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2024 Alina Terina

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Causes and effects of the “Black Sky Regime” in Krasnoyarsk, Russia

Bachelor Thesis

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Methodology:	A comprehensive literature review is the key element of the thesis. Scientific papers, annual statistical reports and other relevant sources will be reviewed. Meteorological and air quality observation of both long-term and selected extreme conditions in Krasnoyarsk will be presented, depending on the data availability.
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In Prague 27.03.2024

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Alina Terina

Abstrakt

Termín "režim černé oblohy" se v médiích vžil pro označení závažných epizod znečištění ovzduší v Krasnojarsku, které se vyznačují nepříznivými meteorologickými podmínkami definovanými vládou. Při těchto epizodách dochází k překročení přípustných limitů koncentrací znečišťujících látek stanovených úřady. Mezi hlavní znečišťující látky, které trvale překračují tyto limity, patří oxid uhelnatý, oxid siřičitý, oxid dusičitý, benzopyren a formaldehyd. Tato bakalářská práce se zabývá analýzou a vyhodnocením různých vědeckých prací, výzkumů a studií, které osvětlují faktory přispívající k opakujícímu se "režimu černé oblohy" a jejich důsledky. Hlavním cílem této práce je poskytnout podrobný popis příčin a zjistit, zda existuje souvislost mezi epizodami silného znečištění ovzduší ve městě a zdravotními problémy, které postihují jeho obyvatele a životní prostředí jako celek. Jedním ze zjištěných faktorů, které přispívají k tomuto jevu, je rychlá industrializace a urbanizace, které bylo město svědkem v minulém století, spolu s nedostatečným územním plánováním. To vedlo k tomu, že se město soustředilo kolem velkých průmyslových závodů, jako jsou hliníkárny, chemičky a kovovýroby, které byly označeny za významné zdroje škodlivých znečišťujících látek, jež podporují "režim černé oblohy".

Rostoucí nároky na počet obyvatel navíc urychlily výstavbu hustě osídlených bytových komplexů, což výrazně ovlivňuje rychlost větru. Závislost města na uhelných elektrárnách pro vytápění navíc tento problém ještě zhoršuje, protože do ovzduší vypouští oxid siřičitý, oxid dusičitý a pevné částice. Zásadní roli při zhoršování znečištění ovzduší hraje také zeměpisná poloha města, pro kterou je charakteristická nezamrzající řeka Jenisej, slabé větry a subarktické klima. V důsledku dlouhodobého vystavení obyvatel škodlivým látkám přítomným v ovzduší byla zjištěna významná karcinogenní rizika, přičemž alarmující je zejména zvýšené riziko respiračních a kardiovaskulárních onemocnění. Byly zaznamenány dopady "režimu černé oblohy" na životní prostředí, které poukazují na existenci vysokého obsahu těžkých kovů v půdě městské oblasti, což vede k její snížené úrodnosti. Kromě toho byly zjištěny zvýšené hladiny těžkých kovů v řece Jenisej. Kromě toho bylo zjištěno, že vládní systém monitorování kvality ovzduší a legislativa jsou zastaralé, příliš zjednodušené a občas nepřesné.

Práce rozsáhle rozebírá základní problémy, které přispívají k tomu, že vláda nečiní proaktivní opatření při řešení krize znečištění ovzduší, a obhajuje zapojení aktivistů jako účinnější řešení. Poskytnutím komplexního a transparentního přehledu o příčinách a dopadech si práce klade za cíl nejen prospět ruské aktivistické komunitě, ale také najít odezvu u mezinárodního publika, podpořit učení a inspirovat k aktivnějším opatřením v boji proti znečištění ovzduší.

Klíčová slova: znečištění ovzduší, městské prostředí, zdravotní rizika.

Abstract

The term "Black sky regime" has been developed by the media to refer to severe episodes of air pollution in Krasnoyarsk, characterized by adverse meteorological conditions as defined by the government. These episodes witness concentrations of pollutants surpassing the permissible limits set by the authorities. Among the key pollutants that consistently exceed these limits are carbon monoxide, sulfur dioxide, nitrogen dioxide, benzopyrene, and formaldehyde. This bachelor's thesis delves into an analysis and evaluation of various scientific papers, research works, and studies that shed light on the factors contributing to the recurring "black sky regime" and their repercussions. The primary aim of this thesis is to provide an in-depth description of the causes and ascertain whether there exists a correlation between the severe air pollution episodes in the city and the health issues affecting its residents and the environment at large. One of the identified factors contributing to this phenomenon is the rapid industrialization and urbanization witnessed by the city in the preceding century, coupled with inadequate urban planning. This has resulted in the city's layout being centered around major industrial plants such as aluminum, chemical, and metal production facilities, which have been identified as significant sources of the harmful pollutants fueling the "black sky regime".

Moreover, the increasing population demands have expedited the construction of densely packed apartment complexes, a choice that has been noted to influence wind speeds significantly. Furthermore, the city's reliance solely on coal power plants for heating purposes further exacerbates the issue by emitting sulfur dioxide, nitrogen dioxide, and particulate matter into the atmosphere. The city's geographical location, characterized by the unfreezing Yenisei River, light winds, and subarctic climate, also plays a pivotal role in exacerbating air pollution. Significant carcinogenic risks have been identified among the population due to their prolonged exposure to the harmful substances present in the atmosphere, with elevated risks of respiratory and cardiovascular diseases being particularly alarming. The environmental impacts of the "black sky regime" have been recorded, indicating the existence of high levels of heavy metals in the soil of the urban area, leading to its reduced fertility. Additionally, elevated levels of heavy metals have been detected in the Yenisei River. Moreover, the governmental air quality monitoring system and legislation have been found to be outdated, oversimplified, and occasionally inaccurate.

The thesis extensively discusses the underlying issues contributing to the government's lack of initiative-taking measures in addressing the air pollution crisis and advocates for activist engagement as a more effective solution. By providing a comprehensive and transparent overview of the causes and impacts, the thesis aims not only to benefit the Russian activist community but also to resonate with the international audience, fostering a learning curve and inspiring more proactive measures to combat air pollution.

Key words: air pollution, urban environment, health risks

List of abbreviations:

AMC-unfavorable weather conditions

PM – particulate matter.

NO_2 – nitrogen dioxide.

SO_2 – sulfur dioxide

CO – carbon monoxide

CPP -Coal power plant

WHO – World Health Organization.

HPP -Hydropower plant

O_3 – ozone

MPC – maximum permissible concentrations

HI -hazard index.

AQI – Air Quality Index

RUSAL – Russian Aluminum

GRP – Gross Regional Product

VPN – Virtual Private Network

EPA - Environmental Protection Agency

AQ – Air Quality

EPA AQI-Environmental Protection Agency Air Quality Index

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1.Introduction

Over the last decades the human population has been rapidly increasing and therefore expanding into new territories, building new urban environments, like cities. Numbers of people choosing to live in the cities has been increasing over the past decades, according to the United Nations statistics over last 200 years, the number of people living in the cities all over the world has advanced from 3% to 50% (Oke et al. 2017). With the expansion of the urban population the limits of the cities expand too. The landscape change behind rapid urbanization contributes to major environmental stress on the surrounding areas. Cities largely contribute to the change of atmospheric composition and the local climate. In return, the affected environment influences the people living in it, putting the population under risk of pollution.

Human activities related to urban growth disrupt the typical atmospheric conditions through the generation of emissions and pollutants from sources such as transportation and industrial activities. Air pollutants are substances that can cause long or short-term danger upon ecosystems, animals, or humans, when represented in adequate concentrations (WHO©2021). These substances can be in liquid, gas, or solid form, but are similarly transported by air flow. The main pollutants that are a cause of concern are listed in table 1.2.
Air pollution is the term used to describe the presence of these substances in the atmosphere, which alters normal atmospheric composition and raises specific health risks. The state of the pollutants reaching the human body is described as exposure and the actual amount of emissions absorbed by a human is considered a dose (Oke et al. 2017). Air pollutants may come from both natural and anthropogenic causes, although the latter is of greater importance when considering how urban environments affect the atmosphere. The pollutants emitted directly to the atmosphere are referred to as primary, and the ones formed in the atmosphere with the primary pollutants as secondary. Sources like fuel combustion, traffic, waste incinerators, power plant smoke are the main producers of major air pollutants (Oke et al. 2017).

The process of combustion involves a series of chemical reactions between hydrocarbons and atmospheric oxygen, resulting in the emission of carbon dioxide and water vapor into the atmosphere. When this combustion takes place at elevated temperatures, atmospheric nitrogen combines with oxygen to produce nitrogen dioxide, a hazardous substance. Further non-carbon or non-hydrogen element production like sulfur can affect the atmosphere (Oke et al. 2017). The solid or liquid particles deposited in the atmosphere by combustion are called aerosol or particulate matter (PM).PM particles normally differ in size; however, the most common ones are referred to as PM 2.5(small enough to be deposited in a bloodstream) or PM 10(mainly deposited in the lungs). Liquid substances that are evaporated in the air are named volatile organic compounds (VOC), and are normally produced by the manufacturing of paints, solvents, refrigerants (Oke et al. 2017).

The presence of air pollutants in the air is measured as a concentration – mass per volume of air, in micrograms per cubic meter or $\mu g/m^{-3}$. Concentrated in the atmosphere, the pollutants are affected by wind, turbulence, and topography. The emissions can get trapped in between the buildings, some deposit just above the ground and some are distributed further by the wind. Air pollution in more vegetated regions is significantly lower compared to urban streets, as the presence of green open spaces facilitates the dispersion of pollutants by the wind, while the dense construction in urban areas promotes the mingling of harmful substances and restricts their spread. The phenomenon of poor air quality on an urban or regional scale is referred to as smog. During the smog, the air becomes hazy, opaque, and sometimes develops an odor. There are two types of smog: sulfur and photochemical (Oke et al. 2017).

Sulfur smog is caused by the emissions from coal and fuel burning-PM and sulfur dioxide (SO_2). This smog is characteristic to the urban areas that rely on heat power plants, furnaces and do not control the industry emissions. It occurs typically in conditions of mid to high altitude, in the winter. London Smog of 1952 serves as an example of sulfur smog. Fuel that was consumed for the heating facilities against the prolonged cold weather produced high amounts of PM and SO_2. Exceeding concentrations of these substances created a smog so thick the sun could not penetrate it. The absence of a strong wind made the conditions even worse. The excess of air pollutants for several days resulted in excess of 12000 deaths that year (Oke et al. 2017).

Photochemical smog is primarily induced by elevated levels of nitrogen oxides (NO) and VOCs originating from vehicular sources. This atmospheric phenomenon thrives under intense sunlight, making it characteristic of summer seasons or tropical regions. The interaction of ultraviolet radiation with NO emissions from automobiles leads to the formation of ozone (O_3). The presence of gentle breezes further compounds the issue, resulting in a murky, brownish atmospheric condition with a pungent smell and reduced visibility. Photochemical smog can cause irritation to the eyes and lungs, cause damage to plant life. Cities such as Los Angeles have been experiencing pollution episodes as such since the 1940s. This is primarily due to the consistent sunny, cloudless weather and abundance of vehicles which creates optimal condition for smog formation. Approximately 1,100 incidents of mortality in Los Angeles between 1956 and 1958 were attributed to severe pollution (Oke et al. 2017).

