IMPACT ASSESSMENT OF COMBINED HEAT AND POWER PLANTS (CHPPs) IN ALMATY: PM2.5 SIMULATIONS OVER THE CITY USING WRF-AERMOD MODELS WITH VERIFICATION USING GROUND LEVEL MEASUREMENTS

Theophilus Bright Ogbuabia, Bachelor Degree in Civil Engineering

Submitted in fulfilment of the requirements for the degree of Master of Science in Civil & Environmental Engineering

NAZARBAYEV UNIVERSITY

School of Engineering and Digital Sciences
Department of Civil & Environmental Engineering
Nazarbayev University

53 Kabanbay Batyr Avenue,
Astana, Kazakhstan, 010000

Supervisor: Ferhat Karaca, Associate Professor ____________________

Co-supervisors: Mert Guney, Assistant Professor
Nassiba Baimatova, Associate Professor

Date of Completion 15/03/2023

Declaration Form

DECLARATION

I hereby, declare that this manuscript, entitled "Impact Assessment of Combined Heat And Power Plants (Chpps) In Almaty: Pm2.5 Simulations Over The City Using WRF-AERMOD Models With Verification Using Ground Level Measurements", is the result of my own work except for quotations and citations which have been duly acknowledged.

I also declare that, to the best of my knowledge and belief, it has not been previously or concurrently submitted, in whole or in part, for any other degree or diploma at Nazarbayev University or any other national or international institution.

Name: Theophilus Bright Ogbuabia

Masters Student

Date: 15/03/2023

Acknowledgement

I appreciate the quality of support I got from Professor Ferhat Karaca throughout the research period. I also appreciate the support of Professors Mert Guney and Nazassiba Baimatova in putting this research owkr together.

I appreciate the leadership of the department of civil and environmental engineering, School of Engineeering and Digital Sciences, Nazarbayev University, for the guidance, assistance and faciliies to carry out this research.

Lastly, I appreciate the support from my friends and family.

Table of Contents

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Air pollution in Kazakhstan has been a major issue over the last few decades as the country's industrial sector is experiencing a major boom. Kazakhstan's largest and busiest city, Almaty, has been ranked by WHO among the most polluted cities in the world. One of the major air pollutants is $PM_{2.5}$, with an average yearly concentration that is about six times higher than the WHO recommended value of 5μg/m^3. Several attempts have been made by the government to curb the air pollution threat in the country, especially in its busiest city, including introducing buses for public transportation that are powered by solar and investing in solar energy and other green energy sources. However, these efforts have not yielded enough results. Hence, there is a need to investigate the various sources of $PM_{2.5}$ so as to direct the preventive efforts of the government to the major sources of these pollutants, which will be more effective in curbing air pollution. One such source is the power plants in Almaty. One of the major sources of $PM_{2.5}$ is the combined heat and power plants (CHPP) which is a system of co-generation of electricity and power. About 80% of power generation in Almaty is done by CHPP, which uses coal as its major source of fuel. In this study, the emissions of the major power plants in Almaty, CHPP-2 and CHPP-3, were used to perform a simulation using the US Environmental Protection Agency's (EPA) approved air dispersion model (AERMOD) and the weather research and forecasting model (WRF). Necessitated by the unavailability of emission data from the power plants, two scenarios of the simulation were done: controlled and uncontrolled. In the controlled and uncontrolled scenarios, the emissions from the CHPPs were calculated using the controlled and uncontrolled emission factors from AP-142 table 1.1-7. The results showed that if the control mechanism in the CHPP functions at maximum efficiency, the impact of the CHPP emission on the total concentration of emission will be negligible, which is about 6% on average, while for an uncontrolled CHPP, the emission will be contributing about 30% on an average to the total $PM_{2.5}$ concentration in Almaty.

Key *Words: Air Pollution, Weather Research and Forecasting Model, Air Dispersion Model, $PM_{2.5}$, Combined Heat and Power Plants (CHPP)*

CHAPTER ONE

1.0 INTRODUCTION

Over the last decade, concerns have exploded over developing countries in Central Asia since the atmospheric particulate matter that has an aerodynamic diameter below 2.5 µm ($PM_{2.5}$) was classified as First-grade carcinogen risk by the World Health Organization (WHO) in 2013 (IARC, 2013). Much research that has been carried out in this regard has shown that the health impact of $PM_{2.5}$ is deserving of high-level attention.

The exponential increase in energy consumption in the forms of heat and electricity in Almaty has led to a poorer Air Quality Index (AQI) in the city. According to a Cambridge university press release in 2014, “there has been a decrease of industrial greenhouse gas emission in the member countries of the Organization for Economic Co-operation and Development (OECD), while the region of Central Asia has experienced an increase.” In 2019, Kazakhstan was ranked 29th as one of the most polluted countries in the world (EIA, 2019), with the most polluted city being Almaty. Due to the lack of monitoring systems in most cities, their air pollution rankings are unknown. According to EIA’s report, the two major energy generation methods in Kazakhstan are thermal generation and the combined heat and power plants. As the world transitions into cleaner energy generation and consumption, Kazakhstan is not left out as the government plans that by 2050, more than half of its energy generation method will be non-thermal.

Co-generation of energy is a promising technology in the energy sector due to its low carbon emission. Combined heat and power plant system allows electricity and heat production simultaneously. According to the Environmental Protection Agency (EPA), CHP can achieve an efficiency above 80% as compared to 50% of thermal generation. The benefits of CHPs include environmental benefits such as low emissions of greenhouse gases such as carbon dioxide (CO_2), oxides (NO_x), and sulfur dioxide (SO_2) (Choi *et al.*, 2019). Energy production costs are also lower than conventional energy generation methods. While there are other sources of air pollution in Almaty, combined heat and power plants still contribute significantly to the total $PM_{2.5}$ concentration in Almaty (Kerimray *et al.,* 2018). In 2021, the CHPs plant in Almaty had about 30% of the total energy production in the city. Hence, there is a need to quantitatively assess the impact of CHPs in Almaty in terms of $PM_{2.5}$ concentration.

The main objective of this project is to assess the impact of the current PM2.5 emissions from CHPs in Almaty using simulation from the community air quality model together with the weather research and forecasting model.

1.1 Research Objectives

The high concentration of air pollutants in Almaty city has become a major concern for the health and well-being of its citizens. The increase in air pollution has been linked to a wide range of health problems, including respiratory illnesses, cardiovascular disease, and even premature death. As such, it is vital to conduct a thorough investigation to determine the primary sources of the pollutants and take necessary measures to reduce their emissions. The sources of atmospheric particles in Almaty city can be both natural and human-made. Natural sources include dust and soil erosion, while human-made sources include transportation, industrial activities, and the burning of fossil fuels. Identifying the primary sources of pollutants will require a comprehensive approach that involves data collection, analysis, and modeling. By doing so, it will be possible to develop effective strategies and policies to mitigate the risks posed by air pollution and protect the health of Almaty's inhabitants. Thus, the rise in air pollution in Almaty city, particularly the high concentration of $PM_{2.5}$, requires urgent attention. A thorough investigation is needed to identify the sources of natural and human-made pollutants to reduce their emissions and protect the health of the city's residents. Hence, the main objectives of this research are:

- To assess the impact of the emissions of CHPs in Almaty with respect to the concentration of $PM_{2.5}$
- To carry out an assessment of the impact of the emissions from CHPs on the weather during the peak level of $PM_{2.5}$ concentration.

CHAPTER TWO

2.0 LITERATURE REVIEW

Since the beginning of the industrialization era, air pollution has been a major concern to governments of nations because the increase in industrial activities results in poor air quality due to the toxic emissions from industries. Studies have shown that in the last 20 years, human exposure to pollutants such as Ozone (O_3), Nitrogen (NO_2), and particulate Matter ($PM_{2.5}$) has increased significantly in many parts of the world, including Africa, Central Asia, and parts of Europe (Sicard et al., 2023). Many air pollution control strategies have been developed to curb the adverse effect of air pollution on human health, yet the mortality rate attributable to pollutants exposure has increased in recent years (Bu *et al.* 2021).

Air pollution in Kazakhstan has been a major issue of concern to the people and the government. Many studies have been conducted to ascertain the nature and extent of pollution caused by various sources of pollutants including power plants, vehicle emissions, production industries, and indoor coal combustion. However, air pollution simulation is relatively new in Kazakhstan.

Carlsen *et al.* (2013) carried out an assessment of the air pollution in Almaty focusing on traffic as a major source of air pollution using the Driving forces, Pressures, State, Impact, Responses (DPSIR) approach and found that $PM_{2.5}$ is one of the major components of the pollutants in Almaty. The health effect that $PM_{2.5}$ poses to the inhabitants of a geographical location cannot be overestimated. Hence, an in-depth study of the source and dispersion of $PM_{2.5}$ in Almaty is necessary. From the study carried out by Assanov *et al.* (2021) on the recent trends in the emission from industries such as power plants and metallurgical companies, it was observed that some of the industrial cities in Kazakhstan, including Almaty, had a higher level of air pollution when compared with the limit set by the Air Pollution Index, 2019 which indicates that the increase in industrialization and power consumption in these cities also increases the risk of poor air quality.

A relationship between the population growth in Astana, Kazakhstan's capital city, the rapid growth in energy consumption, the increased vehicular usage, and the steady decline in the quality of air was established by Kerimray *et al.* (2017) in a study on air pollution in Astana. This scenario can also be said for Almaty, as it has seen a rapid decline in air quality over the last decade, which can also be attributed to an increase in the city's population. In the study of the recent trends and impacts of major urban air pollutants on the health of the inhabitants of Kazakhstan, Kerimray *et al.* (2020) analyzed data from the national air pollution monitoring network on the deaths attributable to the exposure of $PM_{2.5}$. They concluded that about 8,134 deaths could be associated with exposure to $PM_{2.5}$. To show that various anthropological activities, such as driving cars and running large production industries, affect a city's air quality. Kerimray *et al.* (2020) analyzed the various concentrations of different pollutants during the COVID-19 lockdown when the volume of traffic was at its lowest, and various industries were not functioning and found that the concentrations of pollutants such as $PM_{2.5}$, CO, NO_2, and O_3 all had a significant reduction during the period of the lockdown. While reducing or eradicating some anthropological activities is not possible, there is a need to control various industrial activities as these significantly affect air quality and affect people's health.

