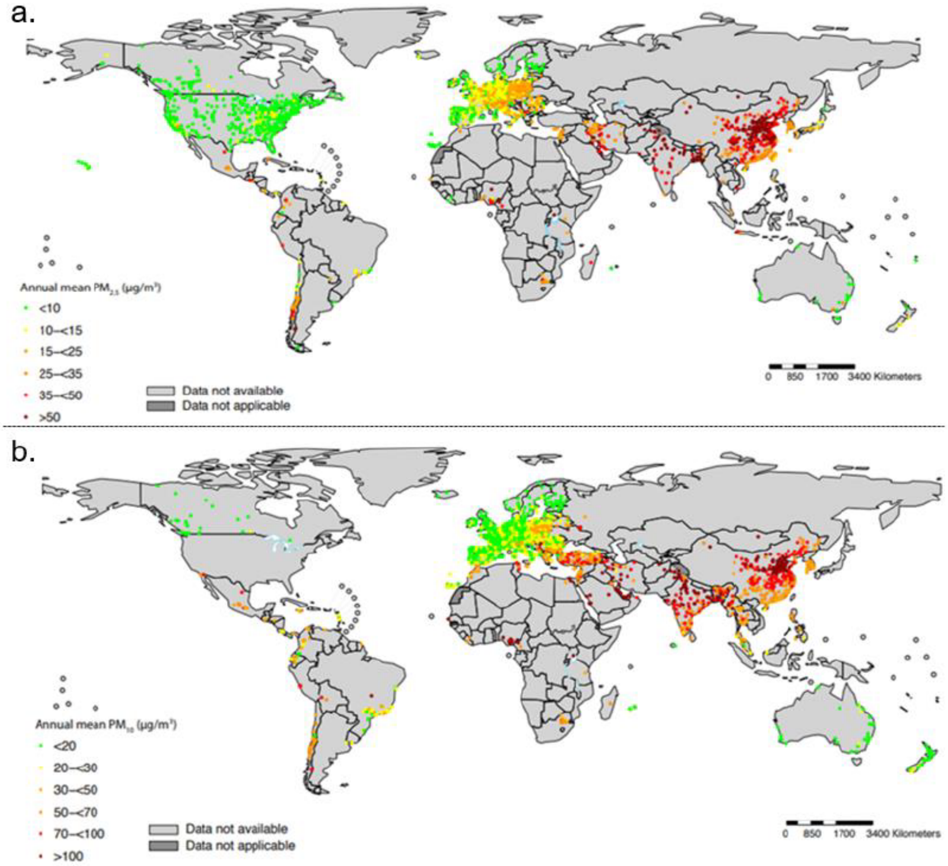


**Figure 1.3:** Map of existing air quality monitoring and ambient concentration levels for $PM_{2.5}$ (a) and $PM_{10}$ (b) between 2010 and 2016 (WHO, 2019).

The Rwanda Environmental Management Authority (REMA) holds the responsibility of formulating, executing, and validating strategies and plans dedicated to environmental protection, conservation, promotion, and management within Rwanda. This mandate is firmly outlined in law no. 63/2013 dated 27/08/2013, elucidating REMA's mission and operations across the country. Despite the government of Rwanda's initiatives to pinpoint significant sources of pollution and enhance public surveillance, in Kigali, ambient air pollution remains an escalating menace to human health, economic progress, and human capital (Fisher et al., 2021; Taghian et al., 2024). Thus, there is a critical imperative to comprehend the shifting trends of ambient air pollution. In 2017, REMA collaborated with the Ministry of Education of Rwanda to initiate the air quality and climate variabilities monitoring project. Aims of this Ph.D. project was to establish nationwide monitoring system to bolster skills and capabilities among Rwandan scientists and staff members from partnered educational institutions. This initiative rely on to address environmental issues concerning air quality and climate variability within Rwanda and the region in general (REMA, 2022). Therefore, through collaboration between the

Romanian Ministry of Foreign Affairs, the Rwandan Ministry of Education, and the Rwandan Ministry of Environment, funding was secured for this PhD thesis. It aims to introduce a solution to tackle the recognized issue of air quality and its associated health impacts in Rwanda and also in the region.

## 1.3 Research Gaps

Upon reviewing literatures, crucial research gaps have been identified in air quality studies:

- While there is a growing global interest in understanding air pollutant emission inventories in developing countries, catalysed by factors like biomass burning, rapid urbanization, and natural phenomena, a significant gap persists in considering the nuanced impact of local topography on these emissions. Addressing this gap is vital as it hinders a comprehensive understanding of how geographical factors intricately shape the dynamics of air pollutants. Urgent research is needed to explore and elucidate the specific ways in which diverse topographies influence the transport, distribution, and concentration of air pollutants in different regions, particularly within developing countries, in order to develop more accurate emission inventories and mitigation strategies.

- On a global scale, limited research has been directed towards comprehensive air quality studies focused on short-term roadside monitoring of traffic emissions. These studies often fail to consider the potential influence of nearby emissions and other sources impacted through atmospheric circulations, leading to incomplete measurements. Notably, there's a significant lack of specific literature reviews that thoroughly examine traffic emissions, encompassing aspects such as vehicle categories, fossil fuel usage in transportation, road characteristics, and road side potential emission sources.

- Despite the evident attention to in-situ monitoring of $PM_{10}$ and $PM_{2.5}$ around Africa, noticeable gap remains within the literature regarding comprehensive trend information for other crucial air pollutants, namely CO, $SO_2$, and $NO_2$. While Figure 1.3 highlights existing gaps, the focus has primarily centred on particulate matter, leaving a significant lack of comprehensive data and trend analysis for these additional pollutants. This gap underscores the necessity for more extensive and inclusive monitoring strategies that encompass a wider spectrum of air pollutants, thus facilitating a more holistic understanding of air quality dynamics in African regions. Addressing this gap is imperative for formulating targeted policies and interventions to mitigate diverse emissions and associated potential impacts.

- While there exists historical knowledge regarding the potential impacts of mining-based activities on the ecosystem and human-health, recent research dedicated to comprehensively understanding the impacts of mining-related on the quality of air is insufficient. There is a crucial need for research that quantifies pollutant emission rates by integrating in-situ monitoring, dispersion modelling, and assessments of related fluxes both vertical and horizontal influenced by wind erosion. This gap highlights the necessity for up-to-date and detailed investigations into the complex interconnection among mining activities, quality of air, wind erosion, and further meteorological perspectives.

- The current research highlights the necessity for a comprehensive investigation into the spatial-temporal variations in pollution levels to pinpoint and prioritize air pollution hotspots within urban environments. However, a notable gap exists in the absence of a universally accepted methodology for defining and delineating these hotspots. These hotspots may vary in terms of their sources, pollutants, and timing. Therefore, there is an urgent need for further research aimed at developing a standardized methodology that can accurately identify and delineate air pollution hotspots, accounting for these various factors.

- Despite the growing interest in utilizing dispersion models such as AERMOD and ISCST3 for global air pollutant dispersion, there exists a significant gap in systematically evaluating these models with regard to their adaptability and performance across diverse digital elevation models (DEMs). The lack of comprehensive research that rigorously assesses how these models behave when confronted with varying DEMs, particularly the application of statistical metrics to evaluate model performance, is evident. Filling this void is crucial for enhancing the reliability and precision of these models in simulating air pollutant dispersion on a global scale. It serves as an important guide for modellers to achieve accurate results, thereby assisting policymakers and stakeholders in making informed decisions regarding air quality management and mitigation strategies.

## 1.4 Objectives of the Study

### 1.4.1 General Objective

Given the global emphasis on environmental protection and identified research gaps in air quality studies, this PhD thesis generally aimed to analyse spatial-temporal distributions of $PM_{10}$, $PM_{2.5}$, $NO_2$, $SO_2$, and CO air pollutants using in-situ measurements and dispersion modelling techniques in Romania and Rwanda. Additionally, aimed to evaluate impact and risk of personal exposure to such pollutants. The complete study provided a thorough understanding of air quality dynamics, thereby contributing to more effective management strategies and offering policy recommendations for mitigating hazardous air pollutants.

### 1.4.2 Specific Objectives

To achieve the overarching goal outlined above, we pursued the following specific objectives:

1. To conduct a comprehensive review of literature on air quality modeling and in-situ monitoring methods to create an exhaustive resource for upcoming scholars and researchers.

2. To analyze in-situ observed data of $PM_{2.5}$, $PM_{10}$, $NO_2$, $SO_2$, and CO originated from the urban background of Kigali city, Rwanda.

3. To analyze in-situ monitoring data of $PM_{10}$ from the Moldova Nouă tailings ponds influenced by wind erosion in southwest Romania.

4. To describe the fundamental principles and state of the art techniques by applying Gaussian Plume dispersion modelling.

5. To quantifyP $M_{2.5}$, $PM_{10}$, $NO_2$, $SO_2$, and CO emission factors counting the influence of urban traffic volume, various vehicle categories, and the specific physical attributes influencing traffic flow in Kigali.

6. To create and implement a structured approach for analysing the impact of wind erosion on the emission rate, including both horizontal and vertical fluxes of $PM_{10}$, originating from the Moldova Nouă tailings ponds.

7. To simulate dispersion patterns of $PM_{2.5}$, $PM_{10}$, $NO_2$, $SO_2$, and CO Kigali urban background.

8. To simulate dispersion patterns of $PM_{10}$ in Moldova Nouă tailings ponds.

9. To evaluate and analyze the impact of complex local topographical features on air pollutant dispersion trends by various digital elevation models (DEMs).

10. To analyze and compare modelled results with in-situ monitored data of air pollutants, employing statistical metrics for model performance evaluation and Taylor diagrams.

11. To identify potential sources of air pollutants within the modelling domain employing three-dimensional bivariate polar plots under dispersion modelling perspective and atmospheric circulation.

12. To quantify environmental quality indicators of hazardous air pollutants in an urban background setting.

13. To identify the vulnerability zones (hotspots) through high probability assessment of personal exposure to hazardous air pollutants.

14. To apply Integrated Impact and Risk Assessment (IIRA) method to assess the impact and risk of personal exposure to $PM_{10}$, $PM_{2.5}$, $NO_2$, $SO_2$, and CO.

## 1.5 Research Questions

The research question of this study focused on elucidating the rationale and methodology behind the application of air pollutant dispersion models. Consequently, the study investigated the following inquiries:

- What are the most critical factors influencing air quality in urban environments and how these factors affect the selection of appropriate air pollutant dispersion models?

- What are the key technical and common considerations for the successively application of air pollutant dispersion models within the context of urban traffic and mining environments?

## 1.6 Significance of the Study

This study titled *Quantification of Air Pollutants Emissions Through In-Situ Measurement and Dispersion Modelling in Romania and Rwanda. Risk Assessment.* It is of significant importance by integrating in-situ monitoring and dispersion modelling methods precisely to quantify air pollutant emissions in Rwanda and Romania. These holistic approaches not only enhance our comprehension of the spatial and temporal dynamics of air pollution but also yields crucial role for policy formulation and regulatory adherence. The study's discoveries are targeted to inform environmental management strategies, uphold sustainable development goals, and provide a substantial scientific contribution to comprehending air quality dynamics and emissions quantification techniques. The study findings confidently guide policymakers in formulating air quality guidelines, urban planning strategies, and regulations essential for good public health. Furthermore, this study fosters bilateral collaboration between Romania and Rwanda, enhancing institutional capacity in advanced research and contributing to global efforts in mitigating the adverse effects of air pollution.

## 1.7 Research Output Arising from the Thesis

### 1.7.1 Publications in Peer-review Journals

1. **Chapter 4**:

   **Elisephane Irankunda**, Zoltán Török, Alexandru Mereuță, Jimmy Gasore, and Alexandru Ozunu. 2024. The First and Extensive Air Quality Mapping of Particulate Matter ($PM_{2.5}$) in Kigali City, Rwanda. **This article is in preparation**.

2. **Chapter 5**:

   **Elisephane Irankunda**, Zoltán Török, Alexandru Mereuță, Jimmy Gasore, Egide Kalisa, Beatha Akimpaye, Theobald Habineza, Olivier Shyaka, Gaston Munyampundu, and Alexandru Ozunu. 2022. The comparison between in-situ monitored data and modelled results of nitrogen dioxide ($NO_2$): case-study, road networks of Kigali city, Rwanda. Heliyon 8, 12 (December 2022), e12390. **Doi.org/10.1016/j.heliyon.2022.e12390, Web of Science (WoS) journal, IF = 4 (2023)**.

**Elisephane Irankunda**, Zoltán Török, Alexandru Mereuta, Alexandru Ozunu, Jimmy Gasore, Egide Kalisa, Beatha Akimpaye, Theobald Habineza, Olivier Shyaka, and Gaston Munyampundu. 2022. Potential Source Identification of $SO_2$ in Kigali-Rwanda. Bulletin of Romanian Chemical Engineering Society 9, 1 (2022), 131–142. **(BDI index Journal, ISSN2360-4697, ID:2777075576)**

3. **Chapter 6**:

   **Elisephane Irankunda**, Zoltán Török, Alexandru Mereuţă, Jimmy Gasore, Alexandru Ozunu. 2024. AERMOD Evaluation for Modelling the Dispersion of Particulate Matter ($PM_{10}$) in Complex Topography of Kigali-Rwanda. Environmental Engineering and Management Journal, 23 (2), 979 - 992, **Web of Science (WoS) journal, IF = 1.1 (2023)**.

4. **Chapter 7**:

   Zoltán Török, **Elisephane Irankunda***, and Alexandru Ozunu. 2024. Modelling the dispersion of $PM_{10}$ via wind erosion from opencast mining Moldova Nouă tailings ponds, Romania. Environ Monit Assess 196, 1 (January 2024), 59. **Doi.org/10.1007/s10661-023-12199-1, Web of Science (WoS) journal, IF=3.1 (2023)**, *** corresponding author**.

   **Elisephane Irankunda**, Carmen Roba, Horaţiu Ioan Ștefănie, Zoltán Török, and Alexandru Ozunu. 2024. Environmental Impact Assessment of Dust Pollution from Moldova Nouă Tailings Ponds, Romania. **This article is in preparation**.

5. **Chapter 8**:

   **Elisephane Irankunda**, Zoltán Török, and Alexandru Ozunu. 2024. Assessment of Urban Air Pollution and Associated Impacts and Risks Exposure through Computational Analysis Method: A Case Study in Kigali, Rwanda. **Submitted in Web of Science (WoS) journal**.

### 1.7.2 Presentations at International Conferences

1. **Irankunda, E.** et al. 2022. IDRiM 2022 - The 12th International Conference of the International Society for the INTEGRATED DISASTER RISK MANAGEMENT. Hosted by Babeș-Bolyai University of Cluj-Napoca, 21-23 September 2022. *AERMOD Dispersion Model for Environmental Air Pollution Risk Assessment Viz $PM_{10}$ Pollutant from Moldova Nouã Tailings Ponds, Romania.*

2. **Irankunda, E.** et al. 2022. The SICHEM2022 Romanian Chemical Engineering Society Romanian Chemical Society Academy of Technical Sciences – Chemical Engineering Section and University POLITEHNICA of Bucharest Faculty of Chemical Engineering and Biotechnologies 17, 18 November 2022 Bucharest, ROMANIA. *Potential Source Identification of $SO_2$ and Comparison Between Modelling Results with In-situ Monitoring Data: Study Case, Road Networks of Kigali-Rwanda.*

3. **Irankunda, E.** et al. 2022. International Conference on Air Quality in Africa (ICAQ'AFRICA2022) hosted online by the CERN, the European Centre for Nuclear Research, on 11th–14th October 2022. *Modelling Source Identification of CO: Case Study Roads Network (RN) of Kigali City, Rwanda.*

4. **Irankunda, E.** et al. 2022. Ph.D. Students' Days Faculty of Food Engineering, Tourism, and Environmental Protection ”Aurel Vlaicu” University of Arad the Second Edition, November 25, 2022. *The Comparison Between In-Situ Monitoring Data and Modelled Results of Particulate Matter ($PM_{10}$) For Environmental Risk Assessment: Study Case, The Closed Moldova Nouă Tailings Ponds – Romania.*

5. **Irankunda, E.** et al. 2023.” Gheorghe Asachi” Technical University of Iasi, Romania 6th International Conference of the Doctoral School May 17 - 19, 2023, Iaşi, România. Excellence in Doctoral Studies through Innovation, Convergence and Interdisciplinarity. *Potential Source Identification of $NO_2$ and Comparison Between Modelling Results with In-situ Monitoring Data: Study Case, Road Networks of Kigali-Rwanda.*

6. **Irankunda, E.** et al. 2023 ”Days of the Romanian Academy of Technical Sciences (ZASTR)” on 5-6 October 2023 at the Transilvania University of Brașov. *Evaluation of Dispersion Modelling of Carbon Monoxide (CO) In Complex Topography of Kigali-Rwanda.*

## 1.8 Thesis Framework

Apart from the bibliography and appendices, this thesis has three main parts: **Part I** – General introduction and literature reviews **(Chapters 1 and 2)**, **Part II** – Personal contributions **(Chapters 3 – 8)**, and **Part III** – General conclusion **(Chapter 9)**.