Serious pollution incidents that occurred in London and Los Angeles serve as both a historical lesson and a source of inspiration for upcoming legislation and air quality management strategies. Nonetheless, extreme pollution events are still a problem in many global cities today. Krasnoyarsk is among them.

For a very long time, air pollution in Krasnoyarsk has been a major issue. Although the exact year when the city began to experience severe pollution events is unknown, some records go at least as far back as the 2000s. Being a very resource-rich area, the city grew rapidly and turned into a major industrial center, which eventually caused it to become one of Russia's most polluted cities. It is affected by sulfur type smog in the winter and photochemical type smog in the summer. During the summer season, the hot weather, windless conditions, and car fumes create a brown haze, and, during the winter, the coal power plants, vehicle exhaust and industrial emissions create a heavy smog. The dispersion of harmful impurities in the air is impeded, resulting in enormous concentrations of industrial emissions, car exhausts, dust, and smoke in the atmosphere. The phenomenon of severe air pollution episodes is recognized in the media as "black sky," because it produces heavy smog that can be seen with the naked eye. However, in reality, it is dingy grey rather than black (Shaparev et al. 2020).

The government is required to alert the public and major industries about the implementation of the regime of adverse meteorological conditions (AMC) during periods of extreme pollution. When pollution concentrations in the air surpass permitted levels, this regime is implemented. As per the regulations, it is advised for residents to stay indoors and is required for enterprises to reduce their emissions by 15% to 20%. The Federal service for Environmental monitoring of Krasnoyarsk only shares the information about the episodes of severe pollution from 2012, therefore the study is limited to a period of 2012 – 2024 (AdmKrsk.ru © 2012).

Table 1.1 Number of Days with the AMC regime implemented by the government per year (AdmKrsk.ru © 2012).

Year	Number of Days
2012	43
2013	27
2014	40
2015	70
2016	61
2017	43
2018	31
2019	13
2020	21
2021	31
2022	24
2023	29

The regime of AMC has been implemented annually, for 30-70 days a year according to the data in Table 1.1, based on the information taken from the website of Federal Service for Hydrometeorology and Environmental Monitoring of Russia. The phenomenon is characterized by the presence of thick smog that covers the entire city, reduced visibility, and the saturation of the air with harmful pollutants and unpleasant odor. Figures 1.1 and 1.2 illustrate the level of visibility experienced under the conditions known as the 'black sky regime'. These visual depictions exhibit a standard level of clarity observed in the occurrence of smog, with Figure 1.1 captured in 2016 and Figure 1.2 in 2023, demonstrating similarity even after a span of 7 years. Such severe air pollution occurrences, accompanied by smog, could persist for multiple days or weeks.

Figure 1.1 (KRSK.AIF.RU©2016).

Figure 1. 2 (NGS24.RU©2023).

The pollutants most commonly found in the air during these occurrences are detailed in table 1.2. Furthermore, the potential health impacts of extended contact with these chemicals are outlined, alongside the risks to the environment.

Table 1. 2 Environmental and Health risks of major air pollutants present in the atmosphere of Krasnoyarsk and their impacts according to (Oke et al. 2017).

	Impact on Human Health	**Impact on the Environment**
CO	Causes fatigue, dizziness, increased heart rate, difficulty breathing.	Affects animals the same way as humans. Contributes to formation of the greenhouse gases CO2 and O3 when oxidized.
SO2	Can harm the respiratory system, make breathing difficult, making the respiratory extremely sensitive, asthma.	Causes acidification of soils and aquatic ecosystems downwind of emissions, can damage forests ecosystems
NO2	Can cause fatigue, dizziness, can aggravate existing respiratory diseases, asthma, increase sensitivity to respiratory infections.	Contributes to the eutrophication of aquatic ecosystems.
PM (both 2.5 and 10)	Can cause asthma, heart attacks, irritation of the airways and coughing.	Particles can acidify lakes and streams, alter the nitrogen balance, deplete nutrients in soil, harm sensitive forests and agricultural crops, and reduce ecosystem diversity, contribute to the acid rain
Formaldehyde	Carcinogen, that can cause diseases like throat and nose cancer, leukemia in humans with long-term exposure. Shorter exposure can cause eye, nose	Contributes to acid rain, when deposited in soil or water, can impact biodiversity, affects animals and in the air can mix

	and throat irritation, dryness, skin rashes and can affect lung function.	with other elements to create more harmful compounds.
Polycyclic aromatic hydrocarbons (PAH)	Benzopyrene can cause skin and eye irritation, is a carcinogenic element, so it can cause skin and lung cancer, can also affect the male and female reproductive and cardiovascular systems	Many PAHs have acute toxic effects on aquatic life and birds and damage leaves of plants. Selected PAHs bio-accumulate in food-chains.

Table 1.2 demonstrates the harm caused by these pollutants; formaldehyde and benzopyrene are recognized carcinogens, which is significant given the whole city population's regular exposure to them. Other components, such as nitrogen and sulfur oxides, as well as particulate matter, have the potential to induce new heart and lung illnesses. It has been stated by Arutyunyan et al. (2015) that the number of "excess" deaths caused by exposure to severe air pollution in 2015 in Krasnoyarsk accounted to 1093 (81 cases from lung illnesses and 727 cases from cardiac disorders). The paper aims to explore and elucidate the cause and effect of Krasnoyarsk's "black sky regime" from the perspective of an individual whose family remains living in the city and who has lived under the aforementioned conditions for 17 years.

1.1 Objectives

Define the concept of "black sky regime" in Krasnoyarsk, Russia, and analyze the primary factors that contribute to the air pollution within the city. Elaborate on each factor and their impacts. Identify the key pollutants associated with air pollution in the city and assess whether these pollutants have an impact on the health of the residents and the environment.

2.Literary Research

2.1 Causes

The present section has defined and described the primary factors contributing to air pollution. The strategic approach of sequentially presenting the study area and delving into the various causes was specifically adopted for this chapter. It was deemed imperative to delve into the historical backdrop of the urban locality in question, as it was understood to wield a significant influence in shedding light on the underlying causes of the recurrent and severe episodes of air pollution that have plagued the city. It was through an examination of the city's past that a deeper understanding of the factors contributing to the detrimental air quality was achieved, thereby paving the way for effective mitigation strategies to be formulated.

2.1.1 Geographical position and temperature inversion.

Krasnoyarsk serves as the administrative hub of Krasnoyarsk krai, the second largest region in Russia, and stands out as a significant economic and cultural focal point in Siberia. Established in 1628 by the Cossacks, it holds the distinction of being the oldest city in Siberia. Situated in southern Siberia, as can be seen in Figure 2.1, Krasnoyarsk is enveloped by the Sayan mountains and forest-steppe, with the Sayan mountain range harboring the renowned Stolby National Park, extensive rock formations, and lush evergreen forests. Positioned along the Yenisei River, which ranks as the largest and longest river in Krasnoyarsk Krai, with a total length of 3,487 km and a basin area of 2,580,000 km^2(Bykonya 2012).

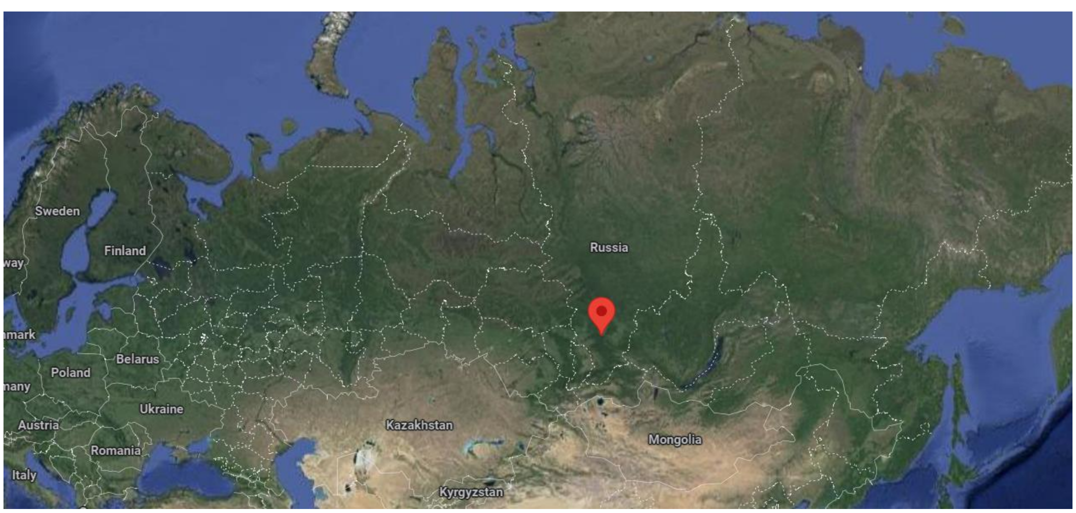

Figure 2.1 Geographical position of Krasnoyarsk, Russia, where the red dot symbolizes the location Krasnoyarsk (GoogleMaps©2024).

The city's topography exhibits a varied, heterogeneous landscape, as depicted in Figure 2.2. Nestled in a lowland, Krasnoyarsk is flanked by hills on the left side of the river and a substantial ridge on the right riverbank, resembling a valley. This distinctive setting contributes to the presence of poor air quality within the city. Research conducted by Rendón et al. (2015) reveals that urban valleys, such as the one in Krasnoyarsk, are particularly susceptible to temperature inversions, the urban heat island effect, and limited air circulation.

Temperature inversions pose a significant challenge in Krasnoyarsk due to its unfavorable positioning amidst the mountains and the non-freezing river, compounded by the absence of a sufficiently robust wind to facilitate the movement of air masses. In essence, a thermal inversion occurs in regions where the typical decrease in air temperature with altitude is inverted, leading to the formation of abnormally structured areas. The colder air becomes concentrated at lower levels, being trapped by the warmer air masses situated above it. Consequently, this phenomenon engenders the development of stable air masses, as the cold air remains trapped beneath the warmer air layer, making it notably resistant to dispersion through wind patterns (Rendón et al. 2015).

Thermal inversions can arise from various conditions; however, the main focus of this paper is particularly on those associated with the case of Krasnoyarsk. One major factor is the swift decrease in temperature of the atmosphere above the ground at night, which occurs as a consequence of the rapid cooling of the earth and air after being exposed to sunlight throughout the day. This particular cause is relevant to the situation in Krasnoyarsk due to its climatic conditions, which are conducive to prolonged periods of extreme cold at night. Moreover, during the winter season, the presence of substantial snow cover contributes to the development of temperature inversions even during daylight hours. The reflective nature of snow hinders the absorption of radiation, thereby impeding the warming of the ground and maintaining lower temperatures in both the ground and the air directly above it, while simultaneously allowing for warming in the higher atmospheric layers (Hakim et al. 2021).