Source apportionment of pollutants has not gained the attention it deserves in Central Asian cities, including Astana. This accounts for the ineffectiveness of the control measures that the people in major cities experience.

Almeida *et al.* (2020) carried out a source apportionment of $PM_{2.5}$ concentration in 16 Central Asian cities, including Kazakhstan's busiest city, Almaty. The summary of their findings is shown in Table 1. From the results, Almeida *et al.* (2020) concluded that traffic has the highest source of $PM_{2.5}$, with about 32% of the total concentration, while coal combustion has only 8%. More detailed research is needed to compare results for better accuracy.

Table 2.1: Showing percentage contribution from various sources. Source of data: Almeida, S.M. et al. (2020) "Ambient particulate matter source apportionment using receptor modeling in European and Central Asia Urban areas,"

Name of Pollutants	Percentage contribution
Secondary sulfate	20%
Unaccounted Mass	13%
Traffic	32%
Industry	5%
Coal Combustion	8%
Soil	11%
Salt	8%
Other	3%

Air pollution modeling is a fast-growing research area that is gaining attention among environmental engineers and scientists because it allows researchers to understand various pollution scenarios, quantitatively investigate the impact of various sources of pollutants, and test different theories. Modeling can also help us to understand the interaction between weather (meteorology) and ambient air pollution (Aeroqual, 2020).

Air pollution modeling usually involves Meteorology and Emission simulation, which results in the concentration estimates of the pollutants. The Weather Research and Forecasting (WRF) Model has gained popularity in air pollution and meteorological modeling and is one of the approved meteorological modeling software by the US EPA. WRF can be coupled with various dispersion models such as AERMOD, CMAQ, and CALPUFF. Afzali *et al.* (2017) applied the coupled models WRF-AERMOD to predict the concentration of air pollutants from different sources in Malaysia. They found that with the use of WRF, the effect of various meteorological variables, such as temperature and wind speed, on the dispersion of air pollutants can be studied. The nature of the mountainous terrain of Almaty necessitated the use of AERMOD. This is because the US EPA recommends AERMOD for air pollution modeling in complex terrain.

Hag *et al.* (2019) assessed the suitability of AERMOD in simulating the concentration of air pollutants in the complex terrain of Islamabad, Pakistan. The study showed that AERMOD underpredicted ground-level concentration by a factor of 2 for the field tracer test. However, its prediction was more accurate for the concentration of primary concerns needed for regulatory purposes: the higher concentration.

To accurately estimate the temporal and spatial distribution characteristics of $PM_{2.5}$ concentration in Wuhan, Huahua *et al.* (2021) simulated the emissions from various sources in the city using the coupled models of WRF-CMAQ for a more accurate result. The coupled model gives a more accurate estimate of PM2.5 concentration. This is because the meteorological output from WRF is used as input into the CMAQ model.

Huahua *et al.* (2021) also analyzed the various factors affecting the diffusion of $PM_{2.5}$ and concluded that the architectural pattern in terms of the height and width of structures and the layout of structures in an environment significantly affects the rate of $PM_{2.5}$ diffusion.

Wang *et al.* (2021) investigated the influencing factors of PM2.5 and O_3 from 2016 to 2020 by comparing distributed lag nonlinear models (DLNM) and the coupled WRF-CMAQ models. They analyzed different years, seasons, pollution levels, and wind directions for $PM_{2.5}$ and O_3. Changes attributed to meteorological conditions and anthropogenic emissions between 2016 and 2020 were evaluated using DLNM and WRF-CMAQ. From their investigation, Wang *et al.* concluded that DLNM and CMAQ both showed that some anthropogenic factors could reduce $PM_{2.5}$ pollution. Furthermore, the similarity between the output of DLNM and CMAQ indicates the level of accuracy of CMAQ in the estimation of $PM_{2.5}$ concentration. The impact of emission control strategies on the concentration of $PM_{2.5}$ was assessed by Jianhua *et al.*

(2016). Results of the investigation showed that applying some control strategies, such as the period of emission, the intensity of emission, etc., can significantly affect $PM_{2.5}$.

The use of modeling software such as WRF, AERMOD, CMAQ, and CALPUFF is relatively new in Kazakhstan. This research on the impact of power plants in Almaty using WRF-AERMOD is intended to provide a quantitative and graphical estimate of emissions from the power plants in Almaty in relation to the various meteorological factors such as temperature, wind speed, and humidity.

CHAPTER THREE

3.1 RESEARCH METHODOLOGY

This section highlights the methods that guide the accomplishment of the research objectives and this includes models that are buttressed in the following sections.

3.2 WRF-AERMOD Coupled Model

The weather research and forecasting model (WRF) coupled with the air dispersion model (AERMOD) has been an effective tool in the air pollution research field because of the compatibility of data among the models. In this study, WRF was used to simulate the meteorology over the city of Almaty, which was then used to obtain the concentration of $PM_{2.5}$ using the air dispersion model, AERMOD. A detailed description of these models and the data required to run the simulation is given in the following section.

3.2.1 Weather Research and Forecasting Model (WRF)

WRF is characterized as "a next-generation mesoscale numerical weather forecast system" by the National Center for Atmospheric Research (NCAR). It can be utilized for both research and operational forecasting initiatives in the atmosphere. The WRF is primarily used to compute various meteorological processes and occurrences and typically outputs meteorological data such as air temperature, relative humidity, atmospheric pressure, solar radiation, and long-wave radiation gained and lost on the surface. Over the years, WRF has been modified to be more suitable for various purposes and scenarios. The computational ability of WRF has been modified over the years such that it now offers a more flexible operational and forecasting platform; it also contains recent development in numerics, physics, and assimilation of data, all of which is the collective effort of a diverse research community.

The domain setup used in the meteorological simulation is shown in Table 3.*1*.

Table 3.1: Overview of the WRF-ARW details used for Meteorology simulation

Vertical coordinate	Terrain - following hydrostatic pressure
Covered area	43.239° N, 76.889° E
WRF Core	ARW
Interval	6 hrs
Map Projection	Mercator
Integration time step	90 sec
Data	NCEP FNL

Grid size	
Horizontal grid system	
No. of Domain	1
Start date and time	2021 – 01- 01 _00:00:00
End date and time	2021 – 01 – 15_00:00:00
Dynamics	Non-hydration
Resolution	10km x 10km

3.2.2 Air Dispersion Model (AERMOD)

The Air Dispersion Model, AERMOD, was introduced by the American Meteorological Society/Environmental Protection Agency Regulatory Model Improvement Committee (AERMIC). It is a complex modeling system that is based on the planetary boundary layer theory, turbulence structure, and scaling concepts. AERMOD can be used to study the emission and/or pollution of flat and elevated sources, including complicated and simple terrains. AERMOD comprises two major data processors: AERMET and AERMAP. AERMET is a meteorological processor which is used to simulate the meteorological condition of the study area using planetary boundary layer structure, while AERMAP is used to process the terrain of the study area. It accesses complex land areas from the USGS database. AERMOD combines the output of the AERMAP, AERMET (in this case, WRF was used), and the emission data calculated by the sources. Figure 3.*1* shows the AERMOD point source calculation table used for one of the sources (CHP-2).

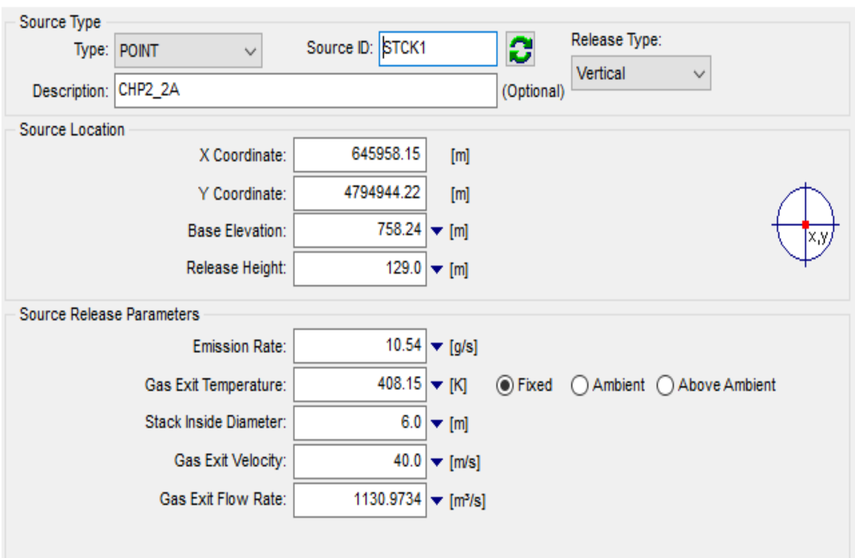


Figure 3.1: Showing typical input data for point source calculation in AERMOD

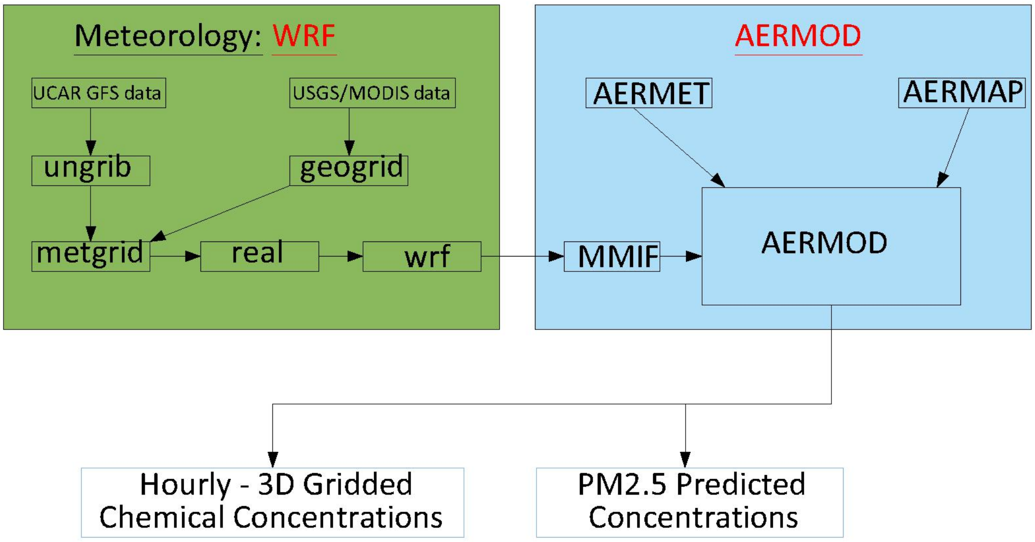


Figure 3. 2: Flow of data from WRF and Emission Center to the CMAQ Model

3.3 Data Collection

The research was done using the coupled WRF-AERMOD model, which requires different sets of data. The flow of data from one model to the other model is shown in Figure 3. *2*. To simulate the meteorology of the study area using WRF, meteorological data were obtained from the United States Geographical Survey (USGS) in the form of GRIB files for the period of the 1st of January 2021 to the 15th of January 2021. The month of January was chosen because, according to the observed data of the United States Embassy in Almaty, the month of January had the highest concentration of $PM_{2.5}$ cumulatively (See figure 3). The WRF simulation output is then processed using the Mesoscale Model Interface Program (MMIF), which converts the prognostic meteorological output field into gridded formats required as a direct input by AERMOD.