**Chapter 1** provides a general impression of the thesis, aims, and concepts of identified research gaps at national and international levels. **Chapter 2** gives literature reviews describing atmospheric air pollutants and air pollutants dispersion models. **Chapter 3** details the specific applied Material and Methodology for the two study cases, Kigali-Rwanda, and Moldova Nouă-Romania cities. **Chapter 4** describes the mapping of particulate matter ($PM_{2.5}$ and $PM_{10}$) through spatial and temporal distributions by applying air pollutant dispersion models and in-situ monitoring methodologies in Kigali city-Rwanda. **Chapter 5** details the potential source characterization and quantification of gaseous air pollutants ($NO_2$, CO, and $SO_2$) through in-situ monitoring and dispersion modelling in Kigali city-Rwanda. **Chapter 6** details evaluating the influence of the complex topography of Kigali City-Rwanda on the dispersion behaviour of particulate matter ($PM_{10}$) using the AERMOD dispersion model. **Chapter 7** compares site observations data with results from dispersion modelling for $PM_{10}$ through wind erosion influences across Moldova Nouă Tailings Ponds, Romania. **Chapter 8** discribes impacts and risks of personal exposure to hazardous air contaminants assessment. While, **Chapter 9** provides the general summary, conclusions, contributions, response to research questions, and way forward for future research works.

The bibliography contains all consulted materials, including books, research articles from different journals, scientific websites, and other web information. The last part of this thesis is the appendix which contains further results graphics and modelling pathways, certificates and awards from the attended international conferences

# Chapter 2

# Methodology: In-Situ Measurement and Dispersion Modelling of Air Pollutants

## 2.1 Road Networks of Kigali City, Rwanda

### 2.1.1 Introduction

The road network of Kigali, the capital city of Rwanda, plays a pivotal role in the city's urban development and connectivity. As one of the most rapidly growing cities in East Africa, Kigali (Figure 2.2) has witnessed significant improvements in its road infrastructure over the past few decades. The road network of Kigali city is a critical component of the city's transportation system, contributing to its economic, social, and cultural development (Figure 2.3). To address the effects of traffic emissions on the

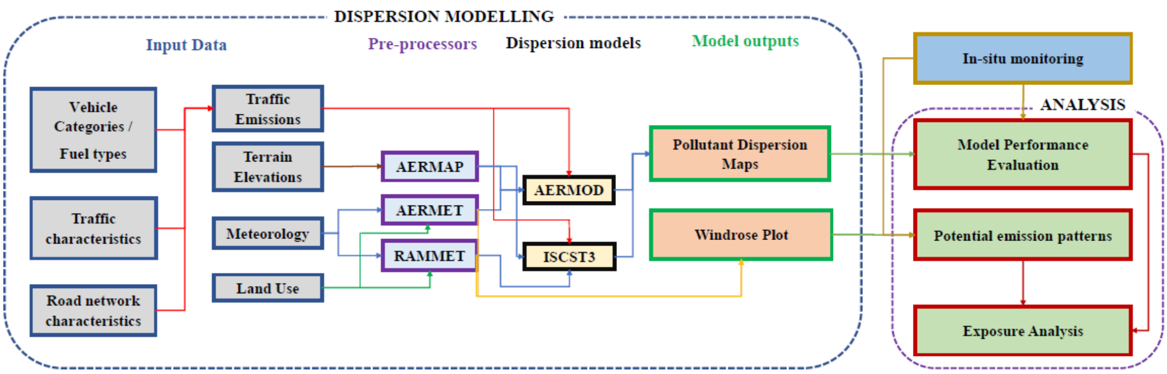


**Figure 2.1:** Methodological framework for street road network of Kigali city, Rwanda

air quality status of Kigali, a methodological framework with three main components was adopted: dispersion modelling, in-situ monitoring, and analysis of personal exposure (Figure 2.1), as described in the following sections of this chapter.

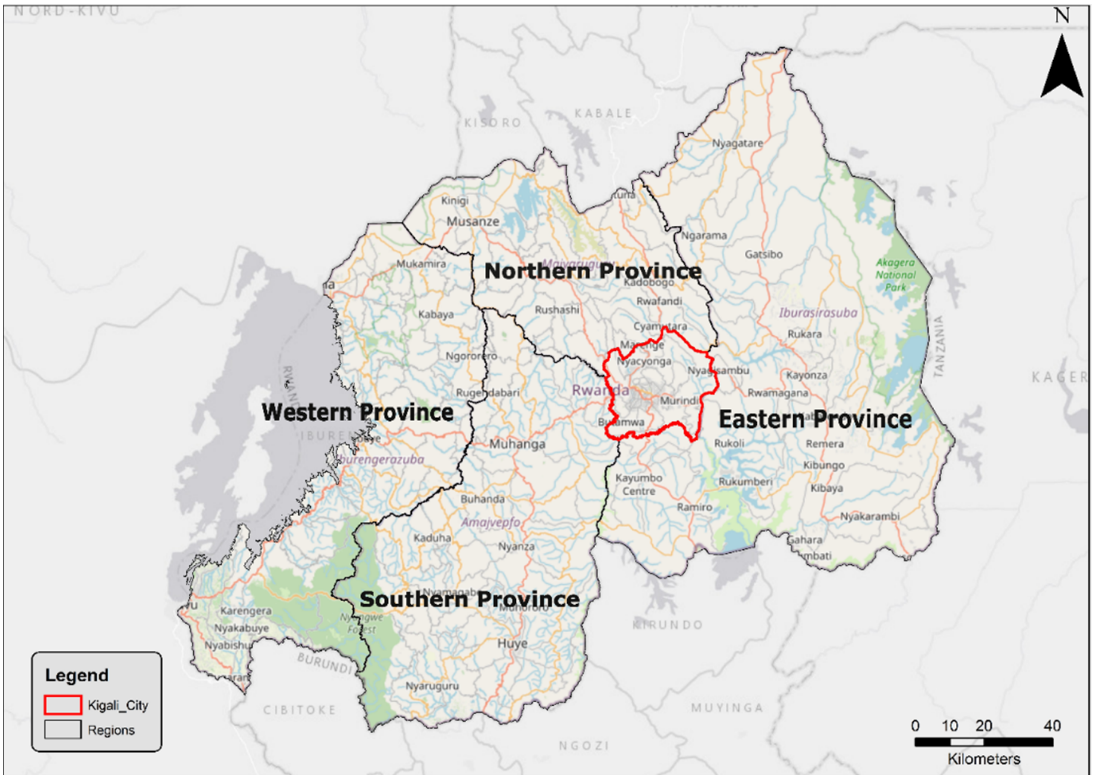


**Figure 2.2:** Kigali, the capital city of Rwanda, the study area

**Figure 2.3:** A busy road with a long queue of large vehicles along a specific considered route. Source: Picture taken by Iradukunda (2021)

### 2.1.2 Measurement and Instruments Calibrations

Simultaneous and real time in-situ measurements of air pollutants such as $PM_{2.5}$, $PM_{10}$, $NO_2$, CO, and $SO_2$ at the above considered six sites (discrete receptors) were accomplished by employing the low cost and real-time affordable multi pollutants (RAMPs) air quality instruments (Figures 2.4 and 2.5) for one year, 2021. The RAMPs were the manufactured goods of Sensevere company, which Sensit-Technologies -Valparaiso, in the USA, now owns. Numerous researchers explained the calibration method of RAMPs (Malings et al., 2019, 2020; Subramanian et al., 2018, 2020; Zimmerman et al., 2018). RAMPs use the passive alpha sense as an electrochemical gas sensor to monitor air pollutant concentration levels. $PM_{2.5}$, $PM_{10}$ are measured using a Met-One neighbourhood PM monitors (NPMs) paired with each RAMP.

The NPMs are a nephelometer equipped with $PM_{2.5}$, $PM_{10}$ cyclones, an inlet heater to mitigate humidity effects, and a pump with a flow rate of 2 lpm (Subramanian et al., 2020). The raw signals of these monitors are sensed four times every minute and then treated and averaged to deliver hourly data utilizing the generalized calibration model (gRAMPs) of RAMPs (Malings et al., 2019; Subramanian et al., 2020) established in Pennsylvania, USA (Pittsburgh). The same RAMPs were also used by Subramanian et al. (2020), while assessing the impact of car-free Sundays in Kigali City -Rwanda. Subramanian et al. (2020), proved the functioning of these RAMPs while investigating their performance by doing local verification with other data monitored at the Mugogo air quality station of Rwanda climate observatory (DeWitt et al., 2019) located at the top of Mugogo Mountain, approximately 70 km from Kigali city. In 2018, the Rwanda Environment Management Authority (REMA), a department of the Rwanda Ministry of Environment, installed these air quality stations in Rwanda with the goal of establishing a nationwide system that provides real-time Air Quality Index (AQI) data. This data is presented in both numerical and colour-coded formats and can be accessed on this website: www.aq.rema.gov.rw. The first report detailing the accuracy and calibration methods was conducted by Subramanian et al. (2020), who utilized the same stations to assess the spatial and temporal variability of air pollution in Kigali. The air quality projects are still fresh in Rwanda and require additional In-situ monitoring sites that capture the entire country for addressing the national air quality and index information.


**Figure 2.4:** Real-time affordable multi pollutant (RAMP) air quality monitors in the laboratory for adjustment and maintenance (left) and the installed RAMP for in-situ monitoring road-side target (right). Picture taken by Subramanian et al. (2020)

**Figure 2.5:** The thesis author making maintenance of RAMP installed at discrete receptor R3 (left) and at discrete receptor R6 (right). The picture was taken during field monitoring activity

## 2.2 Moldova Nouă Tailings Ponds, Romania

To address the effects of mining and industrial activities on the air quality status of the Moldova Nouă city- south-west of Romania, the following methodological framework (Figure 2.6) with three main parts were adopted: dispersion modelling, In-situ monitoring, and analysis of personal exposure was adopted and described in the following sections of this chapter.

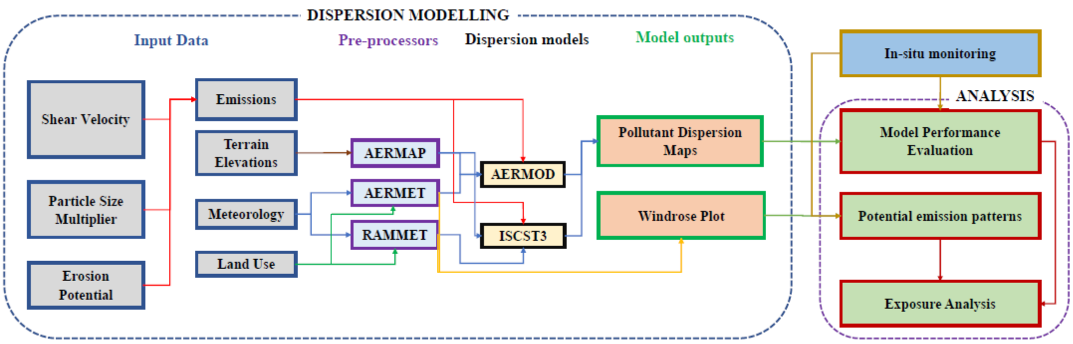


**Figure 2.6:** Methodological framework for Moldova Nouă tailings ponds, Romania

### 2.2.1 Study Area Description

The Moldova Nouă city is in the Caraş Severin (CS) county in the south-west region of Romania, as indicated in Figure 2.7, and has a surface area of 8.514 Km². In CS county, near the cross-border with Serbia country, near the Danube River into the Locvei mountains, is the location of the closed Moldova Nouă tailing pond ($44^0$ 42' N, $21^0$ 38' E , elevation 82 m), the second study area of our research. According to Simona et al. (2019) and Barbu et al. (2009), with the influence of the Mediterranean climate, Moldova Nouă city is experiencing an intense, warm, and dry wind known as Coşava; its direction generally blows from the south-east on the way to the north-west and occasionally the east regions of Romania. According to the CS's plan of activity report (CS, 2020), the county had an approximate population of 2.7 million in 2019. The population distribution by category was about 14.00% were children (0-14 years old), 11.00 % were young adults (15-24 years old), 54.70% were middle adults (25-64 years old), and 20.30% were elderly (above 65 years old) in 2019. The CS County experiences the annual average temperature, precipitation, and relative humidity of 12.92°C, 80.46 mm, and 73.13 %, respectively (CS, 2020). The ambient air quality of Moldova Nouă city is affected by the nearby emissions from points sources (industry stacks), line sources (conveyor, roads), and area sources (the tailings pond and wind erosion from different neighbouring locations) (Barbu et al., 2009; Barbulescu & Barbes, 2017; Raischi et al., 2017)

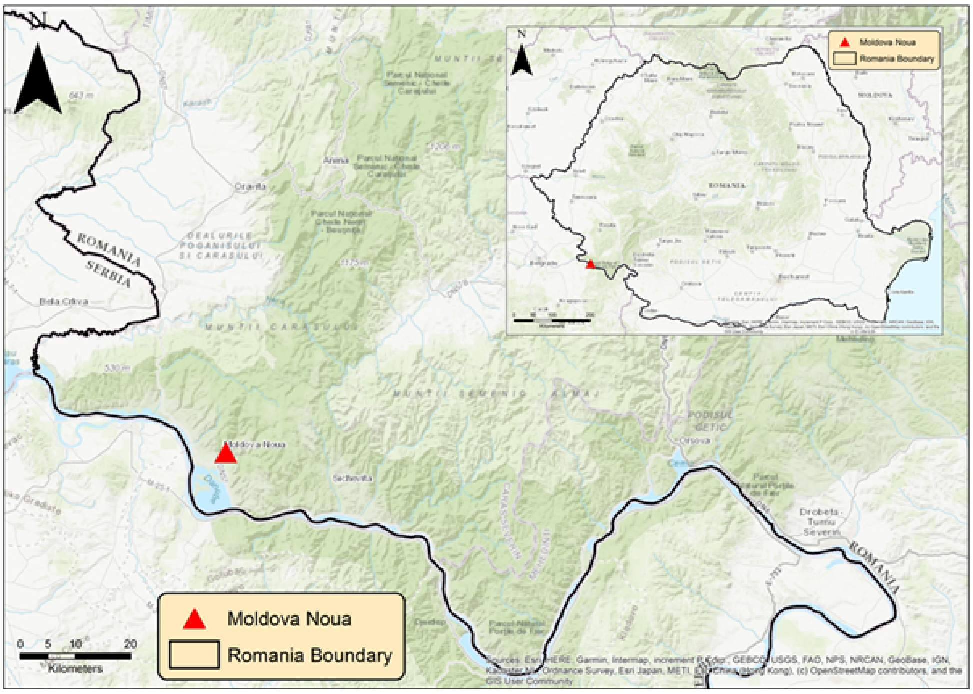


**Figure 2.7:** Location of the closed Moldova Nouă tailings ponds

### 2.2.2 In-Situ Monitoring and Instruments Calibrations

The Romanian National Air Quality Monitoring Network (RNMCA) has established over 100 air quality monitoring stations in line with good air quality and environmental management purposes. The monitoring point selections, monitor calibrations, and data validations conform to the European Environmental Agency-Agency (EEA) and Air Pollution Data Centre regulations (www.eea.europa.eu). The instrument installation of RNMCA focused on the critical zones, including urban traffic, industrial, suburban, and regional stations, to capture the territory's mapping view regarding air quality. All air quality datasets monitored nationwide are released to the community, researchers, or stakeholders after being certified by the National Reference Laboratory for Air Quality (LNRCA) of the Romanian National Environment Protection Agency. In this thesis, we used $PM_{10}$ data monitored in CS county by station number 5 (CS5) and 3 (CS3) of RNMCA (www.calitateaer.ro) (Figure 2.8). The CS5 and CS3 stations integrated targeting tailing ponds of Moldovan-Nouă and surrounding environments dominated by Moldova Nouă urban residential areas.

**Figure 2.8:** CS5 air quality station (left) and CS3 air quality station (right) of the Romanian national air quality monitoring network (RNMCA) used during in-situ monitoring around the closed Moldova Nouă tailings ponds, Romania

## 2.3 Model Setups and Modeling

The AERMOD view version 10.2.1 of Lakes Environment Software is a complete package of three powerful and reputable air pollutant dispersion models: AERMOD, CALPUFF, and ISCST3, recognized and recommended by the US EPA for air quality modelling. It was installed on a desktop computer with the following specifications:

- Processor: Intel(R) Xeon(R) CPU E3-1535M v5 @ 2.90GHz 2.90 GHz
- Installed RAM: 32.0 GB (31.6 GB usable)
- System type: 64-bit operating system, x64-based processor
- Operating System: Windows 10 Pro version 22H2

These dispersion models are extensively used to model the air pollutant concentration and deposition for various sources (point, volume, area, and line) from rural and urban environments, flat, elevated, and complex terrain. In this thesis, we used only the AERMOD and ISCST3 as the Gaussian plume dispersion model (section 2.6.5) to assess the impacts of urban traffic and mining industry activities on the air quality status of the corresponding study cases.