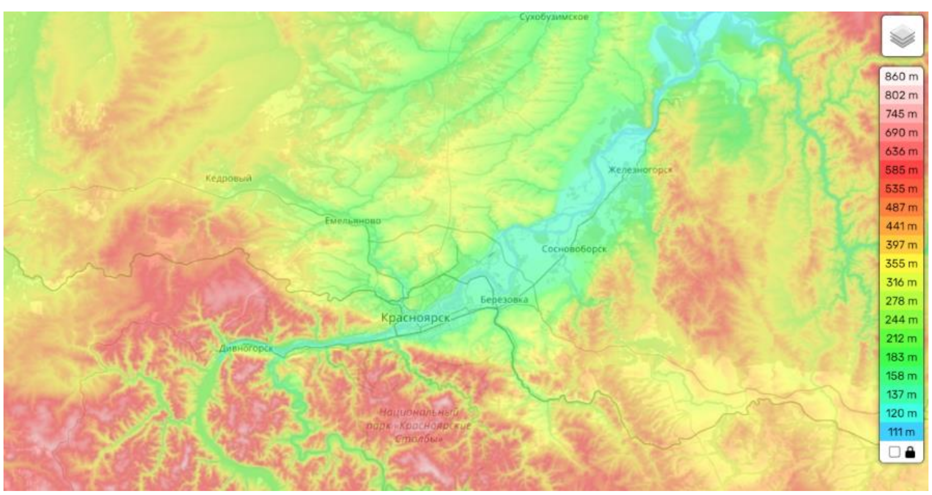

Figure 2.2 Topographic Map of Krasnoyarsk (Topographic-Map 2024).

In the mornings, particularly during the winter months, the Yenisei River experiences a rise in temperature as a result of the presence of dams constructed upstream. This leads to the formation of dense fog, which is then trapped close to the ground by an inversion layer, resulting in reduced visibility and limited air movement. Furthermore, the municipality of Krasnoyarsk depends on coal-fired power stations to fulfill its heating requirements, opting for this energy source over natural gas due to its cost-effectiveness and widespread accessibility. This choice results in the emission of harmful pollutants into the air through the burning of coal and other industrial operations. These pollutants become trapped by the temperature inversion, combining to form harmful smog that lingers at ground level until atmospheric conditions improve. (Britannica © 2020; Hakim et al. 2021).

2.1.2 The Yenisei River.

The city of Krasnoyarsk is based on the Yenisei River, which is one of the largest rivers in the world, and the second longest in Russia. The Yenisei River is characterized by an average width of 500-600 meters in the city (Badmaeva & Sokolova 2017). During the 20th century, the energy of the river was harnessed for the construction of three hydroelectric power plants on the Yenisei River, namely the Sayano-Shushenskaya, Maina, and Krasnoyarsk dams. These dams continue to serve as significant sources of electrical power for the adjacent communities and industrial facilities (Shaparev et al. 2022).

Additionally, Yenisei has been highly influenced by the mentioned dams, which disturb the natural streamflow speed of the river, its temperature and sediment presence. The river does not freeze, even in the cold winter weather in Siberia, with temperatures that can get as low as - 40 degrees Celsius. This phenomenon can be explained by the Krasnoyarsk HPP that is based upstream. The HPP reservoir fills with water over time. The depth of water in the reservoir does not allow for the river to freeze completely, only on the surface, and all the water deeper remains unfrozen. The unfrozen water is eventually released by the dam. The contrast in temperature between the cold air and the warmer river causes the water to evaporate as it flows through Krasnoyarsk. This process causes heavy fog to build above and surrounding Yenisei. This impact is amplified on windless days and weak or no wind conditions are common in the city, with yearly averages of windless days accounting to 41-50%, according to long-term data (Shaparev et al. 2022).

During the summer season, a similar phenomenon occurs where the reservoir's depth causes only the upper layer of water to warm up, leaving the lower levels cold and discharged by the dam. Consequently, the warm air above the cold river generates fog through heat exchange, cooling the air in the process. These processes have been recognized as fog; a meteorological phenomenon characterized as a cloud in close proximity to the ground containing small water droplets (Hakim et al. 2021). Following the saturation of air with water from the Yenisei River, it combines with emissions from coal combustion, including carbon dioxide, methane, nitrous oxide, and vehicular exhaust, leading to the formation of smog (Hrebtov & Hanjali 2017; Shaparev et al. 2022).

2.1.3 Air Temperatures

Krasnoyarsk experiences a humid continental climate bordering on a subarctic climate, according to the Köppen climate classification (Köppen 2011). It is crucial to note the significant difference in temperatures between the winter and summer seasons in Krasnoyarsk. These fluctuations are not only severe, but also hazardous. Winter seasons can be characterized as very cold, humid, and snowy. The cold season normally lasts for three and a half months, with the coldest month being January. For deeper understanding of the changes in temperatures between coldest and warmest seasons, maximum/minimum temperatures for months of January and July from the last 7 years are shown in Figure 2.3 below.

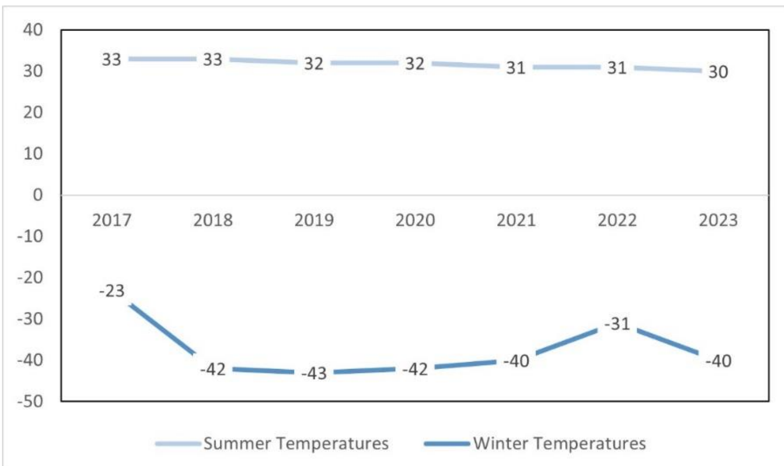

Figure 2.3 Maximum/Minimum temperatures recorded in the months of January and July over the years of 2017-2023, based on data from (WorldWeather©2024).

As Figure 2.3 suggests, the months of January can be characterized as very cold, typical for Krasnoyarsk subarctic climate, reaching temperatures as low as – 43°C over the past years.

Temperature has a significant impact on the air mass characteristics. Warm air has been proven to be less dense than cold air. As the air is heated, the atoms are influenced, causing them to move faster and further in order to occupy as much space as possible, resulting in a large amount of space between them. In contrast, atoms in cold air slow down and move closer together, resulting in a denser space. As a result, cold air masses are heavier and more difficult to move with the wind. That is why cold weather is an issue when discussing air pollution. The presence of dangerous compounds in dense air enables contaminants to remain trapped in the atmosphere for long duration of time (Hakim et al. 2021).

Given that the emissions originating from the primary industrial facilities in Krasnoyarsk persist throughout the entire year, the predominant risk of pollution in this area emanates from the coal power plants, which remain the primary source of heating, utilized by 90% of the city's population (Moiseeva 2023). The harsh cold weather conditions, as illustrated in Figure 2.3, necessitate the continuous operation of the power plants. The heating infrastructure in Krasnoyarsk is decentralized, with a majority of the apartment complexes relying on the coal power plants (CPPs) for heat supply; however, some streets and the private sector still utilize outdated boiler houses from the previous century, where coal, gas, or fuel oil are burned to produce heat and hot water.

Moreover, during the winter season, the sun's lower position in the sky results in minimal warmth reaching the Earth's surface, leading to the atmospheric layer above becoming warmer than the ground, contributing to the phenomenon known as temperature inversion. The relationship between the unfavorable meteorological conditions that Krasnoyarsk is prone to and temperature inversions for the years 2019, 2020 was described by Dergunov & Yakubailic (2021). The analysis revealed that the number of days with temperature inversion was highest during the winter months.

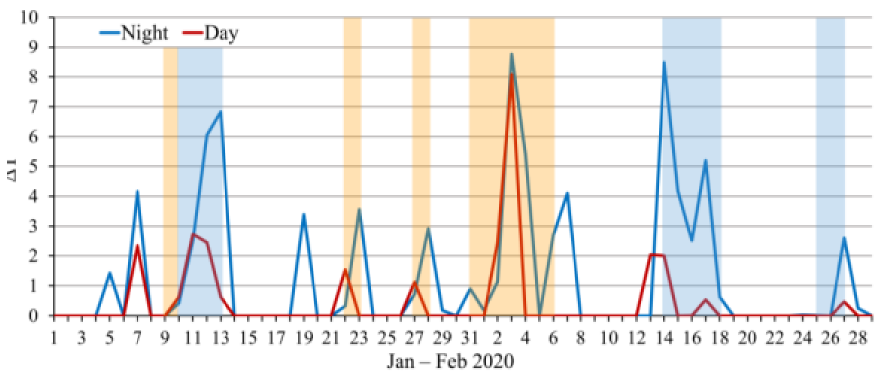

Figure 2.4 Values of temperature inversions (ΔT) in the surface layer of the in January-February 2020, blue markings represent the periods of AMC (Dergunov & Yakubailic 2021).

In Figure 2.4 blue markings are used to define periods of AMC in the city. Figure 2.4 demonstrates the significant correlation between adverse meteorological conditions and temperature inversions.

Warming up car engines in winter is a common practice to ensure proper lubrication and prevent potential issues in the future. Idling, once considered necessary, is now seen as outdated, particularly in newer vehicles. However, the average age of cars by 2023 in the region was 15 years, while in Russia as a whole it was 14 years (Krasnoyarsk.dk.ru © 2023). Research by Debdin & Fadeev (2021) revealed that in Krasnoyarsk, cars emitted 78.1 thousand tons of CO annually.

Nevertheless, the practice of allowing the engine to run before commencing driving remains prevalent in Krasnoyarsk. In the face of extreme temperatures reaching as low as -40 C, individuals yield to the necessity of prolonging the engine's lifespan and choose to engage in idling. According to findings from the US Department of Energy, idling vehicles significantly contribute to the greenhouse effect. This behavior alone results in the emission of up to 30 million tons of CO annually in the United States (regrettably, data regarding Russia's contribution to this issue is currently unavailable) (U.S. Department of Energy ©2015).

The occurrence of extreme pollution events in Krasnoyarsk is not confined to the winter season. During the summer months, the city experiences average temperatures as depicted in Figure 2.3, with temperatures reaching up to +30°C (with July being the hottest month), calm wind conditions, and forest fires. The expansion of urban areas is leading to changes in the reception and loss of solar radiation, as well as alterations in air flow patterns. The growing urban footprint, driven by the demand for new residential and commercial structures, is resulting in the reduction of green spaces. This, in turn, affects natural processes such as heat storage and evapotranspiration, along with heat generation from burning fuels, leading to a rise in average temperatures within urban areas. This phenomenon is known as the urban heat island effect (Oke et al. 2017).