Three types of data are required to perform the simulation using AERMOD software: The gridded meteorology files from WRF (processed by MMIF), the emission data from all sources considered in the research, and, in this case, the two power plants (CHP 2 & 3). The emission data from the two power plants under consideration were calculated using the following formula:

$$E = A * Ef * (1 - \frac{ER}{100})$$

Where:

E = Emissions

A = Activity rate

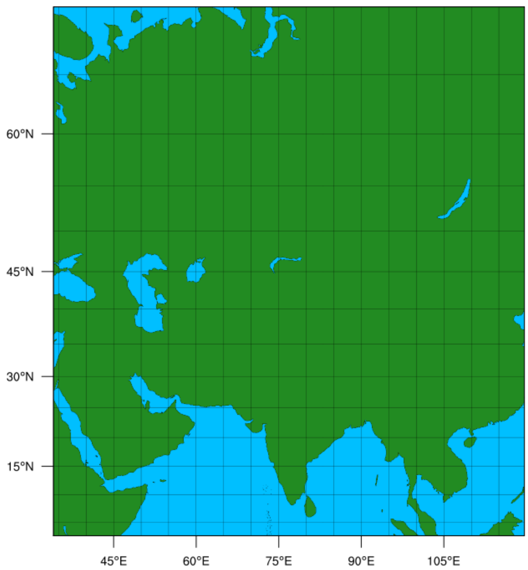
Ef = Emission Factor (obtained from EPA's AP-142, Table 1.1-7)

ER = Overall emission reduction efficiency (%)

Where ER is not known, the emission is estimated as E = Ef * A

3.4 Domain Setup

The area of focus on this project is Almaty which is about 682 km^2. Figure 3 shows the domain configuration for the WPS-Geogrid. The domain comprises 325 grids spaced at 10000m in the west-east region and 225 grids at 10000m in the south-north region of the domain. The reference latitude and longitude are 45 and 76.89, respectively. To provide the geogrid program enough room to perform horizontal interpolation effectively, the domain setup was made to include the entirety of Almaty and beyond.



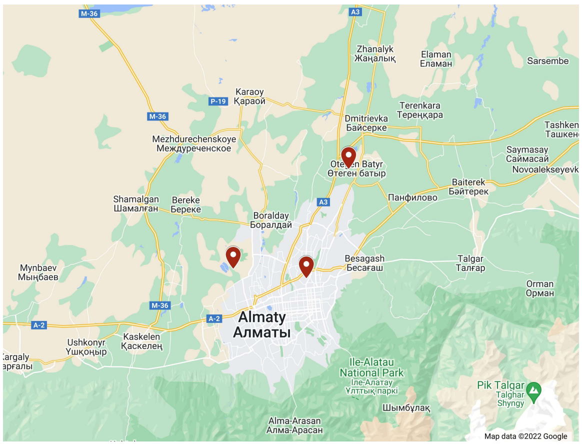


Figure 3. 3 Showing the Domain area over Almaty and the location of CHP 2&3

CHAPTER FOUR

4.0 RESULTS AND DISCUSSIONS

This chapter presents the results obtained from various simulations performed using WRF and AERMOD. Direct comparisons of the various concentrations obtained from simulation and the observed concentration from the US embassy are also presented in the following sections.

4.1 Model Evaluation/Statistical Comparison of Results

The simulation was performed for fourteen days in Almaty using the coupled WRF-AERMOD models. To evaluate the simulated concentration of $PM_{2.5}$, a comparison was made between the observed data of the United States embassy and the concentrations of $PM_{2.5}$ obtained from the AERMOD simulation. Two simulations were performed using the AERMOD system: Controlled Emission and Uncontrolled Emission. The unavailability of information regarding the efficiency of the control mechanism for both power plants in Almaty necessitated the simulation for both controlled and uncontrolled emissions. Figure 4. 1 and Figure 4. *2* shows the scatter plot for the simulated $PM_{2.5}$ concentration and the observed data for the US Embassy for controlled and uncontrolled emissions, respectively. The plot shows no correlation between the simulated and the observed data; this is a result of the unavailability of the efficiency of the control mechanism being used in these power plants. Secondly, the distance between the power plants and the US embassy is about 14km and 23km for CHP-2 and CHP-3, respectively; this also affects the simulated concentration as compared to that of the observed concentration obtained by the US Embassy.

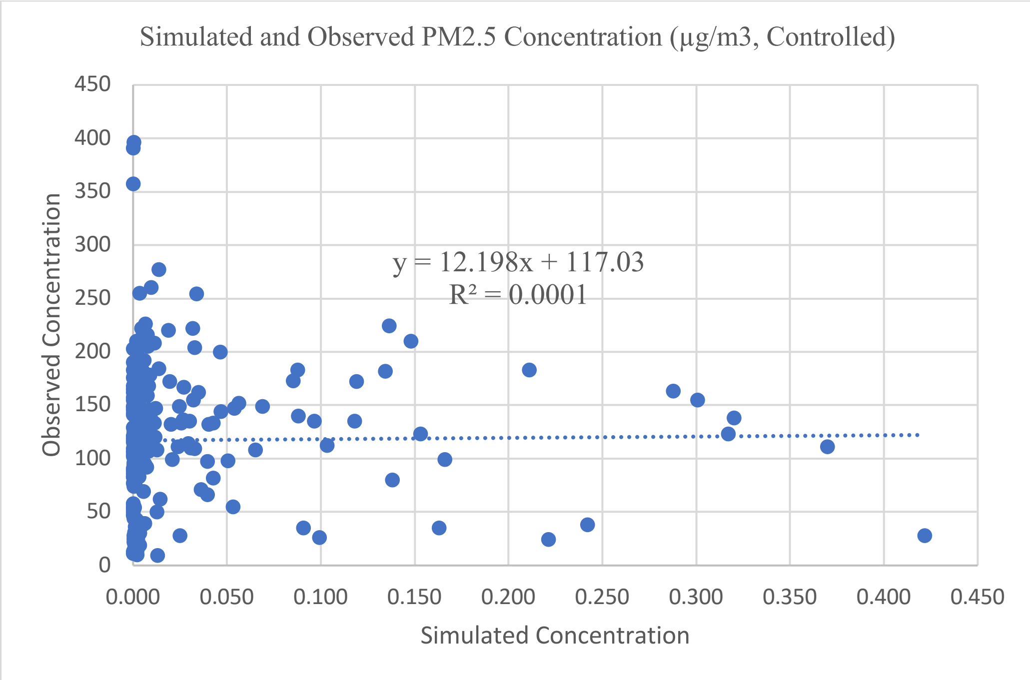


Figure 4. 1 Showing scatter Plot Between Simulated and Observed PM2.5 Concentration (Controlled)