### 2.3.1 Modelling Domain

The modelling domain was structured based on our study areas' objectives and selection. For the Kigali city- Rwanda study case, the modelling domain presented in Figure 2.9 was selected as a circle area with a radius of 6.5 km projected using the UTM coordinate system with the World Geographical System 1984 datum (WGS84). Domain located at UTM zone 36 in the South Hemisphere, including the street road network locations and the six used discrete receptors. These output concentrations were modelled using simple and complex terrain calculation algorithms. With a reasonable time for the model to run, the domain was gridded into a uniform Cartesian grid receptor network with a considerable number of receptors (447 receptors) along with a total number of points 21 for X and Y, x = 1320.71 m, y = 787.53 m as spacing, and x = 26414.20 m, y = 15750.60 m as length.

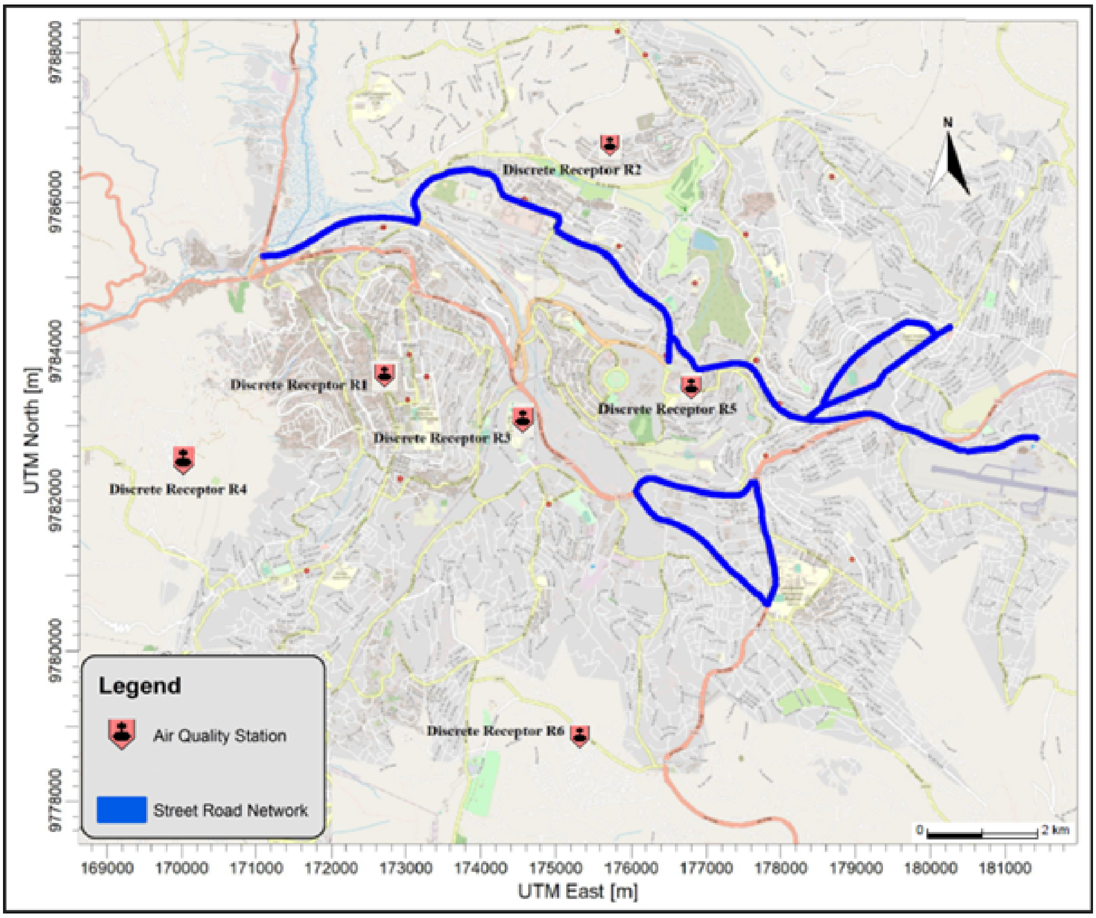


**Figure 2.9:** Modelling domain for Kigali city, Rwanda study case

For the study case of closed Moldova Nouă tailings ponds, the modelling domain presented in Figure 2.10 was selected as a circular domain with a radius of 5.5 km projected using the UTM coordinate system with the World Geographical System 1984 datum (WGS84). Domain was structured to include the location of the considered RNMCA air quality stations (CS5 and CS3). At the same time, the control path was modelled to be one hour (1H), twenty-four hours (24H), Monthly, and annual maximum output concentrations using simple and complex terrain calculation algorithms. With a reasonable time for the model to run, the domain was grided into a uniform Cartesian grid receptor network with a considerable number of receptors (441 receptors) along with a total number of points (x = 21, y = 21), spacing (x = 593.68 m, y = 596.58 m), and length (x = 11873.60 m, y = 11931.60 m).

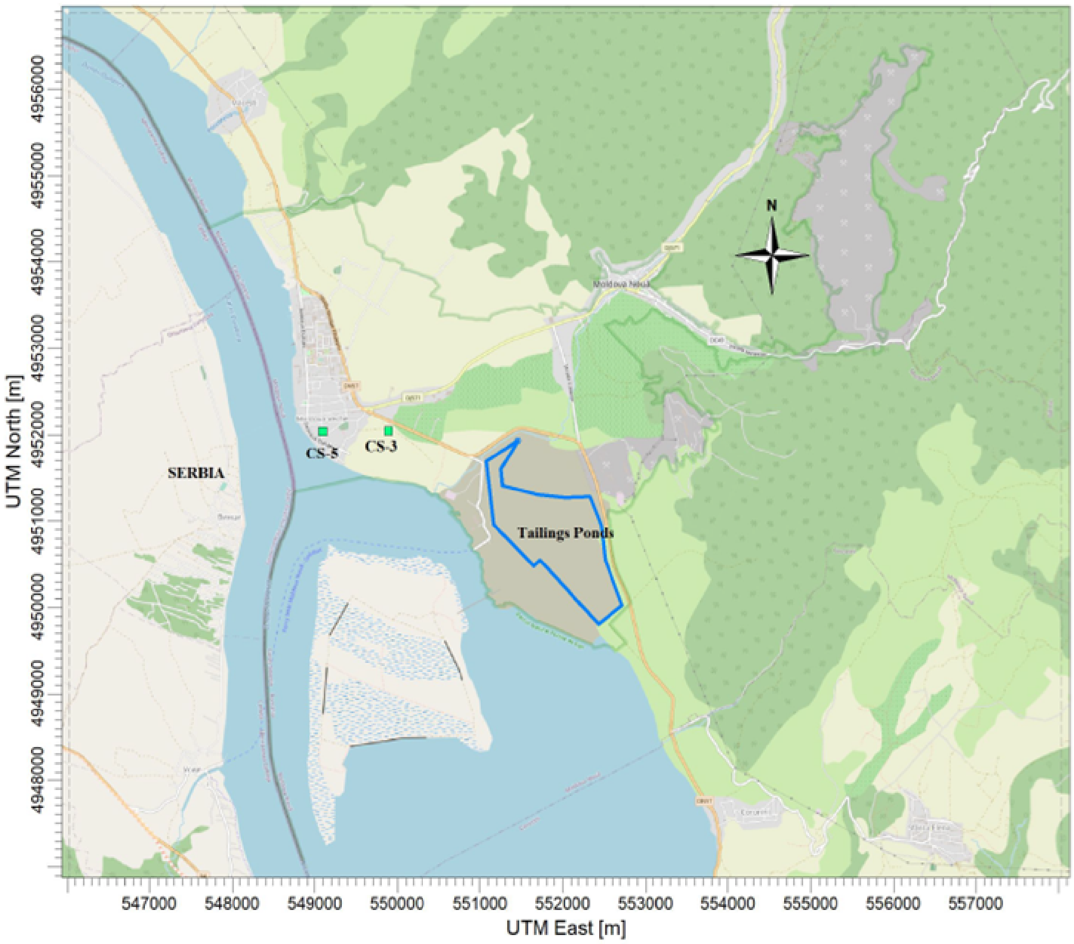


**Figure 2.10:** Modelling domain for closed Moldova Nouă tailings ponds

## 2.3.2 Emission Factors

### 2.3.2.1 Street Road Networks of Kigali City-Rwanda

For the Kigali city study case, the algorithm Tier-1 method described in equations (2.1) and (2.2) of the European Monitoring Evaluation Program/European Environmental

Agency (EMEP/EEA) for the emission factor calculations were used to evaluate the traffic-related emission factors for pollutants. Due to the quality of the available data on vehicle movement, we decided to use the Tier-1 algorithm compared to other available algorithms Tier-2 and 3 (EEA, 2019; Ntziachristos & Samaras, 2021; Usabiaga et al., 2013). The traffic volume related to vehicle movement data was obtained using vehicle manual counts considering regular weekdays, with no event or external factors affecting the vehicle flow and video approach for traffic flow assessment. The current traffic volume datasets of the Kigali city Masterplan from the Transportation Department projected between 2018 and 2050. Data sets were recorded and stored as the Update Traffic Report Kigali city Master Plan-2050 file name with the project reference number C-RW000011 (BPMIS, 2019).

$$E_i = \sum_j \left( \sum_k \left( FC_{j,k} \times EF_{i,j,k} \right) \right) \tag{2.1}$$

Where **E, FC, and EF** stand for Emission of pollutant (g), Fuel Consumption (Kg), and Emission factor of pollutant (g $kg^{-1}$), respectively. The indices: *i* represent the type of pollutant, *j* represents the vehicle category, and *k* represents the fuel category.

$$TE = \sum_j N_j \text{ x } M_j \text{ x } EF_{i,j} \tag{2.2}$$

Where **TE, N, M, and EF** stand for total emission of pollutants for the defined period and spatial boundary (g), the number of vehicles in the defined spatial boundary, the average distance driven per vehicle category during the specified period (km), and mass emission factor for pollutants (g $km^{-1}$), respectively. The indices: *i* represent the type pollutant, *j* represents the vehicle category. Apart from other considered pollutants, the $SO_2$ emission factor calculations assume that all Sulphur content in the fuel is oxidized entirely to $SO_2$ by equation (2.3) (Amouzouvi et al., 2020; Ntziachristos & Samaras, 2021).

$$E_{SO_2} = 2 \times \sum_k \left( V_{k,SO_2} \times FC_k \right) \tag{2.3}$$

Where **V** is the sulfur content in ( g/g fuel)

The application of the Tier-1 algorithm in calculating the urban traffic-related emission factors necessitates categories of vehicles travelling the considered roads. The roads highlighted in Figure 2.11 were primarily selected based on the assessment of their traffic volume, significantly influenced by congestion and traffic flow (refer to Figure 2.3).

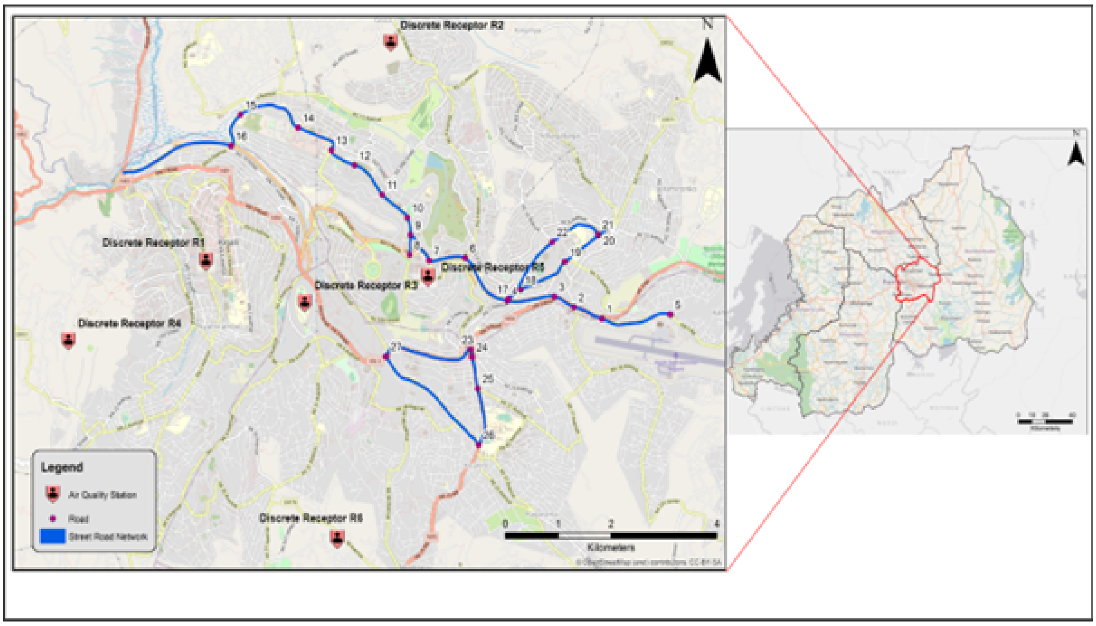


**Figure 2.11:** The modelling domain, including the street road networks and air quality stations

#### 2.3.2.2 The Closed Moldova Nouă Tailings Ponds-Romania

For the study case of closed Moldova Nouă tailings ponds (Figure 2.12), the emission factor is among the required inputs parameter for modelling purposes. Given the environmental characteristics of our study area, we used the emission factor calculated following the guideline approach developed and recommended by the US EPA compiled to the AP-42 fugitive dust emission factors from open-cast mining activities under the influence of wind erosion of the exposed surface area equation (2.4) (EPA, 1985, 2006, 2016; Wagner, 2013).

$$
\begin{aligned}
EF &= k\sum_{i=1}^{N} P_i \\
P &= 58\,(u_* - u_{*t})^2 + 25\,(u_* - u_{*t}) \\
P &= 0 \text{ for } u_* \le u_{*t}
\end{aligned}
\tag{2.4}
$$

Where **EF** stands for emission factor (g $m^{-2}$ for wind-produced particle emission per year, k stands for particle size multiplier and is equal to 0.5 for $PM_{10}$. $\mathbf{P_i}$ stands for erosion potential corresponding to the observed (or probable) fastest mile of wind for the period between the number of disturbances per year (N), $\mathbf{u_*}$ stands for Shear Velocity in (m $s^{-1}$), and $\mathbf{u_{*t}}$ stands for Shear threshold velocity in (m $s^{-1}$). The mass quantity of $PM_{10}$

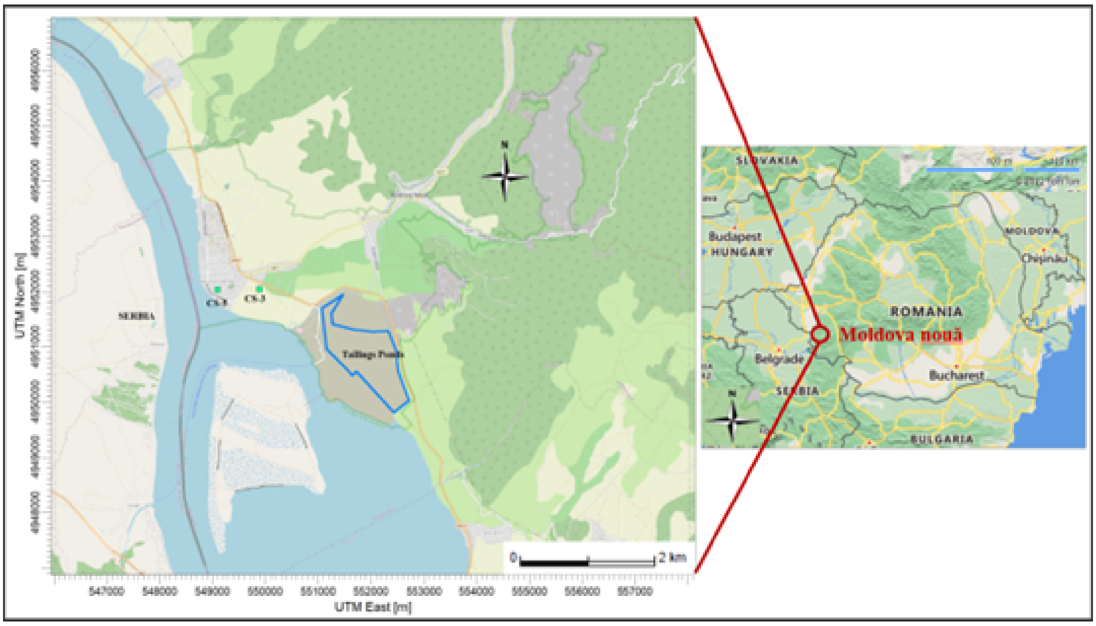


**Figure 2.12:** Location of Moldova Nouă tailings ponds (Research Study Area) and air quality stations (CS3 and CS5)

transported horizontally (horizontal flux) and vertically (vertical flux) from the surface area of tailings ponds per unit time ($\mu$g $m^{-2}$ $s^{-1}$) into the atmosphere were estimated using mathematical models. During the field visit, the physical view of the Moldova Nouă tailings ponds was categorized into eight different zones (Table 2.1) and Figure 2.13). Much more attention was taken to zones of the free, exposed surface area of dust and sand particles (Z1, Z3, Z4, Z6, and Z7). In contrast, other zones (Z2, Z5, and Z8) were excluded due to their physical characteristic (vegetation background). The surface area and width characteristics of rectangular shapes designed in the considered zones, wind profile data, and the modelled concentration within the vicinity of the tailing's ponds were treated as mathematical model inputs, questions (2.5).