Sunlight and high temperatures lead to the reaction of pollutants present in the atmosphere. These pollutants, such as NO and VOC, interact with Ultraviolet (UV) radiation and heat to produce ground-level ozone, a significant pollutant that plays a role in the greenhouse effect, smog formation, and respiratory health issues in individuals. The smog observed in Krasnoyarsk is categorized as a photochemical type, similar to that found in Los Angeles. This type of smog is exacerbated in Krasnoyarsk due to weak winds that are unable to effectively disperse pollutants from the city. Factors such as urban heat island and ozone haze are key contributors to severe pollution events in Krasnoyarsk, with frequent forest fires also playing a role. These wildfires can be initiated by extended periods of drought, strong winds, and/or human activities (Hakim et al. 2021).

The trends of wildfires on the territory of Siberia for the past 10 years were described by Ponomarev et al. (2023). Using satellite monitoring data, it has been determined that the intensity of the fires has been increasing over the years, as well as the overall production of greenhouse gas emissions. Data collected by Ponomarev et al. (2023) states that the total area of wildfires increased from 0.4-0.6 million ha/year in 2002–2011 to 0.5-1.5 million ha/year in 2012–2019. Seasons 2020 and 2021 were record-breaking, with the total affected area of 1.0 and 2.5 million ha, respectively. The illustrated increase in the affected by the wildfires area suggests the increase of the smoke-related emission production. Wildfires emit substantial amounts of greenhouse gases and particulate matter in the atmosphere. Burning of the grasslands and forest causes the carbon dioxide stored in them to be released, contributing to climate change. Excessive presence of particulate matter in the atmosphere contributes to air pollution and endangers the health of nearby residents. The same study done by Ponomarev et al. (2023) defined the values for the average long-term wildfire emissions that increased from 60.0-25.8 tg/year in 2002-2011 to 295.0-102.0 tg/year in 2020-2022 (Ponomarev et al. 2023).

When reaching the city, carbon dioxide emitted by the wildfires undergoes a reaction with nitrogen dioxide and volatile organic compounds, subsequently forming ozone. The presence of smoke from the fires, along with an excess of ozone, plays a significant role in the occurrence of severe air pollution episodes within the city, resulting in the formation of smog. This situation has prompted the implementation of the AMC regime in Krasnoyarsk, as highlighted by Syaufina et al. (2018) and Gosteva et al. (2020).

2.1.2 Socio-economic development.

The Krasnoyarsk Krai region was always rich in valuable natural resources like nickel, platinum group metals, cobalt, gold, and coal, which played a crucial role in its rapid transformation into a major industrial hub in the past. The early 20th century witnessed the construction of the Trans-Siberian railway, a development that significantly fueled the growth of the Krasnoyarsk area. Furthermore, its abundant resources not only attracted domestic investment but also caught the attention of foreign investors (Bykonya 2012).

The 1950s marked a period of notable progress in the development of Krasnoyarsk. Stalin's ambitious five-year plans included the establishment of several key factories, such as Sibtyazhmash (heavy metallurgy), a paper mill, a hydroelectric power plant, and a dockyard with a river port. These newly built facilities played a crucial role during World War II, as factories from the western part of the country were relocated to Siberia, due to the German occupation of the western part of Russia. A total of 400 enterprises were evacuated to Siberia, with 42 of them situated in the Krasnoyarsk (Bykonya 2012). Following the war, many of these factories resumed their operations and shifted back to producing civilian goods.

The support provided by the factories in Krasnoyarsk territory during the war attracted the attention of the government to the city. Other factories were built, with many remaining essential to the city´s function in the 21st century.
Following the financial crisis of 1998, Henry & Douhovnikof (2008) state that the government promoted the utilization of natural resources as a means to stimulate the economy. Henry & Douhovnikof (2008) conducted an analysis indicating that in recent years, the resource sector contributed to a 4% annual economic growth rate out of a total of 7%.
At present, the region plays a significant role in Russia's nickel, copper, primary aluminum, accounting for almost 98% of global output of platinum group metals production levels (FederationCouncil©2023). Major players in this sector include the Krasnoyarsk Aluminum Plant (RUSAL) and the Krasnoyarsk Metallurgical Plant.

The majority of the industry's output comes from extracting raw materials for non-ferrous metals, with coal mining being the second most significant activity, generating an annual average of more than 50 million tons. (FederationCouncil, ©2023). Furthermore, the Krasnoyarsk Territory's forests contribute to this economic landscape with an annual timber harvest exceeding 55 million cubic meters. This region ranks as the third most significant timber producer in Russia (FederationCouncil, ©2023). The socio-economic growth of Krasnoyarsk Krai and its city has been noteworthy, as demonstrated by the significant increase in the gross regional product (GRP) from 70 million rubles (€70 million) in 1998 to 3.5 trillion rubles (€35 million) in 2023, reflecting a 3% GRP growth rate. This expansion underscores the escalating reliance of the Russian economy on the region's natural resources, a trend that is of paramount importance for further analysis of the factors impacting the region's air quality.

The city's swift progress is linked to its advantageous placement in close proximity to plentiful resources, which has drawn in significant mining businesses and an expanding populace. The information put forth predominantly underscores the idea that the city underwent rapid expansion that exceeded its capacity to adapt in terms of urban planning and ecological considerations.

2.1.3 Population and Build up.

The overall geographical expanse of the urban center along with its surrounding suburbs encompasses 348 square kilometers. The city accommodates a considerable populace of 1.2 million individuals, distributed across approximately 41 kilometers extending from west to east, resulting in a population density of 2765 persons per square kilometer (24. Rosstat © 2023). The heightened concentration of inhabitants within the city limits serves as a significant contributing factor to the prevalent air pollution issues observed in Krasnoyarsk. This section delves into an exploration of the underlying reasons behind it.

Figure 2.5 illustrates the consistent growth of the population, showing a significant surge that commenced in the 1950s and led to an increase from 300,000 to 900,000 individuals by the early 2000s. Based on the forecasts depicted in Figure 2.5, it is expected that the city will continue to expand rapidly in the upcoming years. The demographic data plays a crucial role in uncovering the root causes of the environmental pollution issue within the city. The escalating population not only demands more residential infrastructure and energy resources but also contributes to the surge in private vehicle ownership, which is one of the key factors in urban pollution of Krasnoyarsk.

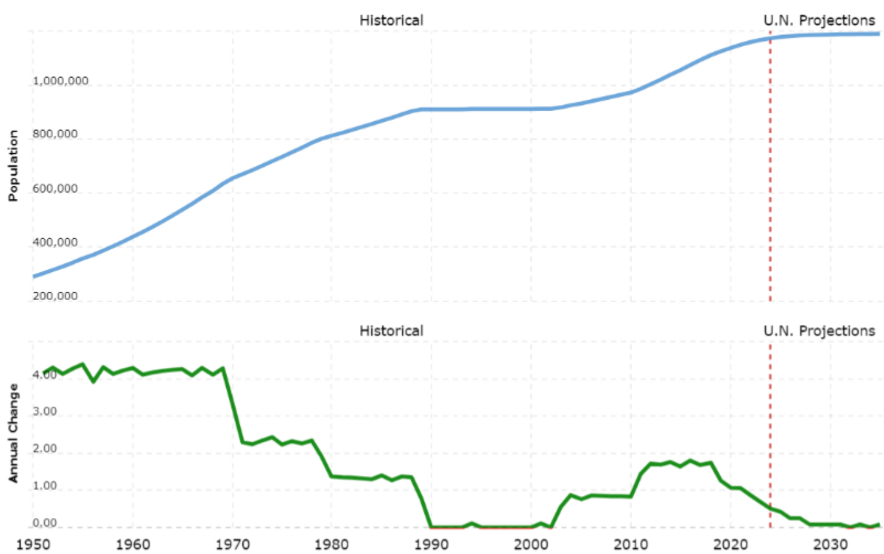

Figure 2.5 Historic population data and future projections (Macrotrends©2024).

The rise in population growth necessitates adequate housing options. In Krasnoyarsk, the construction of apartment complexes is a prevalent urban development trend. This can be exemplified by the micro-district "Pokrovsky" located in the city center, comprising numerous apartment buildings along with amenities like kindergartens and supermarkets within the vicinity. The visual representation of the micro-district can be observed in

Figure 2.6 "Pokrovsky" micro-district (LifeJournal©2015).

Figure 2.6. Such urban planning approach is commonly observed throughout Krasnoyarsk, with Cian reporting the construction of at least 67 new residential complexes and a total of 93 existing ones by the year 2023 (Cian©2024). These complexes typically range from 10 to 25 stories in height, reaching up to 65 meters tall.

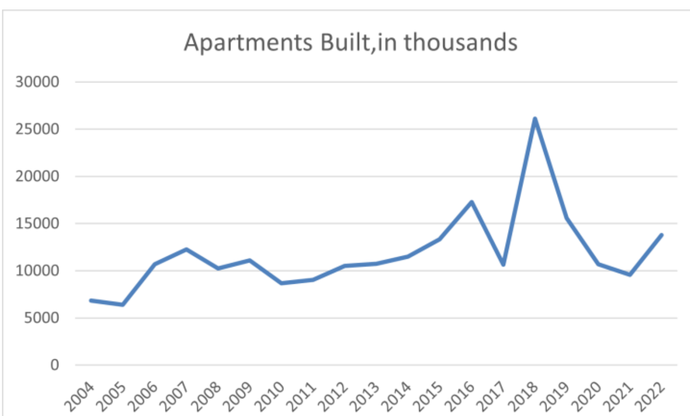

Figure 2.7 Apartments Built in Krasnoyarsk, in thousands based on the data from (Cian©2024).

Figure 2.6 illustrates the relatively scattered layout of the apartment buildings, which have been constructed in a dispersed manner. As the population of the area expands, there is a corresponding increase in the construction of new residential units to accommodate the growing number of residents. In contrast, Figure 2.7 displays a visual representation of the total number of residences that have been built in Krasnoyarsk over the course of the past two decades. The consistent projections of population growth presented earlier indicate a sustained demand for the development of large-scale residential complexes in order to meet the housing needs of the growing population. Quick introduction to the buildup patterns in the city is necessary in order to continue to identify the cause for air pollution in the city, the impact of this factor would be expanded further.

2.1.5 Wind

Wind is defined as the air flow in the atmosphere, which is more likely to flow parallel to the ground, especially in flat terrains. In the presence of mountains, trees, and high buildings the wind can undergo changes, uplift, or sink. Changes in flow and velocity are referred to as turbulence. The stress on the air flow is larger at Earth's surface, because of the friction imposed by the ground and the elements on the ground (buildings, trees). The described influence on the air flow is defined as a drag. Skin drag dominates over flat surfaces, and form drag prevails over rough ones. For example, the presence of buildings perturbing from the ground would cause form drag and disrupt the air flow (Oke et al. 2017).

The behavior of air flow in a vicinity to an isolated sharp-edged cube building has been described by Oke et al. (2017). The wind is directed towards the building, and upon encountering the building's face, flow separation is initiated, leading to the divergence of airflow in various directions: above the roof, along the sides, and downwards the frontal area. The increased velocity of the airflow over the roof exerts pressure on the air currents flowing at the lower section, prompting them to curve in a downward direction, whereas the airflow at the upper part is directed upwards and over the roof, as can be seen in the figure 2.8.