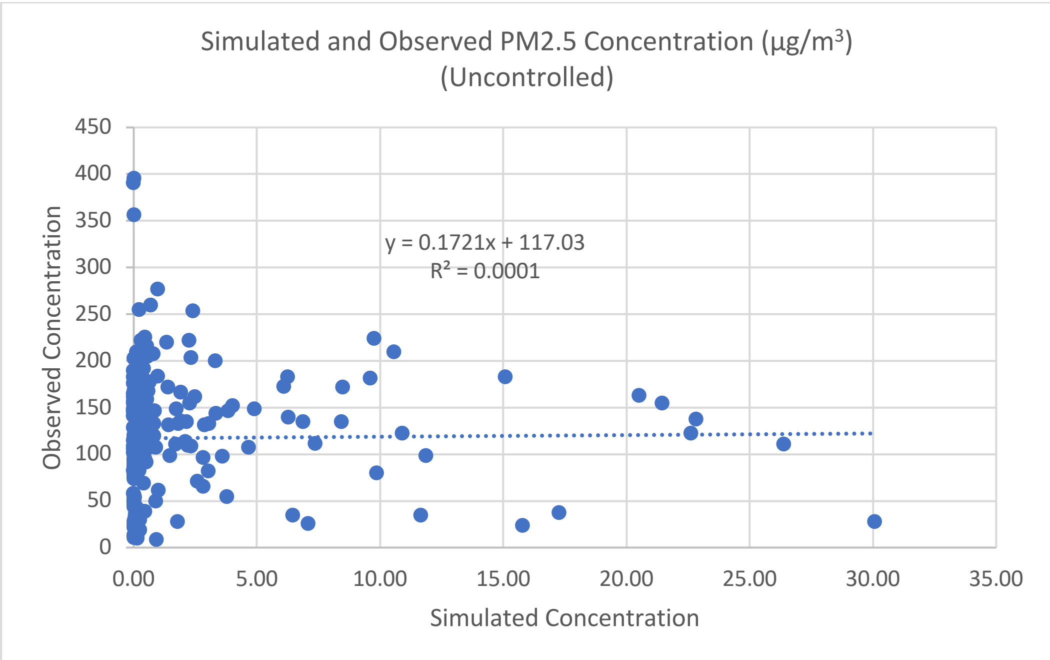
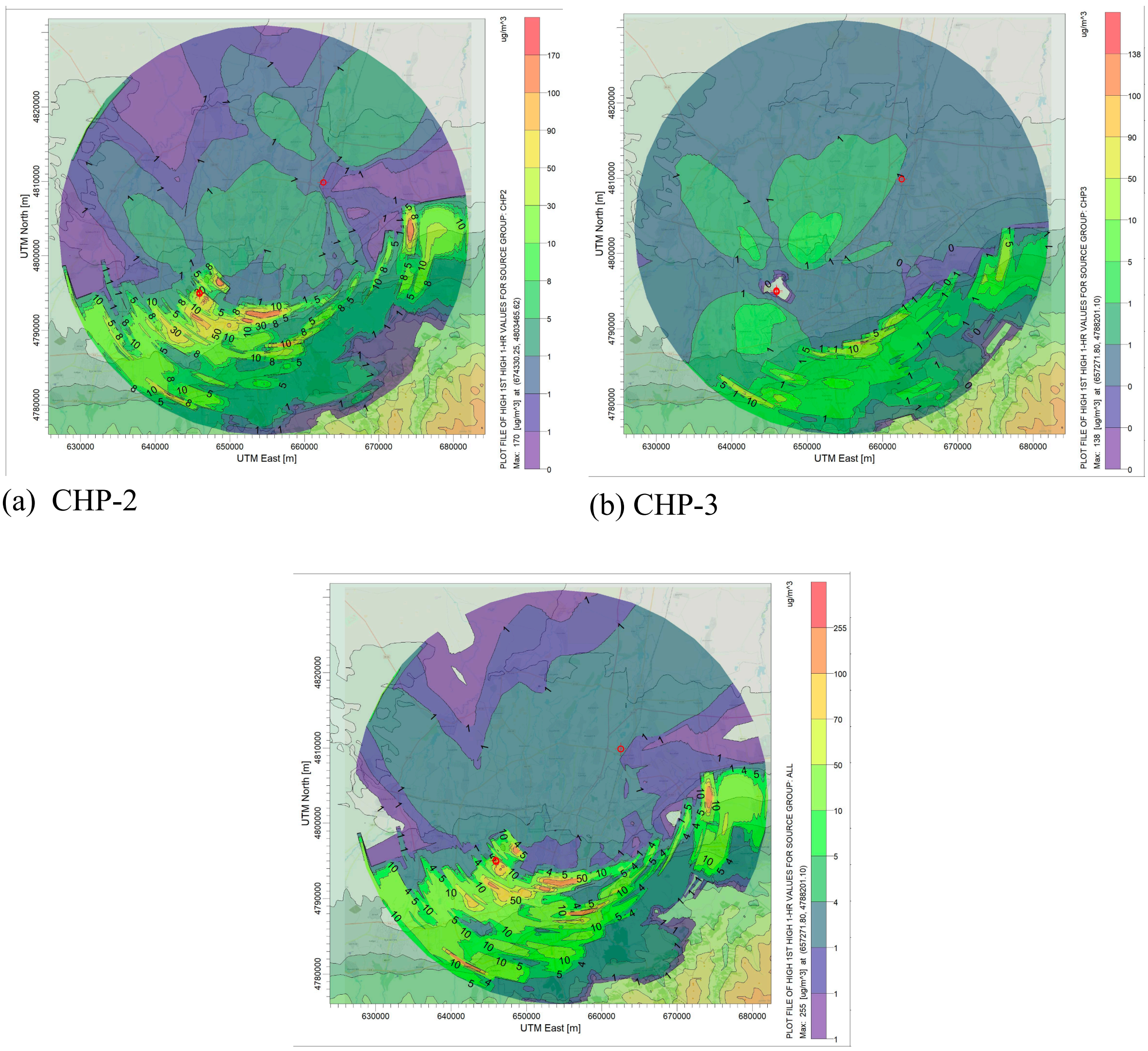


Figure 4. 2 Showing scatter plot between Simulated and Observed PM2.5 Concentration (Uncontrolled)

4.2 Simulation and Dispersion of PM2.5 Concentration in Almaty

The simulation of $PM_{2.5}$ over the city of Almaty was performed as the final stage of the simulation process after the output of the meteorological simulation had been processed using MMIF. The terrain details were obtained from the USGS map using AERMAP. The emissions of the power plants are discharged through chimneys of varying diameters; emissions for CHP-2 are discharged through two chimneys of 7.2m and 6m diameter, while that of CHP-3 is discharged through a single chimney of 8.0m. The power plants' activity rate (coal consumption) is 380 tons/hr and 140.3 tons/hr, respectively (KazNIPIEnergoprom, vol 4, 2021). $PM_{2.5}$ emission was estimated using Tables 1.1-7 of the EPA's AP-142 and the equation given in section 3.3 for both the controlled and uncontrolled emission scenarios. The estimated emission from the power plants, the processed output from WRF, and the topographical details obtained from the AERMAP are used to perform the simulation. The dispersion of $PM_{2.5}$ in the city from both power plants is shown in Figure 4. 3



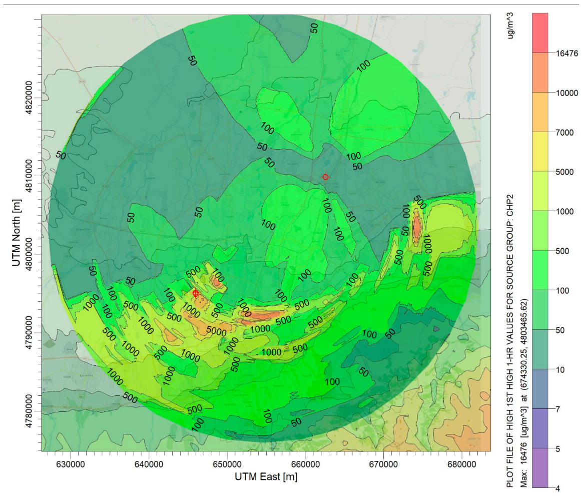
(a) CHP-2

(b) CHP-3

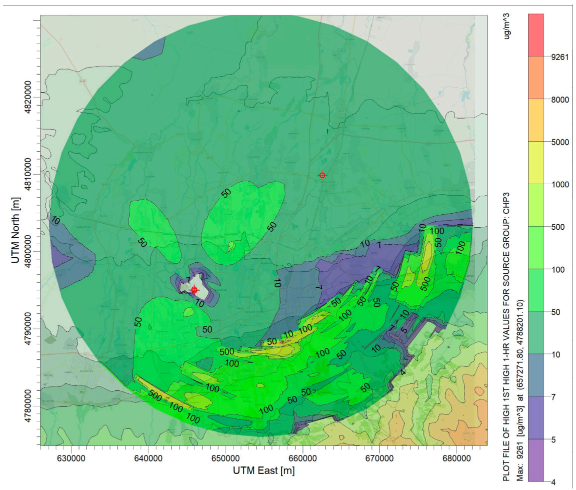
(c) CHP 2&3

Figure 4. 3 Showing Concentration of PM2.5 (μg/m3) in Almaty (Controlled)

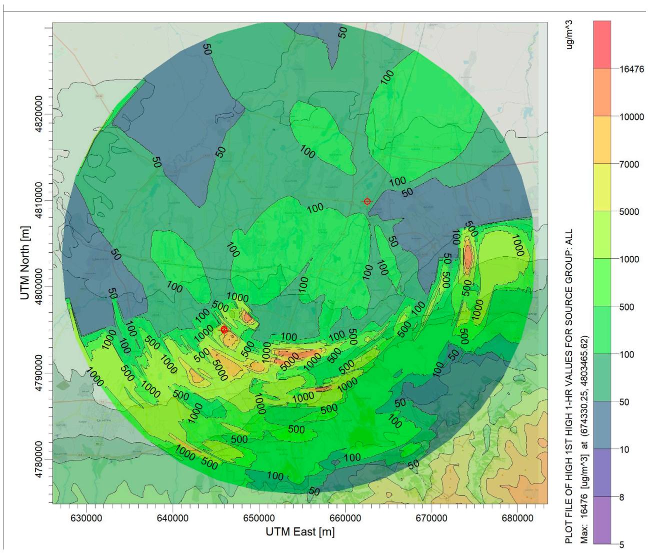
For the controlled simulation, the results show that the maximum concentration of $PM_{2.5}$ was 255.0 μg/m^3 which is the combined effect of the two power plants under consideration, as shown in Figure 4.3 c, while the individual effects on the concentration of $PM_{2.5}$ are shown in a and b of Figure 4.3. Simulation for the uncontrolled scenario shows that the maximum concentration of $PM_{2.5}$ was as high as 16,478 μg/m^3, as shown in Figure 4. 4c. The individual contributions of the power plants to the total concentration of $PM_{2.5}$ are shown in Figure 4. 4 a and b.



(a) CHP-2



(b) CHP-3



(c) CHP 2&3

Figure 4. 4 Showing Concentration of PM2.5 (μg/m3) in Almaty (Uncontrolled)

While the effect of the emission from the power plants for the uncontrolled scenario significantly contributes to the air quality in Almaty, the distance of travel of the emission from the power plants are within the range of 15 to 20 km, as shown in Figure 4. 3 & Figure 4. *4*. Many factors could be responsible for the dispersion of the particulate matter emitted from the power plants, such as building heights, topography, weather, and time of day.

4.3 Analysis of Results

Combined heat and Power Plants are responsible for over 80% of power generation in Almaty (ppp); CHP-2 and CHP-3 generate this with varying capacities. To assess these power plants' impact on air quality in Almaty, the simulation was performed using the same location as that of the US Embassy in Almaty. The US Embassy sensors measure emission data from all known sources, including vehicles, power plants, residential coal burners. At the same time, the simulation was performed, considering only the emission from the power plants as sources (point sources considering emission through the chimneys). The hourly $PM_{2.5}$ concentration data obtained from the US Embassy's archive for the period of January 2021 (1^{st} to 14^{th}) was compared with the hourly $PM_{2.5}$ concentration obtained from the simulation performed using WRF-AERMOD.