**Table 2.1:** Zones characterizing the current physical status of the Moldova Nouă tailings ponds

| Zone | Descriptions |
|---|---|
| Z1 | Dump 1 with Wet Sterile |

| | |
|---|---|
| Z2 | Dump 1 With Wet Sterile and Vegetation Area |
| Z3 | Dry Sterile Dumpster |
| Z4 | Sterile Dump, With Nearby Vegetation Area |
| Z5 | Dump 2, With Vegetation |
| Z6 | The Ground Base of Dump 1 |
| Z7 | Dump 3 With Wet Sterile |
| Z8 | Dump 3 With Dry sterile |

According to Roney & White (2006) and Richards-Thomas & McKenna-Neuman (2020), the Horizontal flux of $PM_{10}$ can be obtained with high precision by the use of the volume-box model approach equation (2.5). The volume-box model stated, "the emissivity of particles from the known surface area is directly proportional to the difference between the horizontal rate of dust particles transported in and out in a conceptualised box."

$$E = \frac{1}{A_s}(m_o - m_i)$$
$$m_o = \int_0^z c\, u(z)\, w_s\, dz \qquad (2.5)$$

Where $\mathbf{A_s}$ and $\mathbf{W_s}$ stand for the surface area and width of the considered place, respectively. Where $\mathbf{m_0}$ and $\mathbf{m_i}$ stand for the horizontal rate of the particle leaving and entering the box, respectively, while the measured concentration of air pollutants (**c**), the hourly average wind speed profile (**u**), monitored at any position (**z**), were regarded as further model inputs. The existing literature reviews conclude the reason for taking $\mathbf{m_i = 0}$, assuming that the Moldova Nouă tailings ponds waste is the only $PM_{10}$ source (Barbu et al., 2009; Popescu, 2016). Therefore, with the finite difference of integral and approximation (Houser & Nickling, 2001; McDowell et al., 2009; Richards-Thomas & McKenna-Neuman, 2020), the horizontal flux of $PM_{10}$ was calculated using mathematical models in equations (2.5). The vertical flux of $PM_{10}$ was estimated following the guideline after Gillette & Passi (1988) and Gillett & Morales (1979), stating that the vertical flux of $PM_{10}$ from the soil surfaces is estimated based on the shear velocity ($\mathbf{u_*}$), for which stand for Kármán constant ($\mathbf{k = 0.4}$ for $PM_{10}$ ), and air density via equation (2.6).

$$F = -k\rho\ u_* \frac{dc}{dz} \qquad (2.6)$$

These equations (2.5) and (2.6) have been used by Houser & Nickling (2001), Wagner (2013), and Richards-Thomas & McKenna-Neuman (2020) to estimate the vertical flux of coarse particle $PM_{10}$ from the sandy surface. Hence, the vertical flux should be related to the horizontal flux via the shear velocity (Houser & Nickling, 2001).

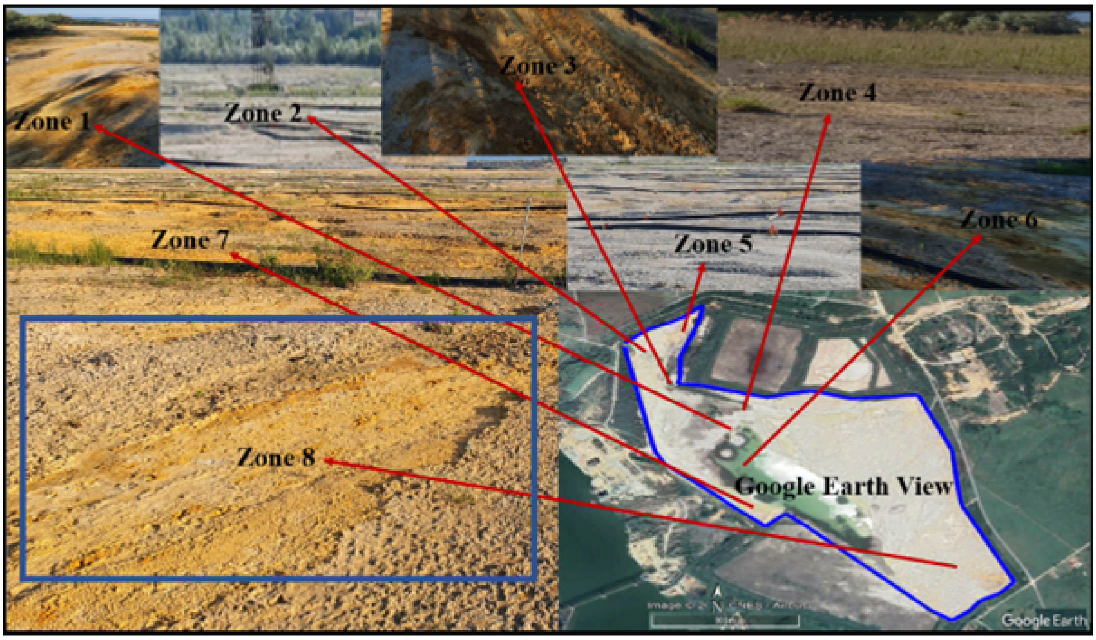


**Figure 2.13:** Field visit pictures showing zones characterizing the physical status of the Moldova Nouă tailings ponds

## 2.4 Statistical Analysis

The statistical analysis for this thesis utilized the capabilities of R version 4.2.2, running on the x86-64-w64-mingw32/x64 platform, customized for Windows (64-bit). R is a widely acclaimed programming language, particularly renowned for statistical computing and data analysis. Employing R Studio as the development environment, this version offers an array of tools optimized for data visualization, statistical modelling, and analysis. For the specific domain of air quality analysis, the open-air package within R stands as a pivotal resource. Open-air specializes in handling air quality datasets, providing a suite of functions and tools designed explicitly for this purpose. Through the integration of R and the open-air package, this research conducts comprehensive analyses, visualizes complex data structures like resampling into daily (24-H) averaging period, and performs statistical modelling tailored to the nuances of air quality datasets (Carslaw & Ropkins, 2012).

## 2.5 Model Performance Evaluation

The statistical analysis considering different metrics presented in equations (2.7) and (2.8) was used to evaluate and compare model outputs and in-situ observations. Therefore, the fractional bias (FB), Mean bias (MB), the fraction of prediction within the factor of two (FAC2) Chang & Hanna (2004), the normalized mean square error (NMSE), the geometric mean bias (MG), normalized mean bias (NMB), and geometric variance (VG) (Barton et al., 2010; Gibson et al., 2013; Hanna et al., 2001) were considered in this thesis to understand the complete intuition linked to the trustworthiness between two used models AERMOD and ISCST3 in estimates air pollutant concentrations.

The $\mathbf{C_p}$ and $\mathbf{C_o}$ represent the concentration level of the predicted and observed values, respectively and $\sigma$ represents the standard deviation. The model's systematic bias indicates over, and under-prediction inferred to in-situ observations are indicated by MG, FB, MB, and NMB indexes. The casual scatter provides the overall measure of how closely modelled results are indicated by VG and NMSE. The FAC2 signifies the robust ratio measure, which proposes a fraction of data between 0.5-2.0. The index of the agreement for the perfect model might have the MG, VG, and FAC2 equivalent to 1.0 and 0.0 for the FB and NMSE indexes (Chang & Hanna, 2004; Gibson et al., 2013). Further details and practical applications related to mathematical equations of such used statistical indexes were made by Chang & Hanna (2004), Haq et al. (2019), and (Barton et al., 2010). Both modelling results and in-situ monitored data were considered and used for assessing the level of human exposure to air pollutants leading to health effects and risks. The assessment was done as a base comparison between study outputs against global WHO air quality limits to identify whether people living in Kigali are exposed to hazardous $PM_{2.5}$. Therefore, these results can be applied to set the corresponding country's air quality standards and guidelines.

For the study case of closed Moldova Nouă tailings ponds, we applied some additional different statistical indexes (system of equation (2.8)) to evaluate the consistency and performance of the AERMOD in simulating the dispersion of $PM_{10}$. The metrics, including the fraction of predictions within a factor or two (FAC2), Mean bias (MB), Mean gross error (MGE), Normalised mean bias (NMB), Normalised mean gross error (NMGE), Coefficient of efficiency (COE), Index of Agreements (IOA), and Taylor diagram indicating the standards deviation (SD) of both observation and modelled values, Root mean squared error (RMSE), and Pearson correlation coefficient (R). Researchers have applied and detailed these indices' formulas and physical interpretation (Khazini et al., 2022; Mohan et al., 2011; Omidvarborna et al., 2018; Srivastava et al., 2021; Verma et al., 2017; B. Zou et al., 2010). In addition, the MB and NMB metrics measure the efficient bias of the model as a marker of the model's over-prediction and under-prediction interconnected to the in-situ field-monitored data. The SD, R, MGE, NMGE, and NMSE show random scatter measures and systematic bias. FAC2 is the robust ratio measure that implies the fraction of data in 0.5-2.0 (Davison, 2023; Srivastava et al., 2021). The COE and IOA confirm the quality of the model spans between -1 and +1, a value approaching +1implying a better model in performance, whereas -1 means that the model estimations deviate from the observations leading to poor estimates of the observations. (Legates & McCabe, 2013; Willmott et al., 2012). The index of the agreement for the perfect model might have the MB, MGE, NMB, and NMGE equivalent to 0.0 and FAC2, R, and NMSE indexes equivalent to 1.0 (Chang & Hanna, 2004; Gibson et al., 2013).

$$\begin{cases} FB = \dfrac{\overline{\left(C_o - C_p\right)}}{0.5\,\overline{\left(C_o + C_p\right)}} \\ MG = Exp(\overline{\ln C_o} - \overline{\ln C_p}) \\ NMSE = \dfrac{\overline{\left(C_o - C_p\right)^2}}{\overline{\left(C_o C_p\right)}} \\ FAC2 = \text{fraction of data that satisfy } 0.5 \leq \dfrac{C_p}{C_o} \leq 2.0 \\ VG = Exp(\overline{\ln C_o} - \overline{\ln C_p})^2 \\ MB = \dfrac{1}{n}\sum_{i=1}^{N}\left(C_{pi} - C_{oi}\right) \\ NMB = \dfrac{\sum_{i=1}^{n}\left|C_{pi} - C_{oi}\right|}{\sum_{i=1}^{n} C_{oi}} \end{cases} \tag{2.7}$$

$$
\begin{cases}
MGE = \frac{1}{n}\sum_{i=1}^{N}\left(C_{pi} - C_{oi}\right) \\
NMGE = \frac{\sum_{i=1}^{n}\left|C_{pi} - C_{oi}\right|}{\sum_{i=1}^{n} C_{oi}} \\
R = \frac{1}{(n-1)}\sum_{i=1}^{n}\left(\frac{C_{pi} - \overline{C_p}}{\sigma_{C_p}}\right)\left(\frac{C_{oi} - \overline{C_o}}{\sigma_{C_o}}\right) \\
COE = 1.0 - \frac{\sum_{i=1}^{n}\left|C_{pi} - C_{oi}\right|}{\sum_{i=1}^{n}\left|C_{oi} - \overline{C_o}\right|} \\
IOA = \begin{cases}
1.0 - \frac{\sum_{i=1}^{n}\left|C_{pi} - C_{oi}\right|}{2\sum_{i=1}^{n}\left|C_{oi} - \overline{C_o}\right|}, \text{ when } \sum_{i=1}^{n}\left|C_{pi} - C_{oi}\right| \le 2\sum_{i=1}^{n}\left|C_{oi} - \overline{C_o}\right| \\
\frac{\sum_{i=1}^{n}\left|C_{pi} - C_{oi}\right|}{2\sum_{i=1}^{n}\left|C_{oi} - \overline{C_o}\right|} - 1.0, \text{ when } \sum_{i=1}^{n}\left|C_{pi} - C_{oi}\right| > 2\sum_{i=1}^{n}\left|C_{oi} - \overline{C_o}\right|
\end{cases}
\end{cases}
\tag{2.8}
$$

## 2.6 Impacts and Risks of Personal Exposure to Air Pollutants with IIRA Methods

The Integrated Impact and Risk Assessment (IIRA) methodology is a quantitative approach used to assess environmental impact and risk, particularly in the context of environmental pollution. The methodology developed and applied by Robu et al. (2007) and Ştefănescu et al. (2013) was specifically utilized in this paper to evaluate the impact and risk associated with ambient in-situ monitored air pollutants in the study area. The IIRA methodology incorporates the following parameters:

- *Environmental Impact (**$EI_i$**)*: This parameter represents the impact of a specific environmental factor (air pollutant) (i). It is determined by the magnitude (concentration) of the environmental factor and its importance unit ($IU_i$). It is given by equation (2.10), which describes the relationship between magnitude and importance unit in calculating the environmental impact.

- *Environmental Risk (**$ER_i$**)*: This parameter considers both the magnitude of the

$\mathbf{EI_i}$ and the probability of occurrence ($\mathbf{P_i}$), and the equation ((2.11)) shows how the environmental risk is calculated as the product of the environmental impact and the probability of occurrence.

The quality indicator parameter ($\mathbf{Q_i}$) was utilized and calculated as the ratio between the allowed maximum guideline concentration of the environmental factor ($\mathbf{MAC_i}$) and the corresponding in-situ monitored concentration ($\mathbf{CO_i}$) as indicated in equation (2.9), presents the formula for calculating the quality indicator parameter.

It is important to note that the values for $\mathbf{MAC_i}$ used in this chapter were obtained from the World Health Organization's current report on maximum admissible concentrations for air pollutants, including particulate matter ($PM_{10}$ and $PM_{2.5}$), nitrogen dioxide ($NO_2$), sulfur dioxide ($SO_2$), and carbon monoxide (CO) (WHO, 2021).

$$Q_{\mathrm{i}} = \frac{MAC_{\mathrm{i}}}{CO_{\mathrm{i}}} \tag{2.9}$$

$$EI_{\mathrm{i}} = \frac{IU_{\mathrm{i}}}{Q_{\mathrm{i}}} \tag{2.10}$$

$$ER_{\mathrm{i}} = EI_{\mathrm{i}} \cdot P_{\mathrm{i}} \tag{2.11}$$

The evaluation technique for determining the $\mathbf{IU_i}$ and $\mathbf{P_i}$ for each air pollutant follows the principles established by Ştefănescu et al. (2013) and Robu et al. (2007), which systematically quantify the importance and probability associated with environmental factors in air, surface water, and soil.

The importance matrix method evaluates $\mathbf{IU_i}$ and quantifies each environmental factor's importance. This method allows for a systematic assessment of the significance of each factor concerning the overall impact. The importance values can be assigned based on expert judgment, stakeholder input, or other relevant criteria. Similarly, the probability of occurrence ($\mathbf{P_i}$) is assigned a value between 0 and 1, where 0 represents zero or negligible probability, and 1 represents a certain or maximum probability. The specific values assigned to $\mathbf{P_i}$ depend on the nature of the environmental factors and the specific study context. In the case of the environmental air pollution project discussed in the study, the probability ($\mathbf{P_i}$) was quantified as 0.27, indicating a moderate probability of occurrence.

**Table 2.2:** Range values and their corresponding descriptions for environmental impact and risk (Robu et al., 2007; Ştefănescu et al., 2013)

| Items | Range Values | Description |
|---|---|---|
| RISK | <100 | Negligible |
| | 100-200 | Minor and monitoring actions are required. |
| | 200-350 | Moderate at an acceptable level where monitoring and prevention activities are needed |
| | 350-700 | Moderate at an unacceptable level where control and prevention measures are needed |
| | 700-1000 | Significant remediation, control, and prevention measures are required. |
| | >1000 | Catastrophic All activities should be stopped |
| Impact | <100 | The natural environment is not affected by industrial/human activities |
| | 100-350 | Environment modified by industrial activities with allowable limits |
| | 350-500 | Environment modified by industrial activities causing discomfort conditions |
| | 500-700 | Environment modified by industrial activities causing distress to life forms |
| | 700-1000 | Environmental modification by industrial activities is dangerous for life forms. |
| | >1000 | Degraded environment, not proper for life forms |

The importance unit ($\mathbf{IU_i}$) was determined to be 273.97, reflecting the significance or weight assigned to the targeted pollutants. These values were determined based on the methodology established by Ştefănescu et al. (2013) and Robu et al. (2007) for assessing the importance and probability of environmental factors. Applying the IIRA method for environmental impact and risk assessment, the obtained values for environmental impact and risk must be classified into their respective range categories. Table 2.2 provides the range values and their corresponding descriptions for environmental impact and risk based on the methodologies established by Ştefănescu et al. (2013) and Robu et al. (2007)).