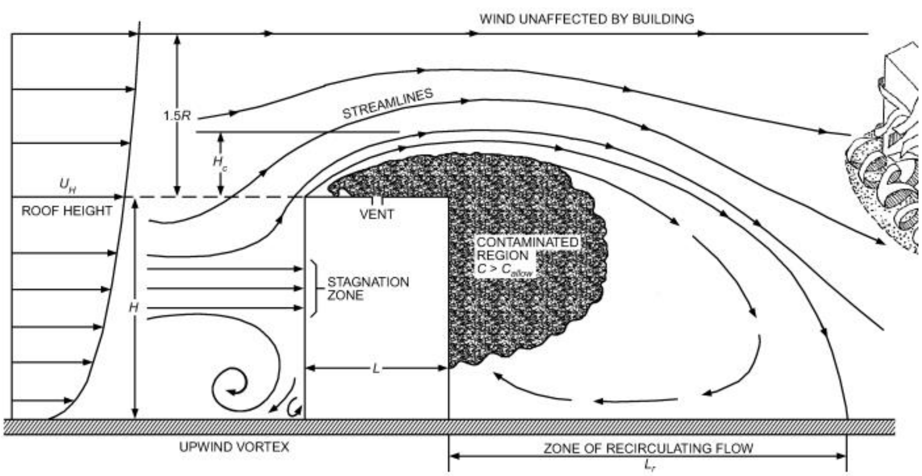

Figure 2.8. Flow Patterns Around Rectangular Building (ASHRAE 2005).

After flowing over the building's roof , the swift upper layer of airflow, along with the robust airflow from the lateral walls, compels the lower section of the airflow to descend and counteract the upward flow, thereby establishing a region of recirculating airflow (Oke et al. 2017).Air pollutants that may be present in the air are drawn into the recirculating flow region behind the obstacle (building) ,which temporarily traps them, creating a downwash effect that leads to a higher surface level pollution concentration near the building, than if the building was not present(ASHRAE 2005).

The urban landscape is commonly characterized by a diverse range of buildings differing in both height and width. In the context of Krasnoyarsk, this variety is exemplified by numerous residential complexes of varying sizes and architectural styles. It is evident that a solitary building can disrupt the natural airflow patterns, highlighting the detrimental effects of such isolated structures on air circulation. This observation underscores the potential consequences of having a multitude of distinct housing developments within the city, each exerting its own unique influence on the local air flow dynamics. It is stated by Badmaeva & Maksimov (2020), on the example of "Pokrovsky" district in Krasnoyarsk, that wind speed was reduced by 25-30% within the neighborhood when compared to the city's other underdeveloped parts. Unfortunately, while the number of high-rise residential areas increases, so does their effect on the wind patterns in the city.

Reduced wind speed is of concern when it comes to air pollution problems. It has been stated by Liu et al. (2020) that pollution or a certain presence of substances in the atmosphere can be influenced by the wind. The precise velocity of the air flow necessary for the dispersion of pollutants within the Earth's atmosphere remains a topic of debate within the scientific community. Nonetheless, findings presented by Liu et al. (2020) suggest that pollution levels are less likely to reach moderate or higher levels when exposed to wind speeds of 5 meters per second or greater. The complex urban layout of Krasnoyarsk and the valley-induced effects contribute to the challenge of having predominantly light winds, as described in the Beaufort wind force scale. Detailed records of wind speeds specific to the city of Krasnoyarsk have been systematically gathered over a span of seven years and are documented in Figure 2.9 for reference and analysis purposes.

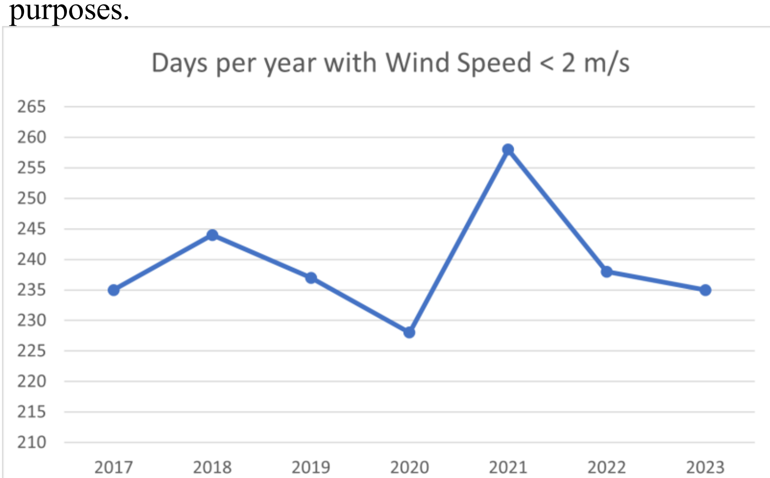

Figure 2.9 The number of days, when the wind Speed was < 2 m/s in the city of Krasnoyarsk 2017-2023, based on the data from (WorldWeather©2014).

Figure 2.9 illustrates the prevalence of light breezes in the city for approximately two-thirds of a year for the past seven years. The findings by Liu et al. (2020) could be relevant to this pattern, under the assumption that the airflow in Krasnoyarsk lacks the necessary strength to facilitate the dispersion of pollutants away from the urban area.

2.1.6 Anthropogenic pollution.

Human activities contribute significantly to the air quality in urban areas; the aforementioned factors play a crucial role in amplifying the effects of emissions. Key pollutants found in the air consist of benzopyrene, formaldehyde, suspended particulate matter, nitrogen dioxide, sulfur dioxide, and carbon dioxide. The main industries contributing to pollution are presented in Figure 2.10, including the fractions of substances they deposit in the atmosphere.

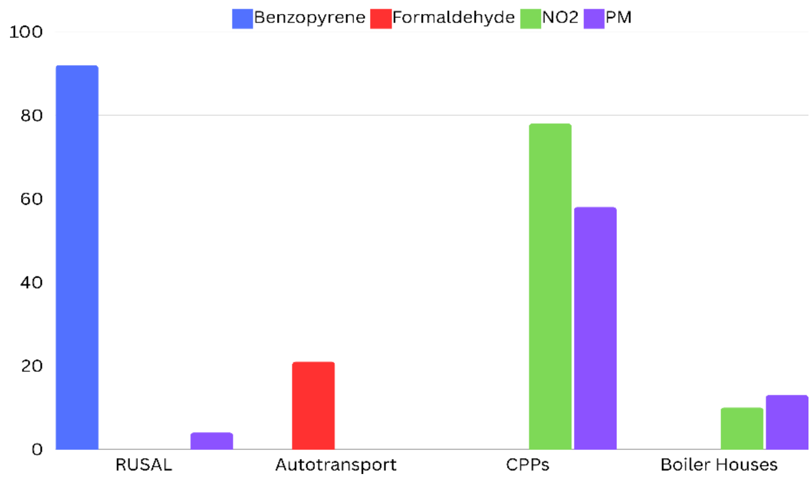

Figure 2.10 The overview of major polluters and industries and the fractions of substances they deposit in the atmosphere, in % (Krasecology ©2012).

Traffic

In the aftermath of the 1990s, there was a substantial surge in the presence of foreign automotive brands, leading to a sharp increase in the average number of cars per individual. As indicated by the Debdin & Fadeev (2021), the overall quantity of various types of automotive vehicles has been steadily rising since 2018, reaching 1,076,539 by 2021 as depicted in Figure 2.11.

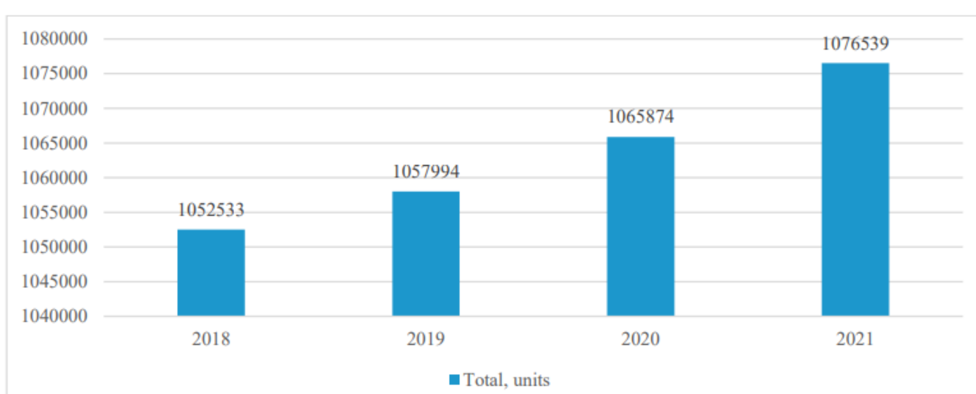

Figure 2.11 Number of cars registered in the Krasnoyarsk Territory, 2018–2021, units (Debdin & Fadeev 2021).

The main pollutants emanating from cars include benzopyrene, formaldehyde, CO, NO_2 and heavy metals such as iron, manganese, copper, and zinc. Private vehicles constitute a significant source of air pollution in Krasnoyarsk, contributing to approximately 60% of the total hazardous material emissions. This is attributed to the widespread usage of cars with elevated levels of toxicity and engine emissions (Debdin & Fadeev 2021; Zlobin 2017).

Furthermore, Debdin & Fadeev (2021) reported that in 2020, 50% of vehicles in the city used petrol, 35% used diesel, and 15% used gas. The current researches exploring the environmental impact of different types of fuel sources is unfortunately constrained by limitations, thereby hindering comprehensive and conclusive evidence on which fuel is more detrimental to the environment. However, the research conducted by Caserini et al. (2013) makes an observation that engines based on diesel produce higher emissions of NO_2 and PM 10. There exists an environmental classification of vehicles, which is determined by a specific criterion based on their environmental impact. In Russia, this classification system was established following the Geneva Convention (1949) and consists of 5 different classes: Euro 1 to Euro 5.

Euro 1, which came into effect in 1992, established emission standards which stated that for petrol vehicles, the allowable level of CO emissions should not surpass 2.72 g/km, while the combined emissions of Hydrocarbon (HC) and NOx should be limited to 0.97 g/km. In the instance of diesel engines, the designated emission thresholds were defined as 2.72 g/km for CO, 0.97 g/km for the combined emissions of HC and NOx, and 0.14 g/km for PM (under the Directive 91/441/EEC).

Euro 2, introduced in 1997, further strengthened the emission regulations, requiring that petrol vehicles emit no more than 2.2 grams of CO per kilometer and restricting the combined emissions of HC and NOx to 0.5 g/km. For diesel engines, the CO limit was decreased to 1.0 g/km, while the limit for the combined emissions of HC and NOx was set at 0.7 g/km, with PM capped at 0.08 g/km (under Directive 94/12/EC & 96/69/EC).