Table 4. 1 Maximum PM2.5 concentration from simulation using WRF-AERMOD and Observed data obtained from the US Embassy website for 1st to 14th of January 2021 (Controlled)

Day	Hour	Simulated Conc	Observed Con	% Contribution
1	7:00	0.13	182.00	0.07
2	8:00	0.14	80.00	0.17
3	2:00	0.01	92.00	0.01
4	16:00	0.29	163.00	0.18
5	12:00	0.21	183.00	0.12
6	4:00	0.71	133.00	0.53
7	19:00	1.82	177.00	1.03
8	16:00	1.11	224.00	0.49
9	20:00	0.15	210.00	0.07
10	17:00	1.97	148.00	1.33
11	16:00	93.12	108.00	86.23
12	3:00	0.02	28.00	0.09
13	14:00	0.00	19.00	0.02
14	11:00	0.42	28.00	1.51

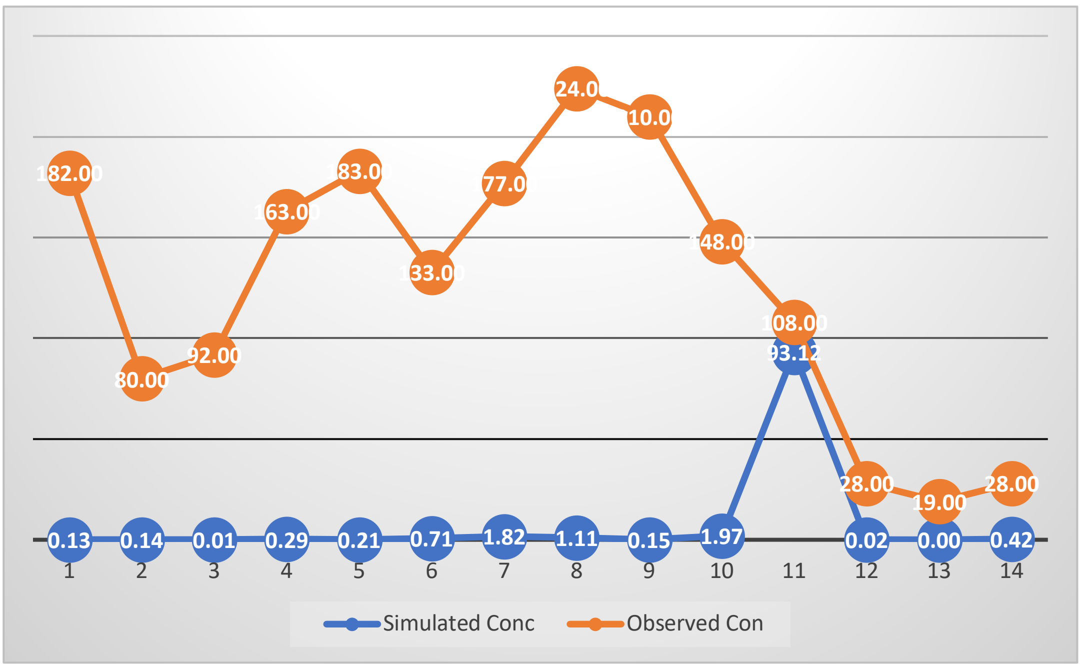


Figure 4. 5 Showing comparison between observed and simulated PM2.5 concentration (Controlled)

Table 4. 1 compares the daily maximum $PM_{2.5}$ concentration obtained from the simulation for the power plants' controlled emission, and the US embassy's observed data. The average percentage contribution to the total $PM_{2.5}$ concentration as measured by the US embassy is 6.55%, which means that if the emission control mechanism of the power plants is working at maximum efficiency, which is 95% (AP-142, table 1.1-4), it will have a relatively negligible contribution to the total $PM_{2.5}$ concentration in Almaty. Complete data of the fourteen-day hourly comparison is shown in Appendix D.

The uncontrolled emission has more effect on the total $PM_{2.5}$ concentration in the city, as shown in Table 4. 1 and Figure 4. 5. This is because the simulation performed with WRF-AERMOD was done with the assumption that the control mechanism of the power plants has zero efficiencies, which means that all the emission from the power plants is released into the atmosphere. The peak concentration usually occurs at nighttime, possibly because fewer vehicles are on the road and other industries within the vicinity are not working at full capacity. The average percentage contribution of the power plants for the uncontrolled scenario is 30.8% which shows that without the control mechanism, the major $PM_{2.5}$ concentration will be from the power plants, especially that of the CHP-2.

The efficiency of the control mechanism installed in the power plants has to be determined, which will help obtain a more realistic impact assessment of the power plants on the quality of air in the city. From the results of the simulation, the efficiency of the control mechanism has to be kept at the maximum performance so as to ensure a negligible $PM_{2.5}$ emission

Table 4. 2 PM2.5 concentration from simulation using WRF-AERMOD and Observed data obtained from the US Embassy website from 1st to 14th of January 2021 (Uncontrolled)

Day	Hour	Simulated Conc	Observed Con	% Contribution
1	7:00	9.59	182	5.27
2	8:00	9.86	80	12.32
3	2:00	0.42	92	0.46
4	16:00	20.50	163	12.58
5	12:00	15.07	183	8.23
6	4:00	50.52	133	37.98
7	19:00	130.10	177	73.50
8	16:00	79.00	224	35.27
9	20:00	10.56	210	5.03
10	17:00	140.28	148	94.78
12	3:00	1.77	28	6.32
13	14:00	0.25	19	1.34

14	11:00	30.06	28	107.37

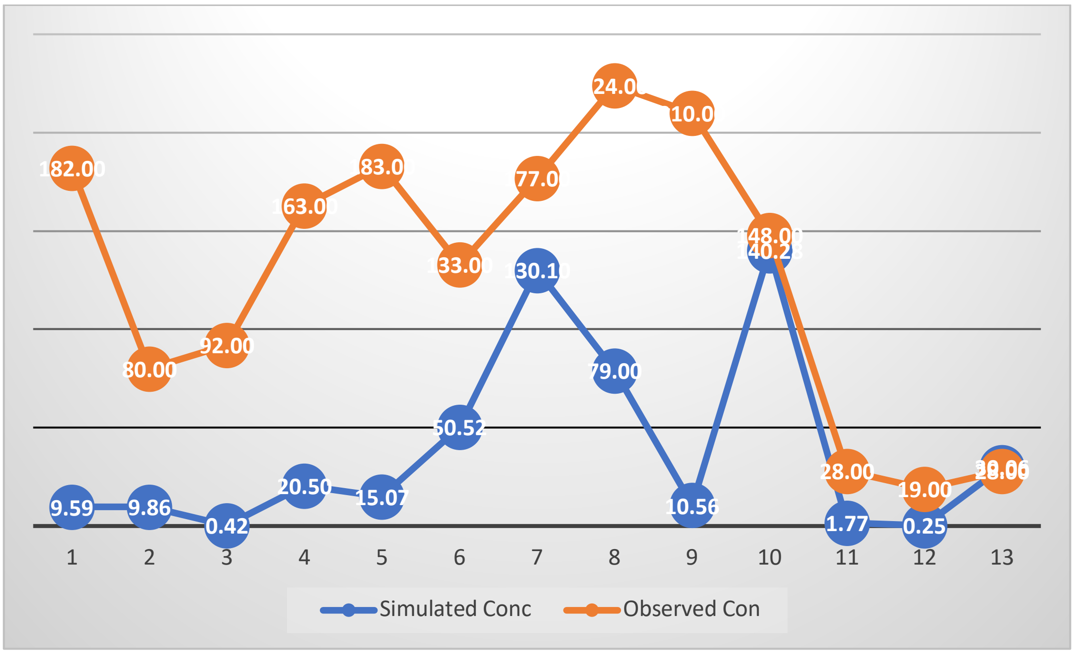


Figure 4. 6 Showing comparison between observed and simulated PM2.5 concentration (Uncontrolled)

4.4 Discussion

The dispersions of $PM_{2.5}$ as a result of the emissions from the combined heat and power plants (CHPP 2 and 3) in Almaty are shown in Figure 4. 3 and Figure 4. *4*. The concentration of $PM_{2.5}$ can go as high as 255 $\mu g/m^3$ when the two power plants are in operation, and the effectiveness of the emission control mechanism is at a maximum (94%). However, the map of the dispersion of $PM_{2.5}$ for the controlled scenario shows that the concentration of $PM_{2.5}$ within a 10 to 15km radius of CHP-2 falls within the range of 8 to 10$\mu g/m^{3,}$ which is about two times higher than the WHO limit as revised in 2021 (IQAir). Emissions from CHP-3 are within the range of 0 and 1$\mu g/m^3$ which means its effect is low as compared to that of CHP-2. When compared to the total $PM_{2.5}$ concentration measured by the US Embassy's sensor, which is about 15km and 25km from CHP-2 and CHP-3, respectively, it shows that the emissions of the power plants, if well controlled (94%), would only contribute about 6% to the total $PM_{2.5}$ concentration in some parts of the city. When the emissions from the power plants are uncontrolled or poorly controlled, the risk of human exposure to higher $PM_{2.5}$ increases. Figure 4. 4 (a, b, and c) show the dispersion of $PM_{2.5}$ from the emissions of CHP-2 and CHP-3 (a & b). The map shows that the concentration from CHP 2 can get as high as 16,476$\mu g/m^3$ while that of CHP-3 can go as high as 9,261$\mu g/m^3$. The map of the dispersion of $PM_{2.5}$ also shows that major parts of the city close to the CHP-2 will risk being exposed to a concentration of $PM_{2.5}$ within the range of 50 to 5000µg/m^{3,} which is higher than the WHO standard.

Both of the scenarios that have been presented pose a risk for the inhabitants of Almaty, especially people that are living close to these power plants. The fully controlled scenario showed that the concentration of $PM_{2.5}$ is still higher than the standard set by the WHO, which is 5µg/m^3. Though the data for the efficiency of the control mechanism that is in use in the power plants are currently not publicly available. The average daily contributions to the total $PM_{2.5}$ as measured by the US embassy is 6% and 30% for the controlled and uncontrolled scenarios, which means there is a high probability of 18% (33.18µg/m^3) of the total concentration of $PM_{2.5}$ coming from the power plants which is about six times higher than the standard set by WHO.

There is an urgent need to ensure that the power plants in Almaty are working under a fully controlled emission status in other to reduce the risk of human exposure to excessive pollutants, especially particulate matter ($PM_{2.5}$). The concentration of $PM_{2.5}$ decreases further away from the source; hence, the authorities should ensure that the location of these power plants are at least 20km away from the city, which will contribute to increasing the quality of air in the city.