When using the IIRA method, it is essential to note that in cases where the in-situ monitored concentration of air pollutants averages zero, indicating a high-quality factor for the corresponding environmental indicator, the method considers a range of sampling periods. In such cases, the quality factor is ignored, and it does not significantly impact the results and conclusions of the assessment. Therefore, classifying the environmental impact and risk values into their respective range categories makes it easier to interpret and understand the severity and significance of the assessed effects and risks associated with the environmental factors under consideration.

# Chapter 3

# General Discussion of the Thesis Results and Future Directions

This chapter provides a comprehensive overview, including a general summary of key findings, conclusions, original contributions, responses to research questions, and recommendations for future researches. In short, the study successfully addressed existing knowledge and research gaps in the air quality domain, as discussed in Chapter 1. Chapter 2 establishes the general background context through literature reviews, focusing on air pollutants and their dispersion in the atmosphere. This includes considerations of meteorology and the planetary boundary layer mechanism. Chapter 3 outlines the experimental and design techniques used in this study as part of the methodology. Monitoring and dispersion results from case studies, specifically focusing on urban traffic and mining, are detailed in Chapters 4, 5, and 7. Chapter 6 underscores the application of air pollutant dispersion models in complex topographic areas. Chapter 8 delves into characterizing the environmental impact and risk assessment of personal exposure to hazardous air pollutants.

## 3.1 General Findings

### 3.1.1 In-situ Monitoring

In Kigali, the $PM_{10}$ annual averages concentrations ranged from 44 to 56 $\mu$g m$^{-3}$, $PM_{2.5}$ levels varied between 25 and 48 $\mu$g m$^{-3}$ at receptors R1 through R6, and $NO_2$ annual averages were 20.35 $\mu$g m$^{-3}$ (R4), 16.07 $\mu$g m$^{-3}$ (R2), and 15.46 $\mu$g m$^{-3}$ (R3). CO annual means were 527.7 $\mu$g m$^{-3}$ (R2), 618.2 $\mu$g m$^{-3}$ (R3), and 721.6 $\mu$g m$^{-3}$ (R6). $SO_2$ annual means were 59.8 $\mu$g m$^{-3}$ (R3), 62.0 $\mu$g m$^{-3}$ (R6), and 34.8 $\mu$g m$^{-3}$ (R2). The trends show that noon hours have lower emissions, indicating significant contributions from urban traffic, especially on working days. Monthly variations suggest persistent air pollution, influenced by factors like atmospheric circulation during the dry season and the atmospheric washout phenomenon. Overall, additional factors, including unpaved traffic routes, influences of complex topographic features, and urban residential areas, contribute to increased air pollution in Kigali city.

In Moldova Nouă, in-situ monitoring of $PM_{10}$ concentrations reveals hourly variations with an increase during evening hours (13:00 to 23:00) and a decrease during morning hours (00:00 to 06:00 AM until noon). The annual average $PM_{10}$ concentration is 29.3 $\mu$g m$^{-3}$ at the CS5 station and 20.9 $\mu$g m$^{-3}$ at the CS3 station. Monthly variations show higher $PM_{10}$ levels in October, November, and December. Weekends exhibit lower concentrations, while wind speed and direction influence concentrations, with south-easterly winds associated with higher levels near ponds and northwestern winds linked to urban emissions in Moldova Veche city. Annual wind speed reaches 4.87 m s$^{-1}$, with pond vicinity winds up to 12.80 m s$^{-1}$. Shear velocity is 0.15 m s$^{-1}$, and threshold shear velocity is 0.005 m s$^{-1}$. Annual horizontal and vertical flux of $PM_{10}$ is 63.3 $\mu$g m$^{-2}$ s$^{-1}$ and 3.0 $\mu$g m$^{-2}$ s$^{-1}$, with maximum values at 598.61 $\mu$g m s$^{-2}$ s$^{-1}$ and 28.11 $\mu$g m$^{-2}$ s$^{-1}$, respectively.

### 3.1.2 Dispersion Modelling

In Kigali, dispersion modelling identifies a concentration hotspot at UTM coordinates X: 178654.94 m, Y: 9783542.26 m for $PM_{2.5}$, $PM_{10}$, CO, $NO_2$, and $SO_2$. Using AERMOD and ISCST3 models, $NO_2$ concentrations at this point were 111.77 $\mu$g m$^{-3}$ (AERMOD: daily 50.42 $\mu$g m$^{-3}$, annual 72.26 $\mu$g m$^{-3}$; ISCST3: daily 200.26 $\mu$g m$^{-3}$, annual 72.26 $\mu$g m$^{-3}$). CO concentrations were 1118.0 $\mu$g m$^{-3}$ (AERMOD: daily 507.0 $\mu$g m$^{-3}$, annual 726.0 $\mu$g m$^{-3}$; ISCST3: daily 1586.0 $\mu$g m$^{-3}$, annual 726.0 $\mu$g m$^{-3}$). $SO_2$ concentrations were 106 $\mu$g m$^{-3}$ (AERMOD: daily 53.4 $\mu$g m$^{-3}$, annual 58.8 $\mu$g m$^{-3}$; ISCST3: daily 135 $\mu$g m$^{-3}$, annual 58.8 $\mu$g m$^{-3}$). ISCST3 modelling showed daily ground levels of 41.1 $\mu$g m$^{-3}$ ($PM_{10}$) and 38.9 $\mu$g m$^{-3}$ ($PM_{2.5}$), with annual concentrations of 14.7 $\mu$g m$^{-3}$ ($PM_{10}$) and 13.9 $\mu$g m$^{-3}$ ($PM_{2.5}$). AERMOD modelling indicated daily ground levels of 22.8 $\mu$g m$^{-3}$ ($PM_{10}$) and 21.7 $\mu$g m$^{-3}$ ($PM_{2.5}$), with annual concentrations of 10.2 $\mu$g m$^{-3}$ ($PM_{10}$) and 9.7 $\mu$g m$^{-3}$ ($PM_{2.5}$). The findings point to local emissions and potential sources linked to traffic, atmospheric conditions, and topography, with higher concentrations from south-east and north-west winds.

In Moldova Nouă, the modelled results pinpoint a $PM_{10}$ hotspot near tailings ponds at UTM coordinates X: 552019.21 m, Y: 4950914.53 m. AERMOD shows a daily average of 563.7 $\mu$g m$^{-3}$ and an annual average of 115.5 $\mu$g m$^{-3}$, while ISCST3 indicates a daily average of 37.4 $\mu$g m$^{-3}$ and a yearly average of 22.5 $\mu$g m$^{-3}$. Emission factor calculations, following US EPA AP-42 for wind-erosion in mining environment, highlight $PM_{10}$ emissions from tailings ponds. The influence of wind erosion, particularly from the east and north-west at varying speeds, aligns with the modelled dispersion map. Higher concentrations (40, 50, 80 $\mu$g m$^{-3}$) correlate with south-easterly winds, suggesting tailing ponds as a likely source. Lower concentrations (10, 30, 50 $\mu$g m$^{-3}$) at northwestern winds imply additional sources from urban and residential emissions in Moldova Veche city, as can be seen in Figure 4.7.

### 3.1.3 Dispersion in Complex Topography

The influence of complex topography on the dispersion of air pollutants was evaluated under different Digital Elevation Models (DEMs), namely, SRTM1 (30 m), SRTM3 (90 m), SRTM30 (900 m), and GTOPO30 (900 m). The model's performance through statistical indexes was also evaluated by comparing the model outputs for each DEM with in-situ monitoring observations. Results concluded that the dairy modelling was 22 $\mu$g m$^{-3}$ with SRTM1 and 23 $\mu$g m$^{-3}$ for other DEMs, while the annual was 10 $\mu$g m$^{-3}$ for all DEMs. In comparison, statistical indexes concluded that the high-resolution choice of DEM significantly impacts the accuracy of the model predictions, with SRTM3 and GTOPO30 providing the best performance among other DEMs. Dispersion patterns indicate that the up-slope or hill features of complex topography act as barriers for airflow, resulting in the accumulation of air pollutants in low-lying areas.

### 3.1.4 Model Performance Evaluation

The thesis study employed various statistical analyses for model performance evaluation, including fractional bias (FB), mean bias (MB), fraction of prediction within the factor of two (FAC2), normalized mean square error (NMSE), geometric mean bias (MG), normalized mean bias (NMB), geometric variance (VG), mean gross error (MGE), normalized mean gross error (NMGE), coefficient of efficiency (COE), index of agreements (IOA), and Taylor diagram indicating the standards deviation (SD) of both observation and modelled values, Root mean squared error (RMSE), and Pearson correlation coefficient (R). In the Kigali-Rwanda case, $PM_{10}$ and $PM_{2.5}$ showed good agreement with AERMOD and moderate agreement with ISCST3 based on NMSE, FB, and FAC2. For $NO_2$, excellent agreement was indicated by FB, NMSE, and FAC2 with AERMOD, while MG and VG suggested moderate agreement. ISCST3 showed reasonable agreement for $NO_2$, but disagreement based on FAC2 and VG. CO exhibited good agreement with ISCST3 and moderate agreement with AERMOD. $SO_2$ agreed well with FB, NMSE, MG, and VG, while FAC2 moderately agreed with both models. Overall, ISCST3 and AERMOD predict pollutant concentrations significantly and agree with in-situ observations, with AERMOD performing slightly better. In the Moldova Nouă case, NMB, NMGE, COE, IOA, SD, RMSE, and R metrics confirm agreements between observations and model results.

### 3.1.5 Understanding Model Uncertainties

The identified significant disagreement through statistical metrics in model evaluations, AERMOD against ISCST3, between in-situ monitoring data and dispersion modelling results for both study cases can be attributed to several factors:

Measurement Error: Air quality monitoring data may be susceptible to inaccuracies stemming from instrument calibration, maintenance issues, or environmental factors. Uncertainty in measurement accuracy can consequently propagate to uncertainties in evaluating model performance. Spatial Variability: Air pollutant concentrations can exhibit spatial variance due to factors such as proximity to emission sources, terrain characteristics, and meteorological conditions. Uncertainties may arise if the model fails to adequately capture this spatial variability. Temporal Variability: Air pollutant concentrations also demonstrate temporal fluctuations across various time scales (e.g., diurnal, seasonal). Uncertainties can emerge if the model inaccurately represents temporal trends or fluctuations.

Emission Inventories: Models often depend on emission inventories to estimate pollutant sources. Uncertainties in emission inventories, such as incomplete or inaccurate data on emission sources, can introduce uncertainties into model predictions. Chemical Transformation Processes: Chemical reactions and atmospheric processes can alter pollutant concentrations over time and space. Uncertainties may arise if these processes are not fully represented or understood in the model. Meteorological Inputs: Air quality models typically necessitate meteorological data (e.g., temperature, wind speed, atmospheric stability) as inputs. Uncertainties in meteorological data, such as inaccuracies in weather forecasts or interpolation methods, can impact model predictions.

Model Sensitivity to Input Parameters: Different air quality models may exhibit varying sensitivities to input parameters such as emission rates, meteorological conditions, and boundary conditions. Understanding the sensitivity of the model to these parameters can aid in assessing uncertainties in model predictions. Model Complexity and Assumptions: The complexity of air quality models and the assumptions they entail about atmospheric processes can introduce uncertainties. Simplifications or parametrizations of complex processes may result in uncertainty in model predictions. Interactions Between Pollutants: Pollutants can interact with each other in the atmosphere, leading to intricate chemical reactions and secondary pollutant formation. Uncertainties may arise if these interactions are not fully accounted for in the model.

Uncertainties during the modelling process may stem from calculations of emission factors and random atmospheric instability that could impact local meteorology. The modelling process might not comprehensively capture all potential local sources of pollution, including traffic, residential, industrial, dust, and other emission patterns, whereas in-situ monitoring data reflects a broader spectrum of emission scenarios. The modelling process involves various assumptions and simplifications utilizing mathematical differential equations of atmospheric planetary boundary layer conditions embedded in the dispersion models used, thereby subjecting them to further uncertainties during the quantification of air pollutant concentrations. AERMOD and ISCST3 are both air pollutant dispersion models utilized for assessing atmospheric pollutant dispersion, albeit differing in their underlying algorithms and applications. AERMOD is recognized for its capability to handle complex terrain and meteorological conditions, while ISCST3 focuses on short-term emissions from sources.

### 3.1.6 Impacts and Risks Assessment

Using the Integrated Impact and Risk Assessment (IIRA) methods, the study evaluated the environmental impact and risk associated with personal exposure to hazardous air pollutants.The study identified potentially vulnerable zones influenced by high population density, traffic, and household emissions, with a high probability of personal exposure ranging from 0.12 to 0.3. IIRA quantitatively measured impact and risk by monitoring $PM_{10}$, $PM_{2.5}$, $NO_2$, $SO_2$, and CO on-site. The IIRA results indicate that personal exposure impacts for $PM_{10}$ and $NO_2$ are within permissible limits (100-350), while $SO_2$ and CO may cause discomfort (350-500). Notably, $PM_{2.5}$ poses risks to both humans and the ecosystem (700-1000). The risk assessment under IIRA suggests preventive measures for $PM_{2.5}$ (200-350), monitoring actions for $SO_2$ and CO (100-200), and negligible risk for $PM_{10}$ and $NO_2$ (less than 100).

## 3.2 Response to the Research Questions

The thesis offers a comprehensive perspective on air quality modelling and provides solutions to the overarching research questions of the study. As a result, this original study addresses the following research questions.

- **What are the most critical factors influencing air quality in urban environments and how these factors affect the selection of appropriate air pollutant dispersion models?**

  **The response:** The case studies presented in this thesis have been instrumental in providing precise explanations for the most critical factors influencing urban air pollution. We begin with the case study of Kigali city, where the modelling of key pollutants such as $PM_{2.5}$, $PM_{10}$, CO, $NO_2$, and $SO_2$ focused on traffic emissions. The modelling results highlighted traffic emissions as a significant factor contributing to air pollution in Kigali. Roadside in-situ monitoring confirmed this factor for some air quality stations. However, utilizing an innovative source identification approach developed in this study, we revealed that unpaved roads and residential emissions also played a substantial role in degrading air quality in Kigali, as evidenced in chapters 4 and 5. These crucial factors were influenced by the city's population growth, which increased the demand for more vehicle usage, resulting in higher traffic levels, increased energy consumption, and associated pollution.

  On the other hand, in Moldova Nouă city, the second case study, in-situ monitoring revealed that the farther one moves away from the tailing ponds, the more exposed they become to traffic and residential emissions, in addition to emissions from the tailing ponds themselves. Therefore, emissions from the Moldova Nouă tailing ponds are critical factors both in the vicinity and the broader region surrounding these ponds, as evidenced in chapter 7. It is important to note that urban areas exhibit variations, and investigations should be conducted based on scientific evidence to draw conclusions regarding the critical factors influencing urban air pollution.

Additional factors contributing to air quality variations include geographical and meteorological conditions in the two studied cases, Kigali and Moldova Nouă cities. Kigali is characterized by hilly terrain, as illustrated in terrain elevation maps, which can influence atmospheric circulation and modifications in the planetary boundary layer. Consequently, this geographical diversity leads to variations in air dispersion and complexity in in-situ monitoring, which may result in fluctuating in-situ monitoring data, as evidenced in chapter 6. In the Moldova Nouă case study, the background environment is significantly impacted by air pollution resulting from mining operations dating back to 1974, as well as meteorological factors such as the Mediterranean climate and the presence of a strong, warm, and dry wind known as Coșava. This wind predominantly blows from the southeast toward the northwest, occasionally affecting the eastern regions of Romania. These influences are discussed in detail in Chapter 7 of the thesis, particularly from the perspective of dispersion modeling.

Considering the available information on emissions inventories, meteorological data, and land use datasets in the two study cases, the utilization of air pollutant dispersion models, specifically AERMOD and ISCST3, was a well-suited choice for air quality modeling purposes. Both AERMOD and ISCST3 are user-friendly models capable of handling the dispersion of air pollutants in a variety of terrains, from simple to complex. They incorporate the planetary boundary layer theory through embedded algorithms and are known for their simplicity and international applicability, making them highly recommended for such operations, as depicted in section 2.10 of this thesis.