Euro 3, implemented in 2001, applied stricter standards for petrol vehicles, with CO emissions at 2.3 grams per kilometer and the emissions of NOx at 0.15 g/km. Diesel engine standards also became more rigorous, specifying limits of 0.66 g/km for CO, 0.56 g/km for the combined emissions of HC and NOx, and 0.05 g/km for PM (under Directive 98/69/EC).

Euro 4, enforced in 2005, followed the trend of tightening the emission standards of NOx limited to 0.08 g/km. Diesel engine requirements did not align with those of Euro 1 and Euro 3, with the limits for CO of 0.50 g/km, the combined emissions of HC and NOx, and PM set at 0.30 g/km, 0.025 g/km respectively (under Directive 98/69/EC & 2002/80/EC).

Euro 5, which was introduced in 2009, established the emission standards for gasoline vehicles allowing CO emissions up to 1.0 g/km and the emissions of NOx up to 0.06 g/km. The standards for diesel engines were altered, with CO emissions capped at 0.50 g/km, the combined emissions of HC and NOx restricted to 0.23 g/km, and PM limited to 0.005 g/km (under Directive 715/2007/EC).

Study by Debdin & Fadeev (2021) revealed that approximately 31% of the registered vehicles adhere to the Euro 1 standard. This particular standard was initially introduced in 1992 across Europe, featuring emission limits that are relatively higher when compared to the more modern Euro 5 standards, which are currently considered safe and environmentally friendly. Moreover, the study indicates that an additional 23% of vehicles comply with the Euro 4 standard, while 14% meet the Euro 3 standard, and 12% adhere to the Euro 2 standard.

Table 2.1 illustrates the proportion of emissions stemming solely from vehicular transport in Krasnoyarsk (total car count of 1,076,539), Los Angeles (with a car population of 7.5 million by 2021 - LaAlmanac©2021), and Moscow (8.4 million registered cars - AutoNews©2021). Emissions from cars in Krasnoyarsk are comparable to those in major cities like Los Angeles and Moscow, differing only by 10% in CO emissions and actually surpassing the levels of NO2 emissions in comparison to both Los Angeles and Moscow.

Table 2.1 Contribution of vehicle emissions to total emissions (%) of each substance in major cities in the world, and Krasnoyarsk (Debdin & Fadeev 2021).

	CO	NO_2	Hydrocarbons
Moscow	96	64	33
Los Angeles	98	66	72
Krasnoyarsk	88	79	32

All the pollutants originating from vehicular traffic pose significant health risks when present in high concentrations, with formaldehyde being particularly hazardous, especially for individuals residing in close proximity to major roads. The data presented in Figure 2.11 demonstrates a consistent increase in the number of vehicles per capita in Krasnoyarsk over time. This trend indicates that the amounts of pollutants released by these vehicles may increase significantly, possibly doubling or even tripling. This is particularly concerning due to the heightened dependence on cars, as there is a lack of a well-developed public transportation system. This further complicates the already severe issue of air pollution in the area, as emphasized by Bezborodov et al. (2019).

Aluminum Smelter (RUSAL)

In 1964, a significant industrial facility dedicated to the production of aluminum, boasting an impressive output of 11 million tons annually, commenced operations in the urban locality of Krasnoyarsk. Subsequently, progressing into the 21st century, this establishment emerged as a primary source of detrimental emissions, notably releasing substances such as benzopyrene and fluorine into the environment, as highlighted in the study by Sibgatulin & Shishatsky (2018). Throughout the year 2020, a substantial aggregate of 352.4 thousand tons of noxious compounds infiltrated the surrounding air, exacerbating the pollution levels within the vicinity. Since its inception, the plant has swiftly evolved into a prominent contributor to the escalating levels of air pollution within the cityscape, with historical data revealing that by 1988, an alarming 3.8 tons of benzopyrene were generated by the factory as documented in Table 2.2, juxtaposed against the established permissible threshold of 0.029 tons per year. (Sibgatulin & Shishatsky 2018).

The severity of the situation in the city escalated significantly due to the presence of highly detrimental elements in the atmosphere, leading to a sharp decline in the factory's popularity among the local residents. This negative sentiment towards the factory captured the attention of the government, prompting them to take action. The Resolution of the Soviet Union Council of Ministers titled “On additional measures to prevent pollution of atmospheric air and water bodies in the Krasnoyarsk region” was approved, aiming to introduce drastic measures for the modernization of the enterprise. The primary focus was on initiating a transition towards the utilization of baked anodes technology. Subsequently, by 1996, a total of two buildings out of the 25 were successfully converted to the aforementioned technology. This conversion helped to mitigate the adverse impact of the plant on the environment, although the issue was not completely resolved at that point. In 1995, the factory was responsible for producing approximately 1.23 tons of benzopyrene annually. As the new millennium approached, the aluminum plant became integrated into the Russian Aluminum (RUSAL) conglomerate, leading to further upgrades and advancements. Despite these improvements, the plant continued to significantly contribute to the production of harmful substances, underscoring the ongoing environmental challenges it posed (Sibgatulin & Shishatsky 2018).

Table 2.2 presents the trends in the release of resinous substances and benzopyrene by an Aluminum plant from 1988,1995 and 2021, along with their comparison to the maximum permissible levels, in tons. These permissible values are established based on regulations set forth by the Ministry of Health of the Russian Federation for residential areas.

Table 2.2 Amounts of benzopyrene produced by the Aluminum smelter (RUSAL) for the years 1988,1995,2021, tons/year (Sibgatulin & Shishatsky 2018).

Substance	1988, in tons/year	1995, in tons/year	2021, in tons/year	Maximum permissible values, tons/year
Resinous substances	5131,4	1634,0	900–1400	76
Including benzopyrene	3,8	1,23	Up to 0,5	0,029

Despite a decrease in emissions, the level of benzopyrene produced in 2021 remains 17 times above the allowable limit of 76 tons. These elevated levels of benzopyrene pose significant risks not only to the environment but also to human health, as they are known to be hazardous and carcinogenic (Bukowska et al. 2022).

Coal power plants

The pollution stemming from the RUSAl plant can be ascribed to the generation of perilous substances. Nevertheless, the air quality within the urban area is further compromised due to discharges from three CPPs, which are under the ownership of the company Sibgen. CPP-1 was established in the year 1943, followed by the construction of CPP-2 in 1979 and CPP-3 in 1992; their positioning within the city is clearly depicted in Figure 2.12, denoted by green triangles. The heating system in Krasnoyarsk demonstrates a decentralized structure, where a majority of sectors rely on the CPPs for their heating requirements. It is essential to highlight that particular zones and individual properties within the city persist in utilizing outdated boiler facilities that trace back to the preceding century. These facilities primarily depend on the burning of coal, natural gas, or fuel oil to produce warmth and supply hot water. Presently, there are a total of 35 operational boiler sites in the city dedicated to offering heating services to the residents of Krasnoyarsk, location of some of them is represented in Figure 2.12 (Moiseeva 2023). The data extracted from the official websites of various city administrations serves as a valuable resource in illustrating the specific streets and districts that are currently benefiting from the heating provided by different plants within those areas.

- Krasnoyarsk CPP-1 - Kirovsky, Leninsky, and part of Sovetsky districts of the city.
- Krasnoyarsk CPP-2 - most of Sverdlovsky, Central, and Oktyabrsky districts of the city.
- "Krasnoyarsk CPP-3 - most of the Sovetsky District, part of the Central District (Pokrovsky district).
- Boiler houses No. 4 and No. 5 – part of the Oktyabrsky district.
- Boiler house No. 12-Norilskaya Street (Zheleznodorozhny District)
- Other boiler houses - Maerchak, Dorozhnaya, Kuibyshev streets, part of Svobodny avenue and Yakovleva, Tolstoy, Belopolsky, Borby, Historic, Profsoyuzov, Belopolsky, Severo-Yeniseyskaya streets (smaller streets part of the Central and Zheleznodorozhny District)

The utilization of low-quality coal in these power plants presents a significant risk to the surrounding environment. The combined emissions generated by the three coal facilities total an estimated 40,000 tons annually, impacting air quality and overall environmental health. When fossil fuels are burned in coal-fired power stations, they release a variety of detrimental substances into the atmosphere, including sulfur SO_2, carbon monoxide (CO), and greenhouse gases like carbon dioxide (CO_2).

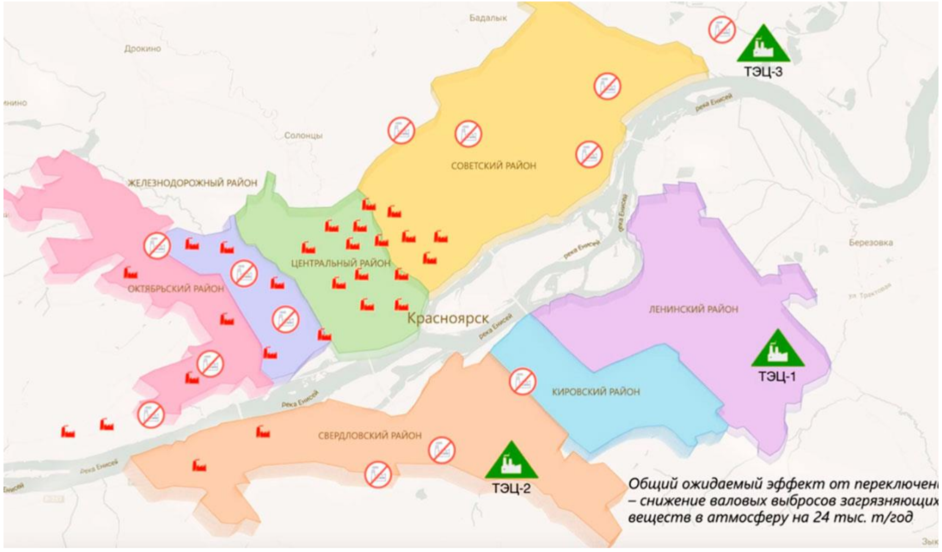

Figure 2.12 Location of the three CPPs in Krasnoyarsk(represented by green triangles) and boiler houses(represented by the small red factory sign, the crossed out ones meaning out of service).Districts are represented by colors: Oktyabrsky (pink), Zheleznodorozhny District (Darker blue),Central District (green),Sovetsky District (yellow),Leninsky district(purple),Kirovsky district (light blue),Sverdlovsky district (red) figure sourced from (DelaRU,©2019).

This information is supported by Popov (2020) and can be referenced in Table 2.3, illustrating the extensive environmental impact of such activities.

The harmful effects of these emissions on both local and global scales underscore the pressing need for sustainable energy alternatives to mitigate environmental degradation caused by coal combustion.

Table 2.3 Emissions from main heating facilities in Krasnoyarsk in 2018, in thousands of tons per year (Popov 2020).

	PM thous.t/year	SO_2 thous.t/year	CO thous.t/year	NOx thous.t/year
All CPPs	11785	21421	374	10512
Boiler Houses	7006	6733	1213	2133

Hydropower plants

It is essential to acknowledge the impact of the Krasnoyarsk Hydropower plant, constructed primarily to meet the high electricity demands of the Aluminum shelter. While the plant itself does not directly emit air pollutants, it significantly affects the river by preventing it from freezing in winter, leading to the formation of fog over the Yenisei riverbed, thereby exacerbating the air pollution issue (Hrebtov & Hanjali 2017).