CHAPTER FIVE

5.0 Conclusion

An impact assessment of combined heat and power plants in Almaty (CHP-2 AND CHP-3) on the quality of air was conducted using the coupled models WRF-AERMOD to simulate the emissions of the power plants and the meteorology. The results were presented for two scenarios: the controlled and uncontrolled scenarios. These scenarios were necessitated due to the unavailability of the performance data of the power plants' control mechanism, which is required to calculate the efficiency of the emission control. The result of the simulation shows that to obtain the lowest $PM_{2.5}$ emission from the power plants, the emission control efficiency has to be kept at maximum (94% according to AP-142, Table 1.1-7), that is about 6% of the total $PM_{2.5}$ concentration in the city of Almaty. The uncontrolled emission simulation shows that the concentration of $PM_{2.5}$ in Almaty will get up to 30% of the total concentration compared to the US embassy's data. The graphical presentation of the dispersion of $PM_{2.5}$ shows that higher values of the concentration of $PM_{2.5}$ as emitted by the power plants are found within 15 to 20km of the location of the power plants and then decrease further out. Factors responsible for the dispersion of $PM_{2.5}$ in Almaty can include the topography of the city, the architectural layout of the city, the temperature of the air, and the time of emission. However, there is a need for an in-depth study of the dispersion of $PM_{2.5}$ in Almaty to have a comprehensive understanding of the air quality in Almaty.

5.1 Research Limitation

The statistical analysis presented in section 4.1 shows no correlation between the observed concentration and the simulated concentration of $PM_{2.5}$. This is due to the unavailability of real-time, publicly accessible monitoring of the emissions of the power plants in Almaty. Hence, measurement of the efficiency of the emission control is not possible. Secondly, to adequately compare the emissions from the power plants, more monitoring stations have to be installed closer to the power plants, increasing the accuracy of the simulation and/or measurement.

REFERENCES

Afzali, A. *et al.* (2017) “Prediction of air pollutants concentrations from multiple sources using AERMOD coupled with WRF prognostic model,” *Journal of Cleaner Production*, 166, pp. 1216–1225. Available at: https://doi.org/10.1016/j.jclepro.2017.07.196.

Ahn, H., Rim, D. and Freihaut, J., 2018. Performance assessment of hybrid chiller systems for combined cooling, heating, and power production. *Applied Energy*, 225, pp.501-512.

Almeida, S.M. *et al.* (2020) “Ambient particulate matter source apportionment using receptor modelling in European and Central Asia Urban areas,” *Environmental pollution*, 266, p. 115199. Available at: https://doi.org/10.1016/j.envpol.2020.115199.

Assanov, D., Zapasnyi, V. and Kerimray, A., 2021. Air Quality and Industrial Emissions in the Cities of Kazakhstan. *Atmosphere*, 12(3), p.314.

Assembayeva, M., Egerer, J., Mendelevitch, R. and Zhakiyev, N., 2018. A spatial electricity market model for the power system: The Kazakhstan case study. *Energy*, 149, pp.762-778.

Benchrif, A., Wheida, A., Tahri, M., Shubbar, R. and Biswas, B., 2021. Air quality during three covid-19 lockdown phases: AQI, PM2.5 and NO2 assessment in cities with more than 1 million inhabitants. *Sustainable Cities and Society*, 74, p.103170.

Bu, X. *et al.* (2021) “Global PM2.5-attributable health burden from 1990 to 2017: Estimates from the global burden of disease study 2017,” *Environmental Research*, 197, p. 111123. Available at: https://doi.org/10.1016/j.envres.2021.111123.

Carlsen, L., Baimatova, N. K., Kenessov, B. N., & Kenessova, O. A. (2013). Assessment of the Air Quality of Almaty. Focussing on the Traffic Component. *International Journal of Biology and Chemistry*, *5*(1), 49–69. Retrieved from https://ijbch.kaznu.kz/index.php/kaznu/article/view/82

Choi, Lee, Woo, Kim and Lee, 2019. Comparison of PM2.5 Chemical Components over East Asia Simulated by the WRF-Chem and WRF/CMAQ Models: On the Models’ Prediction Inconsistency. *Atmosphere*, 10(10), p.618.

Ding, Z., Hou, H., Duan, L., Huang, C., Hu, E., Yu, G., Zhang, Y. and Zhang, N., 2021. Simulation study on a novel solar aided combined heat and power system for heat-power decoupling. *Energy*, 220, p.119689.

Duan, W., Wang, X., Cheng, S., Wang, R. and Zhu, J., 2021. Influencing factors of PM2.5 and O3 from 2016 to 2020 based on DLNM and WRF-CMAQ. *Environmental pollution*, 285, p.117512

Fu, L., Zhao, X., Zhang, S., Jiang, Y., Li, H. and Yang, W., 2009. Laboratory research on combined cooling, heating and power (CCHP) systems. *Energy Conversion and Management*, 50(4), pp.977-982.

Hu, J., Chen, J., Ying, Q. and Zhang, H., 2016. One-year simulation of ozone and particulate matter in Chinausing WRF/CMAQ modeling system. *Atmospheric Chemistry and Physics*, 16(16), pp.10333-10350.

IEA (2020), Kazakhstan energy profile, IEA, Paris https://www.iea.org/reports/kazakhstan-energy-profile

Jung, J., Souri, A., Wong, D., Lee, S., Jeon, W., Kim, J. and Choi, Y., 2019. The Impact of the Direct Effect of Aerosols on Meteorology and Air Quality Using Aerosol Optical Depth Assimilation During the KORUS‐AQ Campaign. *Journal of Geophysical Research: Atmospheres*, 124(14), pp.8303-8319.

Kerimray, A., Bakdolotov, A., Sarbassov, Y., Inglezakis, V. and Poulopoulos, S., 2018. Air pollution in Astana: analysis of recent trends and air quality monitoring system. *Materials Today: Proceedings*, 5(11), pp.22749-22758.

Li, P., Nord, N., Ertesvåg, I., Ge, Z., Yang, Z. and Yang, Y., 2015. Integrated multiscale simulation of combined heat and power-based district heating system. *Energy Conversion and Management*, 106, pp.337-354

Ma, W., Fan, J., Fang, S., Hassan, N., Zhang, Y., Wu, X., Li, Y., Hu, R. and Liu, G., 2021. Energy efficiency indicators for combined cooling, heating, and power systems. *Energy Conversion and Management*, 239, p.114187.

Moniruzzaman, C., Bowden, J. and Arunachalam, S., 2020. Aircraft landing and takeoff emission impacts on surface O3 and PM2.5 through aerosol direct feedback effects estimated by the coupled WRF-CMAQ model. *Atmospheric Environment*, 243, p.117859

Organization for Economic Co-operation and Development, Meeting the Challenge to 2050,

Policy Brief, February 2018.

Sarbassov, Y., Kerimray, A., Tokmurzin, D., Tosato, G. and De Miglio, R., 2013. Electricity and heating system in Kazakhstan: Exploring energy efficiency improvement paths. *Energy Policy*, 60, pp.431-444.

Sicard, P. *et al.* (2023) "Trends in urban air pollution over the last two decades: A global perspective," *Science of The Total Environment*, 858, p. 160064. Available at: https://doi.org/10.1016/j.scitotenv.2022.160064.

Wu, Q., Ren, H., Gao, W. and Ren, J., 2016. Multi-criteria assessment of building combined heat and power systems located in different climate zones: Japan–China comparison. *Energy*, 103, pp.502-512.

Xia, Y., Liu, J., Huang, Z. and Zhang, X., 2016. Carbon emission impact on the operation of virtual power plant with combined heat and power system. *Frontiers of Information Technology & Electronic Engineering*, 17(5), pp.479-488.

Xu, H. and Chen, H., 2021. Impact of urban morphology on the spatial and temporal distribution of PM2.5 concentration: A numerical simulation with WRF/CMAQ model in Wuhan, China. *Journal of Environmental Management*, 290, p.11242

APPENDIX A

Hourly Concentration of $PM_{2.5}$ (Controlled Scenario)

Day	Hour	Simulated Conc	Observed Con	% Contribution
1	6	0,00107	185,00	0,0006
1	7	0,13422	182,00	0,0737
1	8	0,00670	179,00	0,0037
1	9	0,00198	174,00	0,0011
1	20	0,02672	136,00	0,0196
1	21	0,00014	121,00	0,0001
1	22	0,00163	108,00	0,0015
1	23	0,00147	103,00	0,0014
2	1	0,00025	96,00	0,00026
2	2	0,00025	91,00	0,00027
2	3	0,00023	94,00	0,00024
2	4	0,00023	84,00	0,00027
2	5	0,00025	77,00	0,00032
2	6	0,00032	79,00	0,00041
2	7	0,00123	80,00	0,00154
2	8	0,13821	80,00	0,17276
2	9	0,00299	83,00	0,00360
2	20	0,00559	69,00	0,00810
2	21	0,00094	75,00	0,00125
2	22	0,00019	87,00	0,00022
2	23	0,00276	109,00	0,00253
3	1	0,0034	98,00	0,00347
3	2	0,00588	92,00	0,00639
3	3	0,00304	92,00	0,00330
3	4	0,00078	99,00	0,00079
3	5	0,00026	104,00	0,00025
3	6	0,00342	107,00	0,00320
3	7	0,00356	109,00	0,00327
3	8	0,00388	103,00	0,00377
3	9	0,00464	108,00	0,00430
3	20	0,0012	114,00	0,00105
3	21	0,00105	118,00	0,00089
3	22	0,00181	127,00	0,00143
3	23	0,00276	118,00	0,00234
4	1	0,00123	122,00	0,00101

4	2	0,00106	140,00	0,00076
4	3	0,00086	145,00	0,00059
4	4	0,00078	126,00	0,00062
4	5	0,00084	109,00	0,00077
4	6	0,00103	111,00	0,00093
4	7	0,00142	117,00	0,00121
4	8	0,01254	108,00	0,01161
4	9	0,00000	109,00	0,00000
4	10	0,00094	106,00	0,00089
4	11	0,03264	109,00	0,02994
4	12	0,15301	123,00	0,12440
4	13	0,06876	149,00	0,04615
4	14	0,03478	162,00	0,02147
4	15	0,00804	168,00	0,00479
4	16	0,28758	163,00	0,17643
4	17	0,00000	162,00	0,00000
4	18	0,00001	146,00	0,00001
4	19	0,00771	140,00	0,00551
4	20	0,01182	147,00	0,00804
4	21	0,00040	163,00	0,00025
4	22	0,00001	142,00	0,00001
4	23	0,03075	110,00	0,02795
5	1	0,00001	157,00	0,00001
5	2	0,00041	125,00	0,00033
5	3	0,00013	117,00	0,00011
5	4	0,00000	115,00	0,00000
5	5	0,16593	99,00	0,16761
5	6	0,00015	106,00	0,00014
5	7	0,00000	102,00	0,00000
5	8	0,00600	109,00	0,00550
5	9	0,02546	133,00	0,01914
5	11	0,08530	173,00	0,04931
5	12	0,21103	183,00	0,11532
5	13	0,11883	172,00	0,06909
5	14	0,00576	137,00	0,00420
5	15	0,00406	111,00	0,00366
5	16	0,00520	129,00	0,00403
5	17	0,00008	148,00	0,00005
5	18	0,00000	149,00	0,00000