- **What are the key technical and common considerations for the successively application of air pollutant dispersion models within the context of urban traffic and mining environments?**

**The response:** This thesis delves into various types of air pollutant dispersion models, and the effectiveness of their application in urban areas hinges on the specific model in use. In this context, the focus is on AERMOD and ISCST3 as the employed dispersion models. The technical aspects of adequately applying AERMOD and ISCST3 air pollutant dispersion models revolve around ensuring the reliability of the input data necessary for modelling purposes, as detailed in Figures 2.1 and 2.6. The considerations for applying these models also involve the implementation and supervision of long-term and continuous in-situ monitoring, which plays a crucial role in validating the modelling results. Depending on the complexity and variations in atmospheric conditions, the planetary boundary layer, climate, and weather can impact the accuracy and applicability of the modelled outcomes.

Therefore, as discussed in section 2.5 of this thesis, continuous in-situ monitoring is essential for visualizing trends and validating modelling results. In many developing countries, the primary challenge lies in the inadequate funding available for continuous in-situ monitoring or financing air quality projects. To address this issue, it is imperative to engage various stakeholders, including the government, institutions, and research agencies, in collaborative efforts to overcome these challenges.

## 3.3 General Conclusions

The current increase in the global air quality crisis, driven by industrial activities, mining, transportation, and urbanization emissions, raises significant concerns due to its profound health impacts, including respiratory and cardiovascular issues. Urgent attention is required for comprehensive mitigation strategies to address the escalating personal exposure to air pollution. Moreover, air pollution's contribution to environmental crises, such as climate change, weather variability, acid rain, and ecosystem degradation, underscores the need for immediate action from the scientific community, public awareness campaigns, and policymakers. This doctoral thesis delves into critical aspects of air quality, environmental management, and the risks and impacts of human exposure to air pollutants. Focusing on two distinct study cases: One in Kigali, Rwanda, investigating urban air quality amidst growing traffic emissions, and the other in Moldova Nouă tailings ponds in south-west Romania, examining air quality dynamics in an mining environment via wind erosion.

Comprehensive in-situ monitoring campaigns, involving a network of air quality monitoring stations and dispersion modelling approaches, were conducted for both case studies. Data collection methods included simultaneous real-time measurements of $PM_{2.5}$, $PM_{10}$, $NO_2$, $SO_2$, and CO, alongside local meteorological parameters and traffic volume in Kigali, Rwanda. Additionally, simultaneous real-time measurements of $PM_{10}$ from mining activities in Romania were conducted. Modeling methods were examined by applying Gaussian-plume dispersion models, namely the American Meteorological Society and Environmental Protection Agency Regulatory Models (AERMOD) version 10.2.1 and the Industry Source Complex Short-Term version 3 (ISCST3). The models' reliability was assessed using statistical metrics of model performance evaluation. Characterization of further potential emission inventories of air pollutants was made through mathematical functions that give three-dimensional bivariate polar plots of pollutant concentration under the dispersion perspective. The influence of topographic features on the dispersion of air pollutants was examined through the dispersion modeling perspective under different digital elevation models (DEMs). The study developed and applied a systematic method that analyses and quantifies the effects of wind erosion on the emission rate (both horizontal and vertical fluxes) of $PM_{10}$ from the Moldova Nouă tailings ponds. The study proposes using the Integrated Impact and Risk Assessment (IIRA) methodology to evaluate the impact and risk of human exposure to air pollutants.

Results include modelled dispersion maps and the identification of spatial and temporal variation trends of air pollutant concentrations for both case studies. The overall results highlight significant air quality challenges in urban areas of Rwanda, primarily driven by traffic emissions, with a particular focus on pollutants such as particulate matter ($PM_{2.5}$, $PM_{10}$), nitrogen dioxide ($NO_2$), sulfur dioxide ($SO_2$), and carbon monoxide (CO). Statistical metrics suggest that the high-resolution choice of DEM significantly impacts the accuracy of the model predictions, while the upslope features of complex topography create barriers for airflow affecting air pollutants to accumulate in low-lying areas. The study identified potentially vulnerable zones influenced by high population density, traffic, and household emissions, with a high probability of personal exposure ranging from 0.12 to 0.3. The results from three-dimensional bivariate plots confirm that deteriorating air quality is primarily influenced by local topography, dust, traffic, and household emissions in Rwanda. The IIRA results indicate that personal exposure to $PM_{10}$ and $NO_2$ remains within acceptable limits (100-350), while $SO_2$ and CO levels may cause discomfort (350-500). In contrast, $PM_{2.5}$ poses significant risks to both human health and the ecosystem (700-1000). The risk assessment based on IIRA suggests the need for preventive measures for $PM_{2.5}$ (200-350), ongoing monitoring for $SO_2$ and CO (100-200), and negligible risk for $PM_{10}$ and $NO_2$ (less than 100) in Rwanda. In Moldova Nouă Tailings Ponds south-west of Romania, the study elucidates the impact of mining activities on local air quality, emphasizing $PM_{10}$. The dispersion of $PM_{10}$ was observed to extend into

Moldova Nouă city, reaching close to the border with Serbia. The study's findings suggest that the accumulation of $PM_{10}$ is primarily caused by the gathering of air mass due to strong winds passing over heavily burdened landfills and ponds, significantly contributing to air pollution in the Moldova Nouă region. The $PM_{10}$ hotspot was investigated in the vicinity of the tailings ponds, revealing the following values: an annual mean concentration of 115.5 $\mu$g m$^{-3}$, an annual horizontal flux of 63.3 $\mu$g m$^{-2}$ s$^{-1}$, and an annual vertical flux of 3.0 $\mu$g m$^{-2}$ s$^{-1}$.

This thesis concludes that both urban traffic emissions in Rwanda and mining activities in Romania exert a significant influence on local air quality. The results underline the necessity for targeted air quality management strategies and policies in these regions, advocating for measures like emission reductions and thoughtful land-use planning. Additionally, the research underscores the crucial role of comprehensive air quality modelling and monitoring frameworks to facilitate evidence-based decision-making. The study highlights the impact of complex topography on air pollutant dispersion and emphasizes the practical application of dispersion models in areas where in-situ monitoring is challenging or unfeasible. This research contributes valuable insights to inform the integration of models into policymaking in similar regions. By providing a comprehensive analysis of challenges associated with urban traffic emissions and mining-related pollution, this study enhances understanding of the sources and dynamics of air pollutants.

## 3.4 Original Contributions of the Thesis

In addition to the 7 original scientific peer-reviewed articles published based from this thesis, the objectives of this work have been effectively achieved, resulting in significant original contributions focusing on the identified research gaps in the field of air quality through in-situ monitoring and dispersion modelling approaches. As a result, the following specific original contributions have emerged from this thesis.

- This thesis has made an original contribution by providing evidence to inspire further scholars to address gaps in air quality research, particularly in developing countries and vulnerable regions globally affected by air pollution.

- This thesis has addressed the identified gaps in air quality research previously conducted in the East African region, where no prior research had introduced air pollutant dispersion models. As a result, this thesis contributes to the advancement and application of air pollutant dispersion models in air quality studies.

- The detailed and applied methodology in this thesis has furnished information on air pollutant concentration levels, sources, and potential contributors to air quality degradation in an urban environment. This information, in turn, serves as a foundational resource for policymakers and decision-makers, enabling them to establish environmental protection and management measures to mitigate public exposure to harmful air pollutants.

- While Rwanda's location in the heart of the East African Rift Valley exposes it to natural sources of air pollution, such as volcanic eruptions and dust storms, this thesis has made a noteworthy contribution as the first study in Africa to assessing the impact of local topography on the dispersion of air pollutants. It reveals that the up-slope or hilly features of complex topography serve as barriers for airflow, leading to the accumulation of air pollutants in low-lying areas. Consequently, this thesis aids in the identification of areas that require in-situ monitoring and management interventions, providing valuable insights for policymakers, urban planners, and regional environmental managers.

- This thesis utilized long-term and continuous in-situ monitoring carried out at various air quality stations. The data from in-situ monitoring can play a crucial role in ensuring air quality and prioritizing the health of residents within the respective areas. It also serves as valuable input for the establishment of air quality standards and the formulation of pollution regulations and policies in both urban and mining environments.

- The quantification of traffic emission factors for $PM_{2.5}$, $PM_{10}$, CO, $NO_2$, and $SO_2$ air pollutants in this study provides a comprehensive overview of the contributions of various vehicle categories, road characteristics, and energy usage in the transportation sector to air pollutant emissions. Consequently, the information derived from these estimated traffic emission factors is a valuable resource for policymakers and decision-makers in the formulation of city master plans and road improvement strategies. This thesis introduces the methodology for quantifying street and road emission factors, marking its first application in Rwanda. As a result, the thesis contributes to the foundation for using this established method in other street and road networks within the city. This approach can also prove instrumental in setting roadside exposure limits for air pollutants.

- Rwanda, the East African countries, and several other countries, along with the World Health Organization (WHO), up to currently depend on satellite observations and short-term monitoring for generating air quality reports. However, these reports may be subject to underestimation or additional fluctuations or uncertainties. Therefore, this thesis, through its developed methodology, underscores the necessity of long-term and continuous in-situ monitoring and air quality modelling as essential components in the generation of more accurate and reliable air quality reports.

- This thesis has introduced a systematic approach to quantify emission factors in the mining environment, particularly those influenced by wind erosion, for the first time in the Moldova Nouă tailings ponds. Consequently, the results offer valuable insights for mitigating the deterioration of air quality resulting from mining processes and understanding the potential environmental impact of future mining activities.

- The urgency of addressing the risks and consequences of personal exposure to air pollutants was among specific objectives of this thesis. Through the Integrated Impact and Risk Assessment (IIRA) methodology for the first time in Africa, specifically to assess the impacts and risks associated with personal exposure to air pollutants. The thesis findings present evidence-based recommendations useful for residents, policymakers, stakeholders, and urban planners. These recommendations serve as a guide for implementing strategic mitigation measures in response to the identified risks and effects of personal exposure to air pollutants, emanating from both natural and anthropogenic sources.

## 3.5 Limitations of the Study

This study has contributed to a comprehensive understanding of quantifying air pollutants through a combination of in-situ monitoring and dispersion modelling in Kigali, Rwanda, and Moldova Nouă, Romania. Moreover, it has addressed knowledge gaps by demonstrating the applicability of air pollutant dispersion models as supportive tools, particularly in areas where in-situ monitoring proves complex or nearly impossible, a common scenario in developing countries. However, it's worth noting that the study encountered limitations, primarily linked to insufficient air quality monitoring stations.

Therefore, it would have been highly valuable to expand the research area to encompass numerous simultaneous in-situ monitoring points covering both rural and urban areas.

## 3.6 Recommendations for Future Works

The methodology applied in this study confirms suggestions as guidance for future work to improve air quality within developed and developing countries through understanding and presenting the dispersion of air pollutants in the atmosphere.

- For future research in both developed and developing countries, it is advisable to expand the approach used to encompass not only urban but also rural environments. This broader perspective can investigate the contributions of numerous local emission inventories. Data from both rural and urban areas can provide a comprehensive understanding of air quality at local and national levels, which is essential for informing the development of air quality regulations, reports, and innovative policies for environmental management.

- In this study, we investigated air pollutant dispersion using AERMOD and ISCST3 models, emphasizing the significant impact of complex topography on pollutant dispersion. We strongly recommend future research to employ additional specialized models, such as SERVEX, to further enhance understanding in this area.

- In this study, mathematical models revealed that the accumulation of a windy air mass over Moldova Nouă Tailings Ponds increases $PM_{10}$ levels horizontally more than vertically. Future research should incorporate practical methods like wind tunnel experiments for validation. Logistic constraints posed challenges in monitoring the targeted sources, urging a strong recommendation for long-term monitoring (at least one year) in future studies to validate the modelling results.

# Chapter 4

# Data Analysis Presentation and Interpretation

In this chapter, the culmination of extensive research findings is presented and dissected. Through a comprehensive array of tables and figures, this section delves into the empirical outcomes obtained from rigorous experimentation and data collection. Each table and figure serves as a visual representation of the core discoveries, offering insights into the patterns, trends, and correlations within the gathered information. Furthermore, an in-depth analysis accompanies these visuals, unravelling the implications and significance of the findings, thereby laying the groundwork for a nuanced understanding of the research's outcomes.

**Table 4.1:** The reliability of AERMOD through statistical indexes of model performance evaluation using SRTM3 (global 90m)

| **Station** | **FB** | **NMSE** | **MG** | **MB** | **NMB** | **VG** | **FAC2** |
|---|---|---|---|---|---|---|---|
| A | 0.10 | 0.01 | 1.11 | -2.45 | -0.10 | 1.01 | 0.90 |
| B | 0.69 | 0.53 | 2.05 | -23.83 | -0.51 | 1.67 | 0.49 |
| C | 0.69 | 0.53 | 2.04 | -23.80 | -0.51 | 1.67 | 0.49 |
| D | 0.46 | 0.23 | 1.60 | -13.70 | -0.38 | 1.25 | 0.62 |
| E | 0.50 | 0.27 | 1.67 | -15.25 | -0.40 | 1.30 | 0.60 |
| F | 0.71 | 0.58 | 2.10 | -25.12 | -0.52 | 1.74 | 0.48 |

**Table 4.2:** Descriptive statistics of emission rates and wind erosion profiles over the Year 2021 in Moldova nouă tailings ponds

| Parameter [unit] | Mean | SD | SE | CV | Min | Q1 | Q2 | Max |
|---|---|---|---|---|---|---|---|---|
| Wind speed U, [$m\ s^{-1}$] | 4.87 | 2.66 | 0.061 | 0.84 | 0.1 | 1 | 4.8 | 12.8 |
| Shear Velocity U*, [$m\ s^{-1}$] | 0.15 | 0.13 | 0.003 | 0.84 | 0.005 | 0.05 | 0.23 | 0.6 |
| Horizontal Flux E, [$\mu g\ m^{-2}\ s^{-1}$] | 63.3 | 85.67 | 1.973 | 1.18 | 1.67 | 20.98 | 92.32 | 598.61 |
| Vertical Flux F, [$\mu g\ m^{-2}\ s^{-1}$] | 3 | 4.02 | 0.093 | 1.18 | 0.08 | 0.99 | 4.34 | 28.11 |

**Table 4.3:** IIRA analysis and in-situ monitoring at each station (from Station A through F) (-stand for missing concentration)

| Items | Pollutant | A | B | C | D | E | F |
|---|---|---|---|---|---|---|---|
| Environmental risk (ER) | $PM_{10}$ | 71.9 | 88.2 | 87.5 | 69.1 | 72.4 | 92.1 |
| | $PM_{2.5}$ | 123.4 | 230.0 | 229.6 | 179.9 | 187.6 | 236.3 |
| | $NO_2$ | - | 60.2 | 45.7 | 47.5 | - | - |
| | $SO_2$ | - | 64.4 | 110.6 | - | - | 114.7 |
| | CO | - | 97.6 | 114.3 | - | - | 133.4 |
| Environmental impact (EI) | $PM_{10}$ | 266.2 | 326.6 | 324.2 | 255.8 | 268.1 | 341.0 |
| | $PM_{2.5}$ | 457.2 | 851.7 | 850.4 | 666.3 | 694.8 | 875.1 |
| | $NO_2$ | - | 223.0 | 169.4 | 176.1 | - | - |
| | $SO_2$ | - | 238.4 | 409.6 | - | - | 424.7 |
| | CO | - | 361.4 | 423.4 | - | - | 494.2 |
| Environmental Quality Factor parameter (Q) | $PM_{10}$ | 1.0 | 0.8 | 0.8 | 1.1 | 1.0 | 0.8 |
| | $PM_{2.5}$ | 0.6 | 0.3 | 0.3 | 0.4 | 0.4 | 0.3 |
| | $NO_2$ | - | 1.2 | 1.6 | 1.6 | - | - |
| | $SO_2$ | - | 1.1 | 0.7 | - | - | 0.6 |
| | CO | - | 0.8 | 0.6 | - | - | 0.6 |
| In-situ monitored concentration (Co) in $\mu g\ m^{-3}$ | $PM_{10}$ | 43.7 | 53.6 | 53.3 | 42.0 | 44.0 | 56.0 |
| | $PM_{2.5}$ | 25.0 | 46.6 | 46.6 | 36.5 | 38.0 | 47.9 |
| | $NO_2$ | - | 20.4 | 15.5 | 16.1 | - | - |
| | $SO_2$ | - | 34.8 | 59.8 | - | - | 62.0 |
| | CO | - | 5277.0 | 6182.0 | - | - | 7216.0 |