2.2 Effects

2.2.1 Health Risks

The World Health Organization (WHO) has determined that in 2019 4.2 million premature deaths were caused by outdoor air pollution. Out of them 37 % were caused by cardiovascular diseases,18 % by respiratory infections, and 11 % from cancer (WHO ©2021). The aforementioned health risks are associated with the pollutants mentioned in Table 1.2.

WHO's guidelines on thresholds and limits for major air pollutants are regarded as methodologically sound targets that are recommended to be implemented internationally to avert substantial health concerns throughout the population. Nevertheless, Russia developed their own guidelines that are used throughout the country. Russian government defines them as maximum permissible concentrations (MPCs). For the purposes of this investigation, the average annual concentrations were selected to illustrate the levels of emissions found in the atmosphere of Krasnoyarsk. These levels were contrasted with the maximum permissible annual concentrations established in the Federal Law "On Atmospheric Air Protection" of 04.05.1999 N 96-FZ, as amended and the standards outlined by the WHO. The examination of MPCs in relation to the WHO guidelines is deemed necessary in this context due to concerns regarding the safety of certain regulations enforced by the Russian authorities.

The data for annual concentrations was sourced from the monitoring website of Ministry of Ecology (Krasecology), however it is important to note that some of the sections are not accessible without a proper registration and rights from the Ministry of Ecology of Krasnoyarsk Krai, therefore some measurements of concentrations are limited. The available data from years 2011,2017,2022 was listed in table 2.3. The years were selected to adhere to a 5–6-year interval for a more comprehensive analysis. Data for 2023 was not accessible at the time, with 2011 being the earliest year for which data was obtainable.

Concentrations deemed safe in Krasnoyarsk would be classified as severely hazardous under WHO criteria. In Russia, airborne concentrations are measured in mg/m^3.However, in order to accurately compare European and Russian clean air regulations, the WHO limits for safe values were also included in the table, and all concentrations were converted and expressed in $\mu g/m^3$.

The main pollutants of concern specific to the city of Krasnoyarsk are as follows: PM (on Russian air pollution monitoring websites the particulate matter is not separated into 2.5 and 10), CO, NO_2, SO_2, benzopyrene, and formaldehyde(Shaparev et al. 2020).Their average annual concentrations are presented in Table 2.3.Table 2.3 demonstrates that the limits for permissible concentrations of all pollutants differed between the Russian and

WHO sides, leading to the assumption that the Russian government is significantly more lenient on the concentrations that are being considered safe for the population.

Table 2.3 Maximum recorded daily concentration in Krasnoyarsk in 2011,2017,2022 compared to permissible amounts established by Russian government and the WHO (Krasecology ©2012; WHO©2021; Law04.05.1999 N 96-FZ; EPA©2017).

	2011	**2017**	**2022**	**Permissible levels**	
	Average recorded yearly concentration, μg/m³	**Average recorded yearly concentration,** μg/m³	**Average recorded yearly concentration,** μg/m³	**Russian average permissible yearly concentration,** μg/m³	**WHO guidelines for yearly concentrations,** μg/m³
PM	236	30	112.5	100	5-15
CO	1266	1290	759	3000	10
NO_2	44	43.1	37.4	40	10
SO_2	2.5	24	20.3	50	40
Benzopyrene	4200	5100	6.0	100	0.01
Formaldehyde	19.5	5.4	16.4	30	1-20

Even though the Russian permissible yearly concentrations are higher than recommended by WHO, all of the pollutants listed exceed the limits. Particulate matter exceeded MPCs in 2011 by 2 times, and WHO guidelines by up to 47 times, and short or long-term exposure to PM has a high correlation with mortality and respiratory illnesses in the population (WHO©2021). According to the table 2.3 CO concentrations over the mentioned years have not been exceeding the MPCs but exceeding the WHO guidelines-by 120 times. Prolonged exposure to high concentrations CO can be connected with myocardial infarctions (WHO ©2021).

Recorded annual NO_2 levels are slightly higher than the MPCs and 2-4 times higher than the WHO guidelines. Prolonged exposure to high concentrations of NO_2 not only causes respiratory diseases and mortality in humans, but also increases the proportion of ozone in the troposphere (i.e., near the ground, another harmful to people and environment element, formed by the reaction of Volatile organic compounds and sunlight with NO_2(WHO ©2021). SO_2 levels measured did not exceeded MPCs or the WHO guidelines. Studies showed the correlation between exposure to SO_2 and asthma, respiratory diseases, and mortality (WHO ©2021). Benzopyrene concentrations were significantly higher than WHO guidelines throughout all years and higher than MPCs in 2011 and 2017. High exposure to benzopyrene can have an impact on the nervous system, influence DNA mutations, and can increase risk of cancer, especially lung cancer (Bukowska 2022). Long-term exposure to formaldehyde can cause cancer, affect respiratory systems, and cause asthma (WHO ©2021). The levels of formaldehyde found in Table 2.3 in 2011,2017 does not surpass the permissible concentrations.

Overall, the Table 2.3 displays the hazardous concentrations reported throughout the years by all the contaminants and implies that the acceptable values deemed safe in Russia are obsolete and dangerous for the population. The assumption will be further expanded when discussing the health risks observed among Krasnoyarsk residents.

Following studies on the potential health effects of the primary substances that are regularly found in Krasnoyarsk's atmosphere, particular focus would be placed on assessing any new or current medical conditions that have been identified in the Krasnoyarsk population, including cancer, heart and respiratory disorders, and the development of new tumors.

The leading cause of mortality in Krasnoyarsk, as identified by Pavlyuchenko& Nepomnyashchaya (2018), is circulatory system disorders, with cancer ranking second in terms of fatalities. Utilizing correlation and regression analysis techniques, the study aimed to establish the morbidity of cancer. The research considered two main variables: the incidence of neoplasms per 1000 individuals in Krasnoyarsk (in %) and the volume of pollutants discharged into the air (measured in thousand tons) from fixed sources. The document illustrates the percentage of new neoplasm cases recorded from 2006 to 2016. According to the results, the prevalence of cancer has been consistently rising since 2006, displaying an average annual growth rate of 2.7%, translating to 1122 new cases annually (Pavlyuchenko & Nepomnyashchaya 2018). Furthermore, an investigation into the potential relationship between the incidence of new cancer cases and pollutant emissions from industrial facilities in the Krasnoyarsk Territory, conducted by Pavlyuchenko & Nepomnyashchaya (2018), revealed an additional significant finding: for every additional 1000 tons of emissions, the rate of cancer occurrences increased by an average of 0.0175% during the period spanning from 2006 to 2016.

More recent research by Cherkasova & Khilyuk (2022) delved into the repercussions of air pollution within the region of Krasnoyarsk. The study analyzed the mortality and morbidity rates prevalent in the city of Krasnoyarsk by sourcing data from official governmental reports. To evaluate the potential risks associated with air pollution, the researchers employed risk assessment calculation formulas outlined in the Method for Emergency Risk Assessment and Standards of Permitted Emergency Risks. By focusing on both individual and population-based carcinogenic risks specifically related to benzopyrene, Cherkasova& Khilyuk (2022) were able to pinpoint the alarming findings. The outcomes of the study unveiled that in the year 2020, a significant number of additional cancer cases, totaling 749 per annum. The results obtained show that there is a worrying connection between high levels of air pollution and the risk of cancer in the population.

It is imperative to determine if there exists a comparable correlation among respiratory, cardiovascular, and additional medical conditions that residents of Krasnoyarsk could potentially develop as a result of exposure to pollutants in the atmosphere.

The potential health risks of the Krasnoyarsk population were determined by May& Zaitseva (2022) in their research. The study collected the airborne annual and daily concentrations of the pollutants from the monitoring stations, stationary and non-stationary. The risk factor was calculated according with the "Guidance on the risk assessment of exposure to pollutants" by Ministry of Health of Russia. More current data on reference exposure levels and critical organs and systems was considered as well.

The unacceptable level of carcinogenic risk was determined by May & Zaitseva (2022) to be 1×10^{-4}. Levels reaching higher than 1×10^{-3} were identified as harmful and excessive. For non-carcinogenic risks, a measurement of a hazard index (HI) was used for determination. Levels of the hazard index (HI) in relation to individual affected organs and systems, where HI > 3.0 was considered acceptable, 3 - 6 was regarded as alarming, and levels > 6 were considered exceedingly high.

Risk assessment was additionally verified by in-depth biological, medical, and immunologic studies conducted in 2020-2022 amongst the different cities. The health condition of 1.2 thousand individuals who permanently reside in cities affected by mining and chemical industries was examined and contrasted with the health conditions of residents in cities unaffected by these industries.

Results obtained by May & Zaitseva (2022) are summarized in table 2.4. As evidenced by the data presented in table 2.4, it becomes apparent that the population residing in the city of Krasnoyarsk faces a significantly elevated susceptibility to various respiratory ailments, a situation that is indeed cause for great concern. This worrisome condition is underscored by the alarming incidence rate of 58.7, a value that surpasses the threshold of HI > 6, which is already deemed to be exceedingly high and detrimental, by tenfold.

The risk of developing blood disorders is also extremely high, surpassing the unhealthy threshold of HI > 6 by a factor of ten, with an index of 58.4. Moreover, the lifetime risk of developing cancer is three times higher than 1×10^{-4}.

*Table 2.4. Ranges of human health risks from long-term inhalation exposure to ambient air pollutants (based on estimates as of 2017). *Hazard index, HI, (May & Zaitseva 2022).*

	Lifetime carcinogenic risk	Risk of respiratory diseases, HI*	Risk of diseases of the nervous	Risk of diseases of the blood, HI*	Developmental disorders in the offspring, HI*

			system, HI*		
Krasnoyarsk	**$3{,}8 \times 10^{-4}$**	< 1,0–**58,7**	< 1,0–**6,15**	< 1,0–**58,4**	< 1,0

The research, which was conducted by May & Zaitseva (2022), delves into the gravity of the health hazards that the inhabitants of Krasnoyarsk were confronted with in the year 2017, as indicated by the documented concentrations at that time. Upon analyzing the data presented in Table 2.4, it becomes evident that the levels of pollutants present in the atmosphere in the year 2022 have undergone a significant decrease in comparison to the levels recorded in 2017. Nevertheless, they persistently remain higher than the acceptable thresholds deemed safe. Consequently, there is reason to believe that even in recent years, the population of Krasnoyarsk is still subjected to an elevated risk of health complications. Therefore, the valuable findings derived from the research conducted by both Pavlyuchenko & Nepomnyashchaya (2018) and May & Zaitseva (2022) effectively contribute to the assumption that the recurring instances of severe air pollution indeed serve as a contributing factor to the exacerbation of the development of extreme health risks faced by the population.