5	19	0,00001	129,00	0,00001
5	20	0,00028	93,00	0,00030
5	21	0,02390	111,00	0,02153
5	22	0,00907	138,00	0,00657
5	23	0,02001	132,00	0,01516
6	1	0,05636	152,00	0,03708
6	2	0,00000	141,00	0,00000
6	3	0,37001	111,00	0,33334
6	4	0,70847	133,00	0,53268
6	5	0,31714	123,00	0,25784
6	6	0,00156	95,00	0,00164
6	7	0,00099	183,00	0,00054
6	8	0,00292	156,00	0,00187
6	9	0,00582	192,00	0,00303
6	10	0,00098	169,00	0,00058
6	11	0,00651	226,00	0,00288
6	12	0,13645	224,00	0,06092
6	13	0,00326	255,00	0,00128
6	14	0,00518	182,00	0,00285
6	15	0,00120	147,00	0,00082
6	16	0,00241	147,00	0,00164
6	17	0,03190	155,00	0,02058
6	18	0,00002	148,00	0,00001
6	19	0,09656	135,00	0,07153
6	20	0,00075	117,00	0,00064
6	21	0,00099	96,00	0,00103
6	22	0,00124	100,00	0,00124
6	23	0,00115	131,00	0,00088
7	1	0,00302	117,00	0,00258
7	2	0,00305	154,00	0,00198
7	3	0,00294	155,00	0,00190
7	4	0,00323	139,00	0,00232
7	5	0,00393	110,00	0,00357
7	6	0,00467	117,00	0,00399
7	7	0,00546	113,00	0,00483
7	8	0,00538	104,00	0,00517
7	9	0,00730	92,00	0,00793
7	10	0,00819	107,00	0,00765
7	11	0,03965	97,00	0,04088

7	12	0,10339	112,00	0,09231
7	13	0,04032	132,00	0,03055
7	14	0,32006	138,00	0,23193
7	15	0,00114	149,00	0,00077
7	16	0,01955	172,00	0,01137
7	17	0,00001	176,00	0,00001
7	18	0,00000	165,00	0,00000
7	19	1,82436	177,00	1,03071
7	20	0,30067	155,00	0,19398
7	21	0,02677	167,00	0,01603
7	22	0,00220	201,00	0,00109
7	23	0,00222	190,00	0,00117
8	1	0,03167	222,00	0,01427
8	2	0,03272	204,00	0,01604
8	3	0,01113	208,00	0,00535
8	4	0,01354	184,00	0,00736
8	5	0,00428	222,00	0,00193
8	6	0,00292	208,00	0,00140
8	7	0,00169	193,00	0,00088
8	8	0,00386	188,00	0,00205
8	9	0,00881	178,00	0,00495
8	10	0,00273	203,00	0,00134
8	11	0,00340	193,00	0,00176
8	12	0,00224	181,00	0,00124
8	13	0,08752	183,00	0,04783
8	14	0,11811	135,00	0,08749
8	15	0,00159	210,00	0,00076
8	16	1,10774	224,00	0,49453
8	17	0,00223	161,00	0,00139
8	18	0,00000	106,00	0,00000
8	19	0,00158	88,00	0,00180
8	20	0,00152	97,00	0,00157
8	21	0,00758	109,00	0,00695
8	22	0,01135	133,00	0,00853
8	23	0,00740	159,00	0,00465
9	1	0,00399	179,00	0,00223
9	2	0,00298	161,00	0,00185
9	3	0,00280	152,00	0,00184
9	4	0,00493	116,00	0,00425

9	5	0,02072	99,00	0,02093
9	6	0,05043	98,00	0,05146
9	7	0,03621	71,00	0,05100
9	8	0,03959	66,00	0,05998
9	9	0,01417	62,00	0,02285
9	10	0,00539	103,00	0,00523
9	11	0,00826	125,00	0,00661
9	12	0,08800	140,00	0,06286
9	13	0,05378	147,00	0,03659
9	14	0,03000	135,00	0,02222
9	15	0,04667	144,00	0,03241
9	16	0,00146	183,00	0,00080
9	17	0,00510	215,00	0,00237
9	18	0,04635	200,00	0,02318
9	19	0,00015	203,00	0,00007
9	20	0,14788	210,00	0,07042
9	21	0,00734	216,00	0,00340
9	22	0,00965	260,00	0,00371
9	23	0,03378	254,00	0,01330
10	1	0,00031	396,00	0,00008
10	2	0,00001	391,00	0,00000
10	3	0,00003	357,00	0,00001
10	4	0,01375	277,00	0,00496
10	5	0,01877	220,00	0,00853
10	6	0,00043	129,00	0,00033
10	7	0,00006	119,00	0,00005
10	8	0,00010	89,00	0,00011
10	9	0,00008	77,00	0,00010
10	10	0,05304	55,00	0,09644
10	11	0,04250	82,00	0,05183
10	12	0,00878	112,00	0,00784
10	13	0,00309	130,00	0,00238
10	14	0,02932	114,00	0,02572
10	15	0,00254	158,00	0,00161
10	16	0,02441	149,00	0,01638
10	17	1,96583	148,00	1,32826
10	18	0,00000	147,00	0,00000
10	19	0,00000	155,00	0,00000
10	20	0,00014	168,00	0,00008

10	21	0,00000	190,00	0,00000
10	22	0,00001	183,00	0,00001
10	23	0,00798	205,00	0,00389
11	1	0,00300	191,00	0,00157
11	2	0,00840	146,00	0,00575
11	3	0,00056	110,00	0,00051
11	4	0,00006	91,00	0,00007
11	5	0,00002	83,00	0,00002
11	6	0,00003	86,00	0,00003
11	7	0,00001	58,00	0,00002
11	10	0,16299	35,00	0,46569
11	11	0,01260	50,00	0,02520
11	12	0,00375	96,00	0,00391
11	13	0,04264	133,00	0,03206
11	14	0,06522	108,00	0,06039
11	15	0,01161	120,00	0,00968
11	16	93,12316	108,00	86,22515
11	17	0,00623	95,00	0,00656
11	18	0,00003	103,00	0,00003
11	19	0,00138	101,00	0,00137
12	2	0,00022	44,00	0,0005
12	3	0,02476	28,00	0,0884
12	6	0,00032	14,00	0,0023
12	7	0,01311	9,00	0,1457
12	8	0,00207	10,00	0,0207
12	9	0,00137	17,00	0,0081
12	10	0,00140	18,00	0,0078
12	11	0,00116	18,00	0,0064
12	12	0,00102	36,00	0,0028
12	13	0,00059	54,00	0,0011
12	14	0,00040	159,00	0,0003
12	15	0,00035	182,00	0,0002
12	16	0,00018	151,00	0,0001
12	17	0,00058	188,00	0,0003
12	18	0,00113	191,00	0,0006
12	19	0,00123	145,00	0,0008
12	20	0,00088	89,00	0,0010
12	21	0,00025	74,00	0,0003
12	22	0,00046	86,00	0,0005

12	23	0,00015	83,00	0,0002
13	1	0,00008	50,00	0,00016
13	2	0,00008	54,00	0,00015
13	3	0,00008	53,00	0,00015
13	4	0,00012	47,00	0,00026
13	5	0,00015	57,00	0,00026
13	6	0,00010	54,00	0,00019
13	7	0,00007	52,00	0,00013
13	8	0,00007	47,00	0,00015
13	9	0,00007	13,00	0,00054
13	10	0,00013	11,00	0,00118
13	11	0,00219	14,00	0,01564
13	12	0,00073	23,00	0,00317
13	13	0,00081	20,00	0,00405
13	14	0,00357	19,00	0,01879
13	15	0,00290	32,00	0,00906
13	16	0,00023	28,00	0,00082
13	17	0,00131	25,00	0,00524
13	18	0,00143	23,00	0,00622
13	19	0,00143	23,00	0,00622
13	20	0,00235	34,00	0,00691
13	21	0,00036	25,00	0,00144
13	22	0,00024	22,00	0,00109
13	23	0,00354	30,00	0,01180
14	1	0,00070	31,00	0,00226
14	2	0,00630	39,00	0,01615
14	3	0,00327	30,00	0,01090
14	4	0,24199	38,00	0,63682
14	5	0,00172	43,00	0,00400
14	6	0,00208	34,00	0,00612
14	7	0,00180	22,00	0,00818
14	8	0,00181	17,00	0,01065
14	9	0,00230	24,00	0,00958
14	10	0,00216	33,00	0,00655
14	11	0,42163	28,00	1,50582
14	12	0,22140	24,00	0,92250
14	13	0,09933	26,00	0,38204
14	14	0,09057	35,00	0,25877
14	15	0,00478	39,00	0,01226

14	16	0,00504	38,00	0,01326
14	17	0,00063	28,00	0,00225
14	18	0,00124	29,00	0,00428
14	19	0,00153	17,00	0,00900
14	20	0,00250	19,00	0,01316
14	21	0,00239	19,00	0,01258
14	22	0,00135	27,00	0,00500
14	23	0,00144	32,00	0,00450