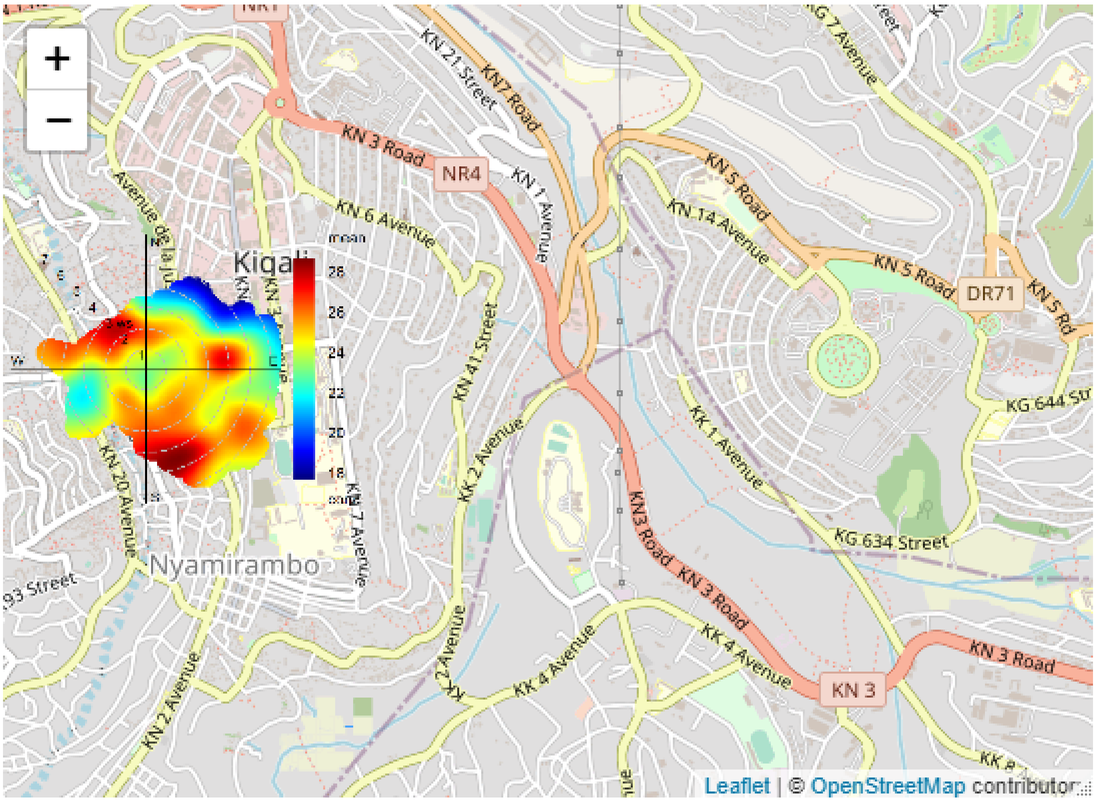


**Figure 4.1:** Sample: Mapping of Identified $PM_{2.5}$ Hotspots in Kigali City

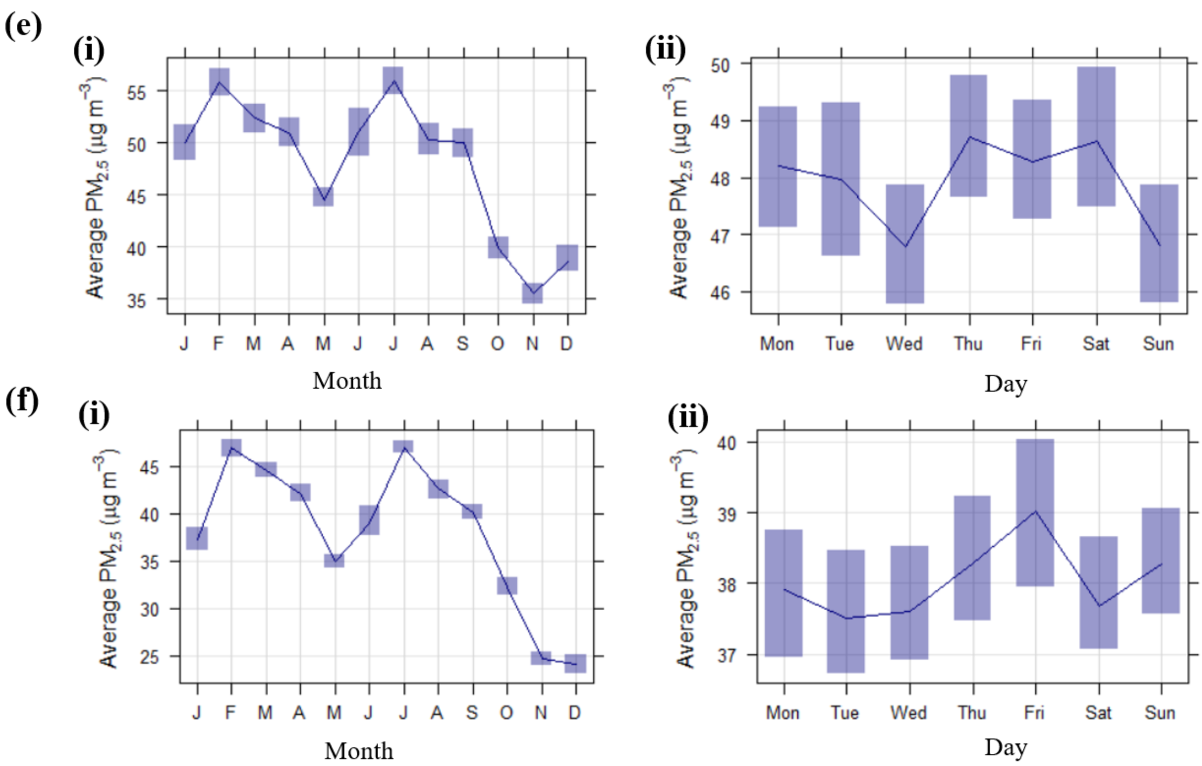


**Figure 4.2:** Smooth temporal trends of $PM_{2.5}$ at discrete receptor R3

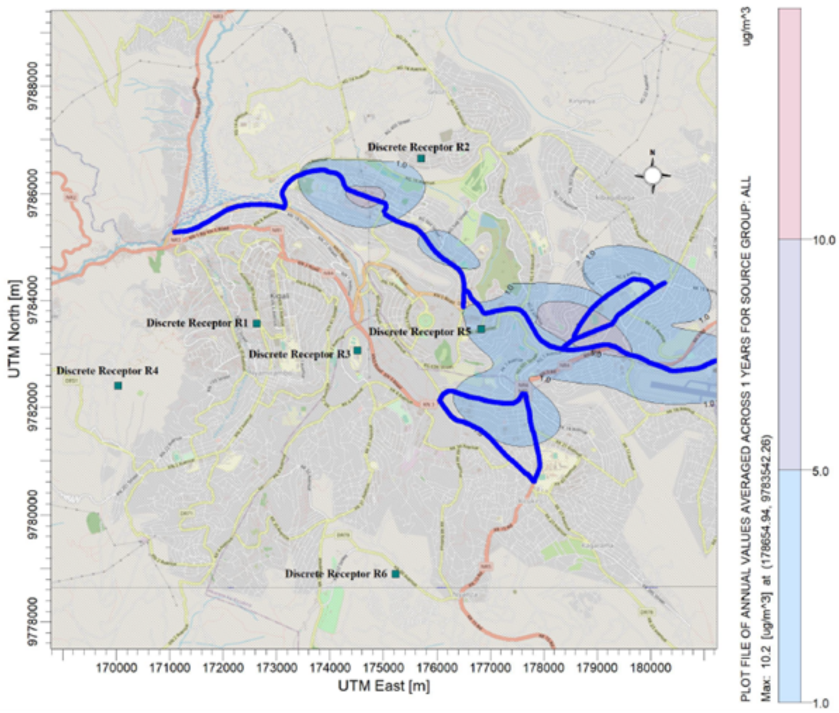


**Figure 4.3:** Spatial maps of annually maximum ground-level concentration for $PM_{10}$ with the AERMOD dispersion model

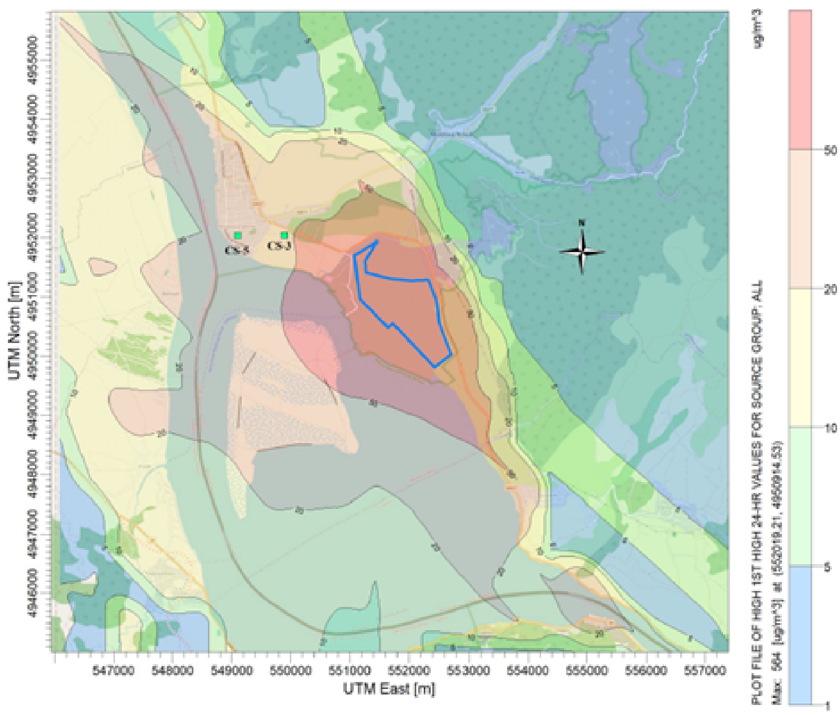


**Figure 4.4:** Modelled spatial dispersion maps of the daily maximum ground-level concentration of $PM_{10}$ for the year 2021 with the AERMOD dispersion model (Török et al., 2024)

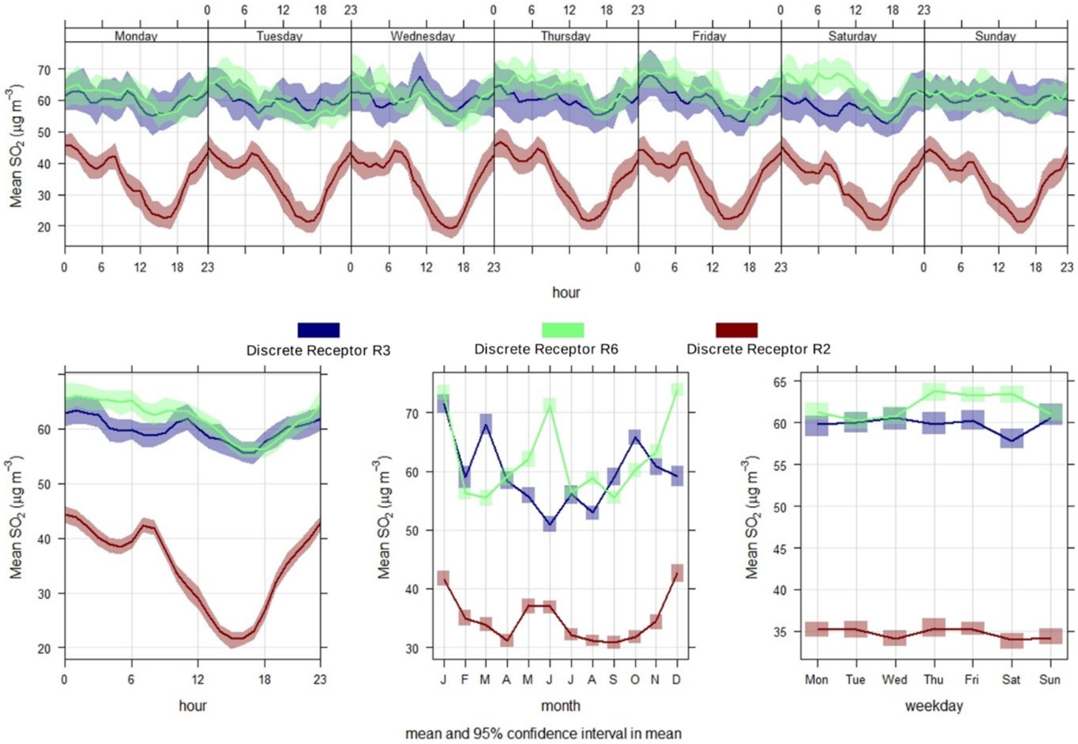


**Figure 4.5:** The temporal variability trends of in-situ observation for $SO_2$ over 2021 (Irankunda et al., 2022)

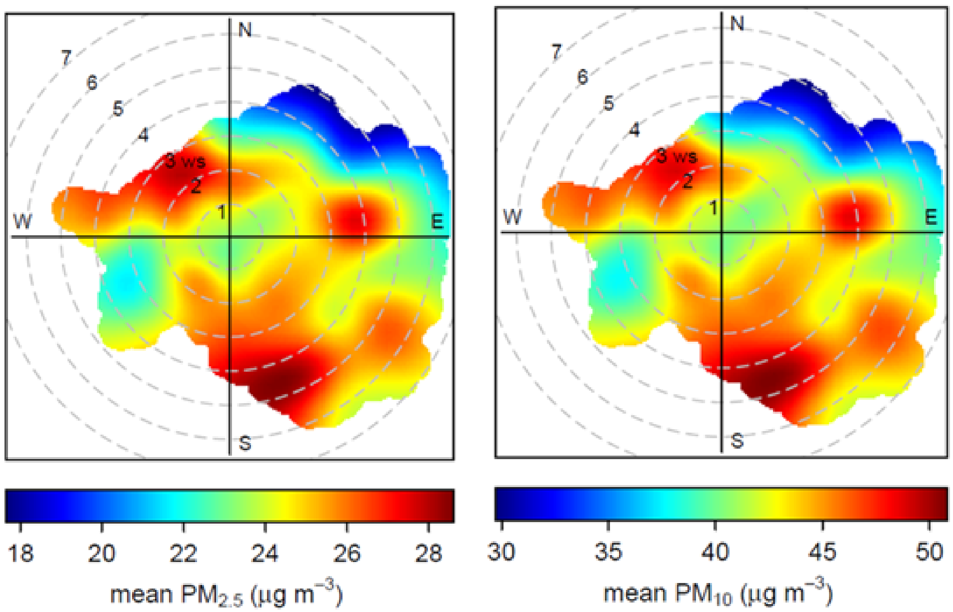


**Figure 4.6:** Bivariate polar plots of $PM_{2.5}$ and $PM_{10}$ at discrete receptor R1

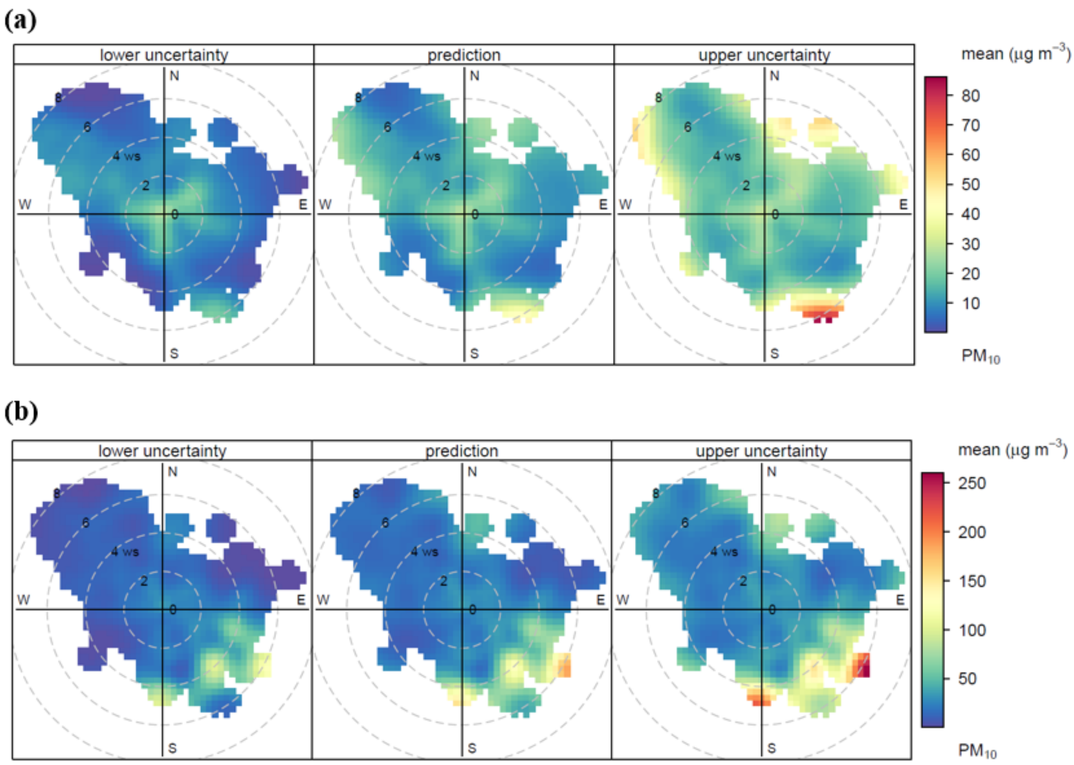


**Figure 4.7:** Dispersion of Air pollution at three level of uncertainty lower, middle and upper for CS5 (a) and CS3 (b) air quality station (Török et al., 2024)

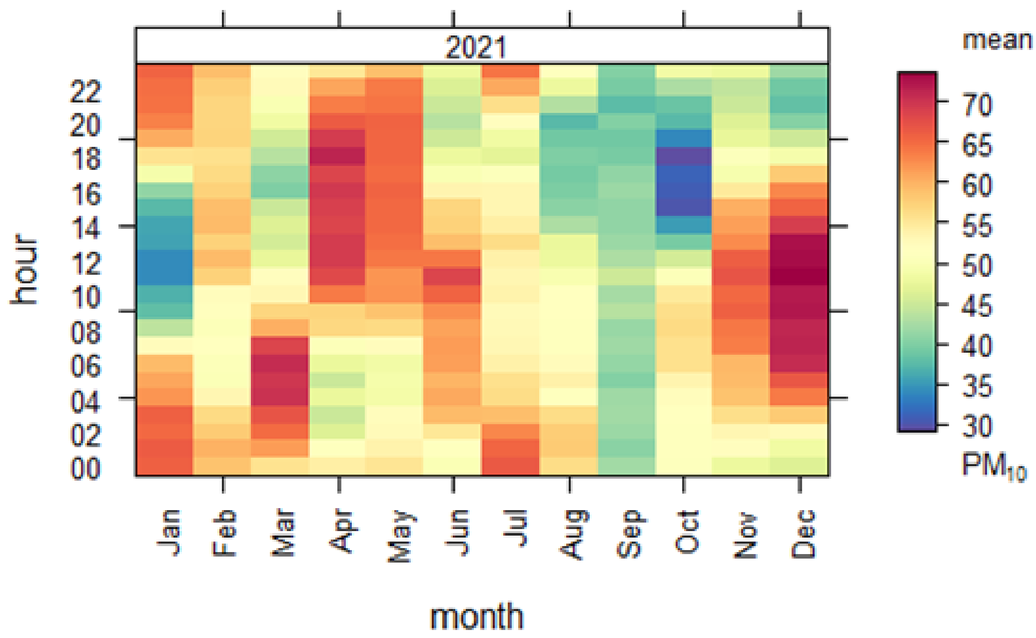


**Figure 4.8:** The trend heat map of $PM_{10}$ at discrete receptor R3

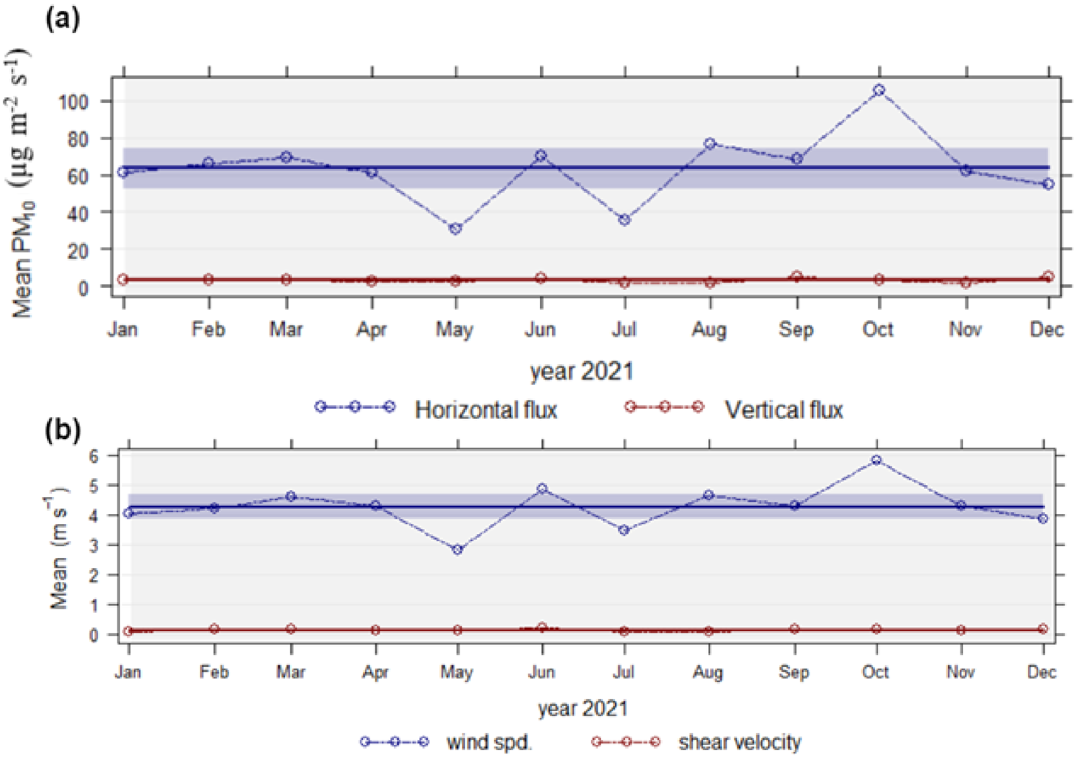


**Figure 4.9:** Monthly variation trends of horizontal and vertical fluxes of $PM_{10}$ (a) and Shear velocity and wind speed (b) over 2021 in Moldova nouă tailings ponds (Török et al., 2024)

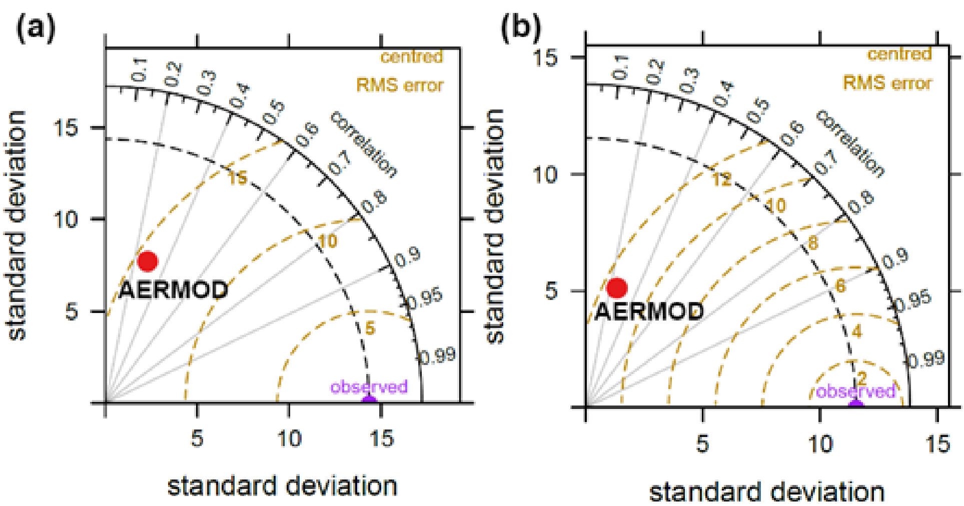


**Figure 4.10:** Taylor diagram for CS3 (a) and CS5 (b) air quality stations (Török et al., 2024)

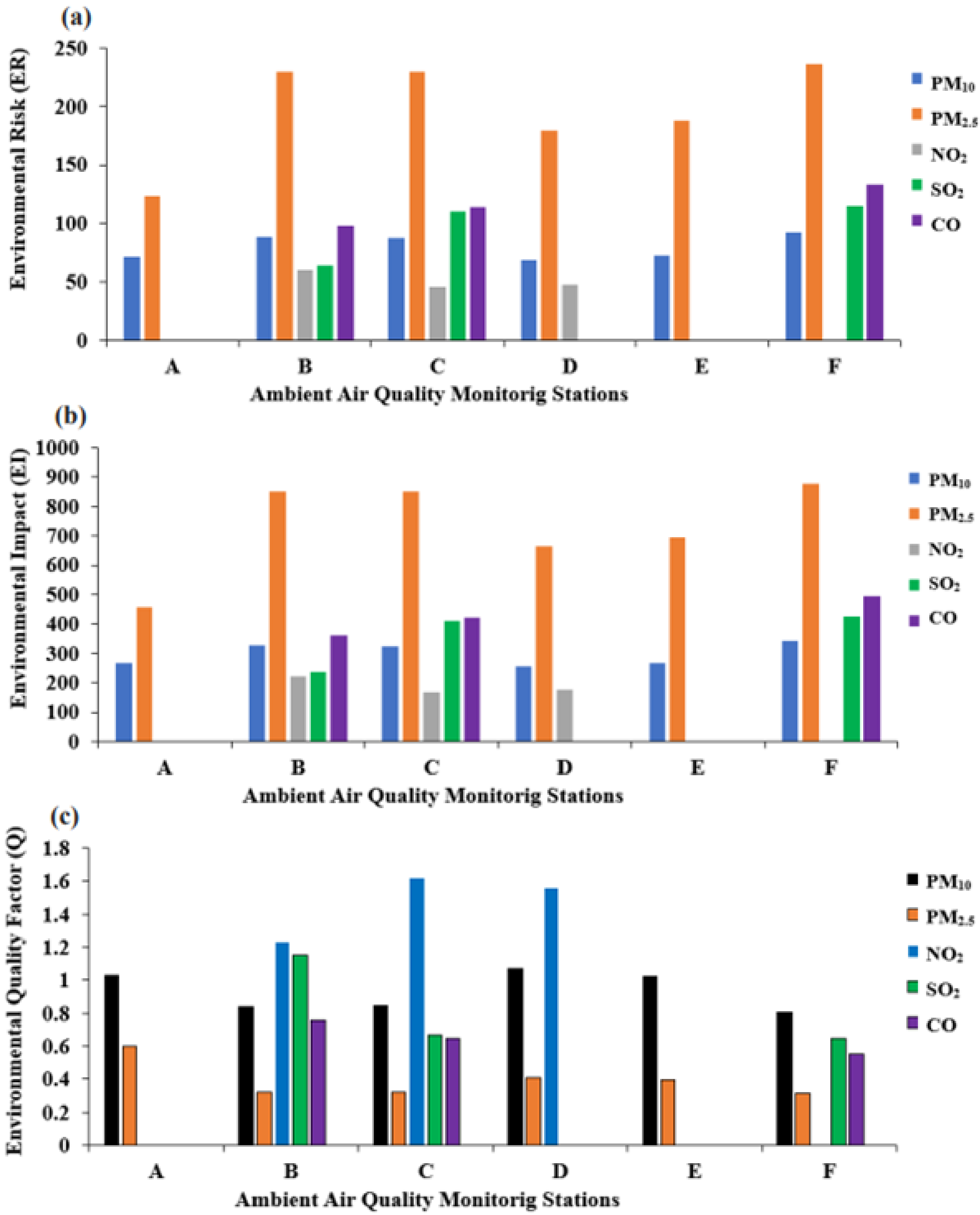


**Figure 4.11:** Quantitative assessment of environmental risk (a), impact (b), and quality factor (c) for each air pollutant.

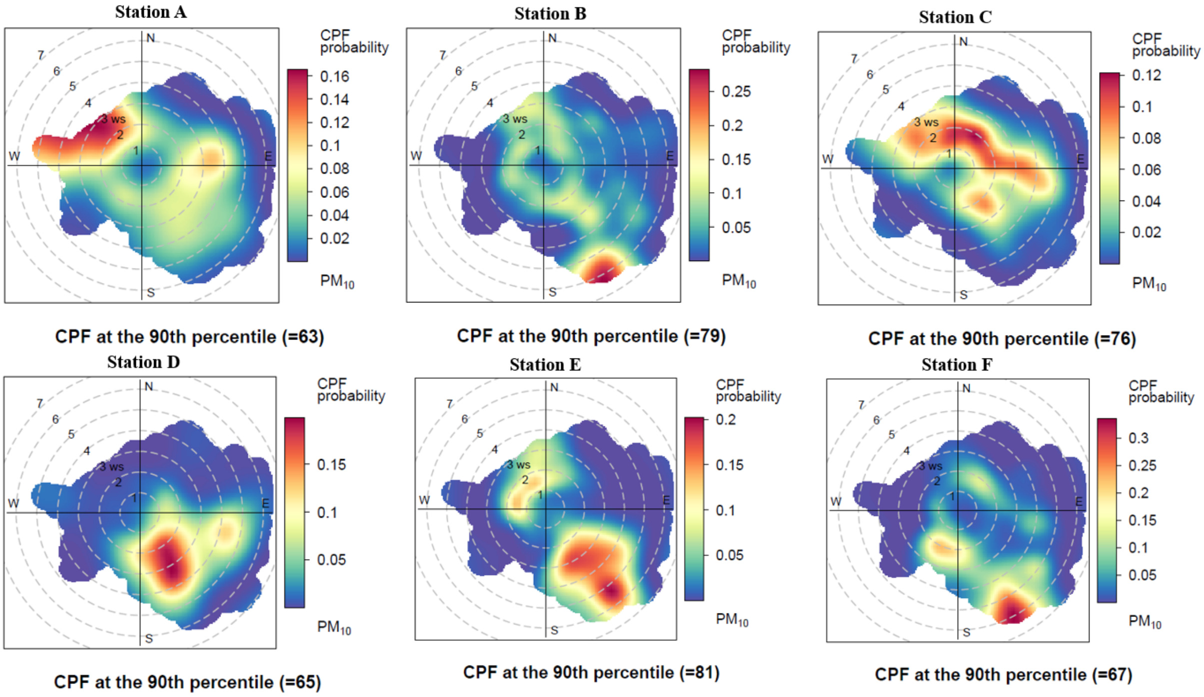


**Figure 4.12:** Conditional Probability Functions (CPF) for $PM_{10}$

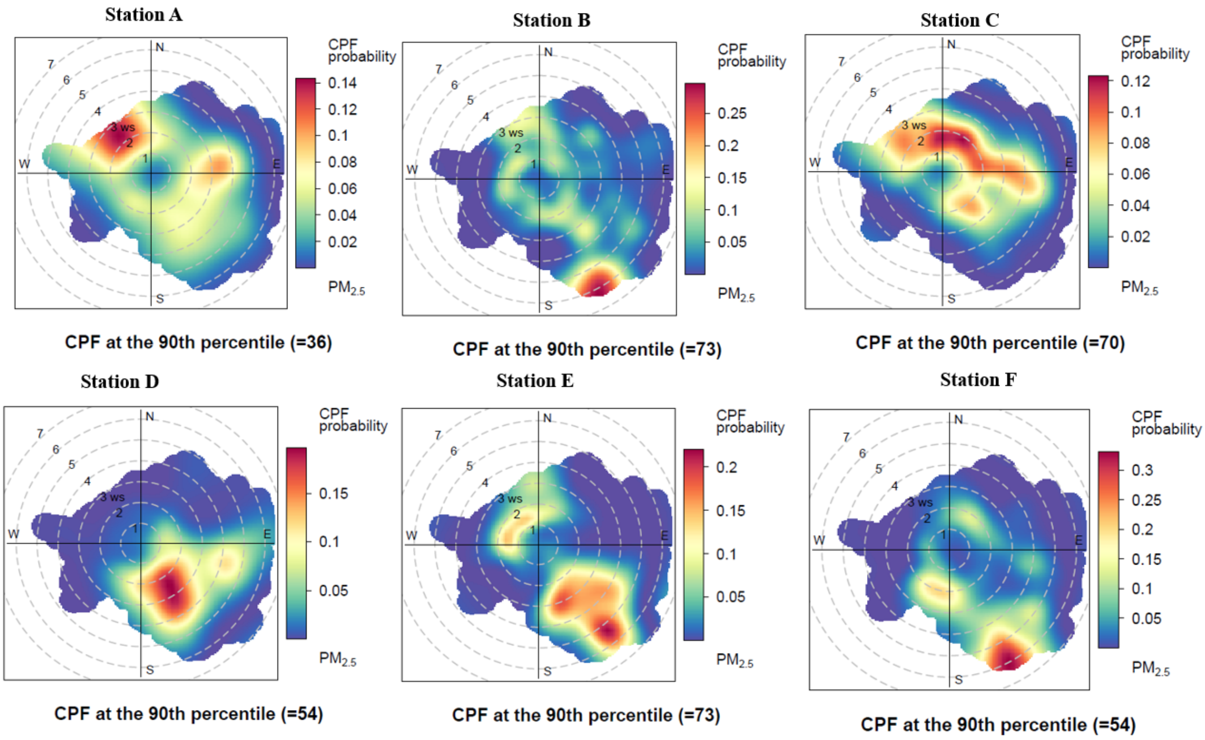


**Figure 4.13:** Conditional Probability Functions (CPF) for $PM_{2.5}$

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