APPENDIX B

Day	Hour	Simulated Conc	Observed Con	% Contribution
1	6	0,07632	185,00	0,0413
1	7	9,58785	182,00	5,2680
1	8	0,47762	179,00	0,2668
1	9	0,14133	174,00	0,0812
1	20	1,90518	136,00	1,4009
1	21	0,01026	121,00	0,0085
1	22	0,11623	108,00	0,1076
1	23	0,10481	103,00	0,1018
2	1	0,01796	96	0,01871
2	2	0,01751	91	0,01924
2	3	0,01675	94	0,01782
2	4	0,01639	84	0,01951
2	5	0,01804	77	0,02343
2	6	0,02280	79	0,02886
2	7	0,08763	80	0,10954
2	8	9,85708	80	12,32135
2	9	0,21331	83	0,25700
2	20	0,39861	69	0,57770
2	21	0,06690	75	0,08920
2	22	0,01343	87	0,01544
2	23	0,19650	109	0,18028
3	1	0,24212	98	0,24706
3	2	0,41957	92	0,45605
3	3	0,21658	92	0,23541
3	4	0,05571	99	0,05627
3	5	0,01846	104	0,01775
3	6	0,24409	107	0,22812
3	7	0,25406	109	0,23308
3	8	0,27648	103	0,26843
3	9	0,33080	108	0,30630
3	20	0,08569	114	0,07517
3	21	0,07461	118	0,06323
3	22	0,12915	127	0,10169
3	23	0,19710	118	0,16703
4	1	0,08763	122	0,07183
4	2	0,07536	140	0,05383
4	3	0,06106	145	0,04211
4	4	0,05574	126	0,04424
4	5	0,06024	109	0,05527
4	6	0,07346	111	0,06618

4	7	0,10157	117	0,08681
4	8	0,89444	108	0,82819
4	9	0,00013	109	0,00012
4	10	0,06712	106	0,06332
4	11	2,32676	109	2,13464
4	12	10,90812	123	8,86839
4	13	4,90323	149	3,29076
4	14	2,48250	162	1,53241
4	15	0,57330	168	0,34125
4	16	20,50123	163	12,57744
4	17	0,00005	162	0,00003
4	18	0,00046	146	0,00032
4	19	0,55009	140	0,39292
4	20	0,84316	147	0,57358
4	21	0,02822	163	0,01731
4	22	0,00076	142	0,00054
4	23	2,19656	110	1,99687
5	1	0,00038	157	0,00024
5	2	0,02930	125	0,02344
5	3	0,00951	117	0,00813
5	4	0,00017	115	0,00015
5	5	11,85285	99	11,97258
5	6	0,01047	106	0,00988
5	7	0,00018	102	0,00018
5	8	0,42866	109	0,39327
5	9	1,81882	133	1,36753
5	11	6,08232	173	3,51579
5	12	15,06901	183	8,23443
5	13	8,48500	172	4,93314
5	14	0,41090	137	0,29993
5	15	0,28982	111	0,26110
5	16	0,37082	129	0,28746
5	17	0,00538	148	0,00364
5	18	0,00032	149	0,00021
5	19	0,00090	129	0,00070
5	20	0,01970	93	0,02118
5	21	1,70394	111	1,53508
5	22	0,64647	138	0,46846
5	23	1,42673	132	1,08086
6	1	4,02102	152	2,64541
6	2	0,00015	141	0,00011
6	3	26,38856	111	23,77348
6	4	50,51587	133	37,98186
6	5	22,61289	123	18,38446

6	6	0,11097	95	0,11681
6	7	0,07093	183	0,03876
6	8	0,20819	156	0,13346
6	9	0,41478	192	0,21603
6	10	0,07015	169	0,04151
6	11	0,46397	226	0,20530
6	12	9,74362	224	4,34983
6	13	0,23222	255	0,09107
6	14	0,36961	182	0,20308
6	15	0,08588	147	0,05842
6	16	0,17209	147	0,11707
6	17	2,27682	155	1,46892
6	18	0,00142	148	0,00096
6	19	6,88477	135	5,09983
6	20	0,05379	117	0,04597
6	21	0,07079	96	0,07374
6	22	0,08873	100	0,08873
6	23	0,08178	131	0,06243
7	1	0,21560	117	0,18427
7	2	0,21741	154	0,14118
7	3	0,20959	155	0,13522
7	4	0,23000	139	0,16547
7	5	0,28018	110	0,25471
7	6	0,33325	117	0,28483
7	7	0,38935	113	0,34456
7	8	0,38367	104	0,36891
7	9	0,52064	92	0,56591
7	10	0,58380	107	0,54561
7	11	2,82636	97	2,91377
7	12	7,37024	112	6,58057
7	13	2,87454	132	2,17768
7	14	22,82194	138	16,53764
7	15	0,08139	149	0,05462
7	16	1,39376	172	0,81033
7	17	0,00040	176	0,00023
7	18	0,00012	165	0,00007
7	19	130,09812	177	73,50176
7	20	21,43757	155	13,83069
7	21	1,90890	167	1,14305
7	22	0,15661	201	0,07792
7	23	0,15825	190	0,08329
8	1	2,25818	222	1,01720
8	2	2,33269	204	1,14348

8	3	0,79380	208	0,38163
8	4	0,96558	184	0,52477
8	5	0,30515	222	0,13745
8	6	0,20807	208	0,10003
8	7	0,12016	193	0,06226
8	8	0,27531	188	0,14644
8	9	0,62805	178	0,35284
8	10	0,19475	203	0,09594
8	11	0,24224	193	0,12551
8	12	0,15983	181	0,08830
8	13	6,24943	183	3,41499
8	14	8,43408	135	6,24747
8	15	0,11318	210	0,05390
8	16	78,99711	224	35,26657
8	17	0,15940	161	0,09901
8	18	0,00030	106	0,00028
8	19	0,11237	88	0,12769
8	20	0,10852	97	0,11188
8	21	0,54036	109	0,49574
8	22	0,80944	133	0,60860
8	23	0,52755	159	0,33179
9	1	0,28457	179	0,15898
9	2	0,21278	161	0,13216
9	3	0,19949	152	0,13124
9	4	0,35173	116	0,30322
9	5	1,47739	99	1,49231
9	6	3,59592	98	3,66931
9	7	2,58180	71	3,63634
9	8	2,82241	66	4,27638
9	9	1,01010	62	1,62919
9	10	0,38430	103	0,37311
9	11	0,58883	125	0,47106
9	12	6,27307	140	4,48076
9	13	3,83387	147	2,60807
9	14	2,13900	135	1,58444
9	15	3,32705	144	2,31045
9	16	0,10377	183	0,05670
9	17	0,36358	215	0,16911
9	18	3,31058	200	1,65529
9	19	0,01045	203	0,00515
9	20	10,56313	210	5,03006
9	21	0,52378	216	0,24249
9	22	0,68896	260	0,26498
9	23	2,41282	254	0,94993

10	1	0,02204	396	0,00557
10	2	0,00060	391	0,00015
10	3	0,00231	357	0,00065
10	4	0,98217	277	0,35457
10	5	1,34108	220	0,60958
10	6	0,03071	129	0,02381
10	7	0,00426	119	0,00358
10	8	0,00745	89	0,00837
10	9	0,00554	77	0,00719
10	10	3,78234	55	6,87698
10	11	3,03009	82	3,69523
10	12	0,62601	112	0,55894
10	13	0,22000	130	0,16923
10	14	2,09363	114	1,83652
10	15	0,18080	158	0,11443
10	16	1,74060	149	1,16819
10	17	140,28056	148	94,78416
10	18	0,00006	147	0,00004
10	19	0,00025	155	0,00016
10	20	0,01014	168	0,00604
10	21	0,00010	190	0,00005
10	22	0,00070	183	0,00038
10	23	0,56946	205	0,27779
11	1	0,21379	191	0,11193
11	2	0,59937	146	0,41053
11	3	0,03989	110	0,03626
11	4	0,00398	91	0,00437
11	5	0,00129	83	0,00155
11	6	0,00221	86	0,00257
11	7	0,00102	58	0,00176
11	10	11,64267	35	33,26477
11	11	0,89840	50	1,79680
11	12	0,26730	96	0,27844
11	13	3,04390	133	2,28865
11	14	4,65752	108	4,31252
11	15	0,82956	120	0,69130
11	16	6651,93994	108	6159,20365
11	17	0,44472	95	0,46813
11	18	0,00235	103	0,00228
11	19	0,09851	101	0,09753
12	2	0,01560	44	0,0355
12	3	1,76869	28	6,3168
12	6	0,02253	14	0,1609
12	7	0,93607	9	10,4008

12	8	0,14747	10	1,4747
12	9	0,09788	17	0,5758
12	10	0,09974	18	0,5541
12	11	0,08304	18	0,4613
12	12	0,07274	36	0,2021
12	13	0,04235	54	0,0784
12	14	0,02818	159	0,0177
12	15	0,02512	182	0,0138
12	16	0,01287	151	0,0085
12	17	0,04169	188	0,0222
12	18	0,08079	191	0,0423
12	19	0,08742	145	0,0603
12	20	0,06286	89	0,0706
12	21	0,01817	74	0,0246
12	22	0,03263	86	0,0379
12	23	0,01062	83	0,0128
13	1	0,00552	50	0,01104
13	2	0,00552	54	0,01022
13	3	0,00558	53	0,01053
13	4	0,00868	47	0,01847
13	5	0,01075	57	0,01886
13	6	0,00715	54	0,01324
13	7	0,00504	52	0,00969
13	8	0,00508	47	0,01081
13	9	0,00524	13	0,04031
13	10	0,00906	11	0,08236
13	11	0,15616	14	1,11543
13	12	0,05189	23	0,22561
13	13	0,05754	20	0,28770
13	14	0,25457	19	1,33984
13	15	0,20718	32	0,64744
13	16	0,01629	28	0,05818
13	17	0,09328	25	0,37312
13	18	0,10189	23	0,44300
13	19	0,10167	23	0,44204
13	20	0,16781	34	0,49356
13	21	0,02544	25	0,10176
13	22	0,01728	22	0,07855
13	23	0,25216	30	0,84053
14	1	0,04973	31	0,16042
14	2	0,44922	39	1,15185
14	3	0,23344	30	0,77813
14	4	17,25269	38	45,40182
14	5	0,12279	43	0,28556

14	6	0,14836	34	0,43635
14	7	0,12826	22	0,58300
14	8	0,12885	17	0,75794
14	9	0,16397	24	0,68321
14	10	0,15433	33	0,46767
14	11	30,06284	28	107,36729
14	12	15,79011	24	65,79213
14	13	7,08710	26	27,25808
14	14	6,46061	35	18,45889
14	15	0,34064	39	0,87344
14	16	0,35949	38	0,94603
14	17	0,04460	28	0,15929
14	18	0,08843	29	0,30493
14	19	0,10938	17	0,64341
14	20	0,17845	19	0,93921
14	21	0,17067	19	0,89826
14	22	0,09634	27	0,35681
14	23	0,10288	32	0,32150