2.2.2 Environmental Risks

The adverse impact of human activities on the environment surrounding us is a matter of great concern, as it has been observed to result in the pollution of water, air, and soil, thereby jeopardizing the delicate balance of ecosystems and posing significant risks to human health and well-being (Manisalidis et al. 2020). In the context of this particular section of the thesis, the aim is to delve into the exploration of potential environmental hazards that may have been brought about by the severe air pollution episodes in Krasnoyarsk, specifically focusing on their impact on the soil and water systems.

It has been stated by Pasheva & Mamontova (2022) that soil pollution indicators in Krasnoyarsk and Krasnoyarsk Krai are worse than the Russian average. Soil pollution can manifest in various ways, such as the direct infiltration of heavy metals from various sources, the transportation of contaminants through wind, the effects of acid rain, and the presence of agrochemicals. Salinity and desertification also have an impact on soil quality. Soil salinization, as defined by Pasheva & Mamontova (2022) refers to the accumulation of significant quantities (equivalent to 0.2% of the soil's mass) of sulphates, chlorides, and carbonates in soil layers that are accessible for root system penetration, thereby inhibiting the viability of plants. This phenomenon can occur due to two main factors - natural causes (such as precipitation and groundwaters) and human activities (such as irrigation practices). Overuse of irrigation can result in soil salinization and the inability of plants to sustain themselves due to water scarcity. Moreover, excessive agriculture and deforestation can cause soil to dry out and lose essential nutrients. Furthermore, the presence of heavy metals in soil, which can be deposited from metal and chemical plants, industrial waste, pesticides, and fertilizers, can further impact soil productivity (Pasheva &Mamontova 2022).

Soil can get contaminated through the water sources or from the atmosphere and precipitation containing various pollutants. One of the main effects of heavy air pollution is acid rain. It occurs when SO_2 and NO_2 are deposited in the atmosphere and mixed with oxygen, water, and other chemicals to mix sulfuric and nitric acids (EPA ©2023). When reaching the soil, acid rains increase the concentration of acid in the soil, damaging the plants and organisms.

As presented in table 2.5, the levels of pollutants within the region of Krasnoyarsk are high enough to cause harm to the soils and their natural productivity. Aside from the mentioned pollutants, the proximity of metal and chemical factories to the city poses an immediate threat to the soils. Prolonged accumulation of metals in soil was determined by Tyulyush & Korotchenko (2018) and eventually result in soil degradation and function as a catalyst for various reactions, such as changes in pH and soil composition. A study by Tyulyush & Korotchenko (2018) collected and recorded concentrations of heavy metals in soil samples of different districts of Krasnoyarsk. Phytotesting and chemical analysis were used in determining the potential effect of pollutants on plants. The phytotesting method uses 3 types of test plants: one monocotyledonous and two dicotyledonous. Soil samples were picked from districts/zones of the city with different anthropogenic influence, overall totaling in 8 posts. Soil samples were collected by Tyulyush & Korotchenko (2018) from the areas located at a distance of more than 150 m from the nearest automobile roads (it is considered that such a distance excludes aerogenic ingress of heavy metals into the soil from motor vehicle exhaust gases). The evaluation of phytotoxicity was conducted using the experimental method of test-plant seed germination, expressed as a percentage. The following classification to assess the results was employed by Tyulyush & Korotchenko (2018) :

1. No contamination - seeds displayed a germination rate of 90-100%, with strong sprouting and robust growth.
2. Mild contamination - germination ranged from 60-90%, with seedlings exhibiting nearly normal length and strong, uniform growth.
3. Medium contamination - germination occurred at a rate of 20-60%, resulting in shorter and thinner seedlings, some of which displayed deformities.
4. Severe contamination - germination was very poor, with less than 20% of seeds sprouting, and the resulting seedlings being small in size.

The concentration of the heavy metals in plants was obtained by atomic absorption spectroscopy with usage of PinAAcle 900 (Tyulyush & Korotchenko 2018).
It has been stated by Tyulyush & Korotchenko (2018) that mobile forms of heavy metals are considered to pose a more significant impact, therefore the obtained results for the mobile heavy metals are listed in table 2.5.

Table 2.5 Content of mobile forms of heavy metals in the soil of different districts of Krasnoyarsk (Tyulyush &Korotchenko 2018).

	Contaminant content, mg/kg								
Sample	Lead	Cadmium	Copper	Iron	Nickel	Zinc	Maganese	Cobalt	Chrom
1	10,53	0,07	12,71	1181,0	15,26	18,92	247,8	7,63	5,42
3	19,90	0,24	12,07	1181,0	13,86	33,16	243,0	6,85	4,61
5	9,15	0,21	8,41	1165,0	13,41	25,59	250,9	6,67	4,01
7	63,36	1,41	26,89	1313,0	13,61	46,30	250,7	6,58	5,25
8	23,76	0,21	9,04	1377,0	14,47	19,72	253,2	7,32	5,14
9	46,61	0,85	22,92	1398,0	14,38	47,67	236,8	6,86	7,88
20	9,08	0,15	8,82	1211,0	8,18	26,55	171,1	3,47	2,91
21	11,09	0,26	9,81	1312,0	15,71	15,56	207,7	5,34	4,36

MPCs *	6	1	3	-	4	23	140	5	6

*Hereinafter, rationing according to maximum permissible concentrations (MPC) of chemical substances in soil; approximate permissible concentrations (APC) of chemical substances in soil. in soil;

The results obtained were subsequently juxtaposed with the MPCs of chemical compounds discovered in soils, in adherence to governmental regulations. As evidenced in table 2.5, it is apparent that all of the collected samples demonstrate contamination, with metal concentrations surpassing the accepted thresholds across districts.

High concentrations of certain particularly harmful heavy metals, as indicated in table 2.5, have the potential to significantly diminish soil productivity and plant vitality. Through phytotoxicity experiments conducted by Tyulyush & Korotchenko (2018), it was observed that the rate of germination in crops was adversely affected in 5 out of 8 districts, leading to their classification under medium contamination of the soil. This underscores the importance of considering the level of anthropogenic pollution alongside the specific plant species when evaluating the germination of test cultures. It is crucial to recognize that the presence of these harmful heavy metals can have cascading effects on the overall ecosystem, impacting not only plant life but also potentially affecting other organisms within the environment.

The contamination of water resources is a consequential outcome of severe pollution. The Yenisei River, which serves as the primary water resource, is susceptible to this contamination. The origins of water pollution come from the discharge of wastewater by various industries, atmospheric precipitation carrying anthropogenic pollutants from air and soil, as well as the biological, chemical, and physical contamination of water(Badmaeva & Sokolova 2017).In the city of Krasnoyarsk, the main anthropogenic factors contributing to the pollution of the Yenisei River include industrial facilities such as KrasCom (a wastewater plant), KramZ (a metallurgy plant), Rusal (an aluminum plant), and Krasnoyarsk ZhBI Plant (a concrete production facility) (Badmaeva & Sokolova 2017).

The research conducted by Badmaeva & Sokolova (2017) aims to investigate the current condition of river contamination. Water samples were collected at a location situated two kilometers upstream from the city for subsequent analysis. The composition of pollutants in the water was assessed through the examination of eight constituents, namely, iron, copper, zinc, nickel, cadmium, aluminum, manganese, and petroleum products. As per the Federal Service for Hydrometeorology and Environmental Monitoring, the water quality is classified as dirty-very dirty. The study by Badmaeva & Sokolova (2017) revealed that the average pollution level of oil products in water is 0.069 mg/l, surpassing the established norm of MPCs. This contamination of water with oil products not only leads to a discernible change in taste and odor but also affects its color, pH levels, and the ability to exchange gases with the atmosphere, thereby deteriorating its overall quality. Furthermore, the concentration of iron in water ranges from 0.113 to 0.117 mg/l, slightly exceeding the MPC, and this is primarily attributed to the discharge of wastewater from the aforementioned industrial enterprises. Interestingly, the concentration of copper in the water was measured at 0.9 mg/l, which falls within the permissible limits set by regulatory authorities (Badmaeva & Sokolova 2017).

The concentration of zinc recorded by Badmaeva & Sokolova (2017) surpasses the MPCs by a factor of five, with an average value of 5.4 mg/l. Numerous zinc compounds, particularly sulfates and chlorides, exhibit toxic properties. The introduction of zinc into natural water bodies arises from the erosive processes involving rocks, minerals, and sewage effluents. Moreover, the concentration of nickel in water was determined to be 0.68 mg/l, surpassing the permissible threshold. The presence of nickel in water is attributed to its infiltration from soil, as well as the decomposition of plant and animal organisms. Additionally, nickel compounds are introduced into rivers through wastewater discharge. Heightened levels of nickel can adversely affect cardiovascular and respiratory health, as well as impact the well-being of animal and plant life. It is important to note that nickel is classified as a carcinogenic element (Badmaeva &Sokolova 2017).

The research by Badmaeva & Sokolova (2017) also disclosed a notable surplus of cadmium content in water, specifically 0.18 mg/l (at the maximum allowable concentration of 0.001 mg/l). The primary source of contamination arises from human activity, particularly from the combustion of fuel, the cement industry, mining, ore processing, and waste. Elevated levels of cadmium are toxic, particularly when combined with other hazardous substances. Following the study, the aluminum levels fluctuate within the range of 11.9-12.6 mg/l, which exceeds the maximum permissible concentration for this element (0.5 mg/l according to the MPC). Additionally, aluminum tends to accumulate in fish and invertebrates, consequently affecting their uptake of ions. The accumulated aluminum in invertebrates has the potential to enter the terrestrial food chain, thereby continuing to impact animal life. Finally, the manganese content reached a level of 6.5 mg/l, which surpassed the maximum allowable concentration limit. Sources of anthropogenic manganese include fertilizers and pesticides that contain this particular substance. Although small concentrations of this substance are not detrimental to the body, continuous accumulation can result in harm (Badmaeva & Sokolova 2017).

The review on analysis conducted by Badmaeva & Sokolova (2017) contributed to substantiating the proposition that urban air pollution is manifesting in environmental repercussions. This is evident in the contamination of soils by heavy metals, resulting in their diminished productivity, as well as in the saturation of water sources with heavy metals, consequently influencing aquatic ecosystems.

3.Discussion

The thesis examined the factors contributing to the "black sky regime" in Krasnoyarsk, with a primary emphasis on anthropogenic and natural influences. Nevertheless, a crucial aspect of this issue also stems from the intricate nature of the framework governing AQ management, as well as the legal, social, and economic aspects.

Krasnoyarsk, as previously stated, has served as a significant industrial hub for an extensive period, particularly during periods of robust economic expansion, such as the early 2000s, wherein Krasnoyarsk played a pivotal role in driving economic progress. The sustained development of the economy continues to heavily rely on the proceeds generated from the extraction and processing of raw materials, as well as the manufacturing of chemical and heavy machinery as highlighted by Labzovskii et al. (2023). These vital industrial activities predominantly take place in cities like Krasnoyarsk, shaping the city's urban infrastructure to revolve around these industrial entities. As previously discussed, the significant reliance on industrial revenues exerts a considerable strain on the urban environment. It could be inferred that governmental authorities might exhibit minimal interest in imposing restrictions on the operations of these enterprises, given their crucial role in bolstering the national economy. The various industries driving the rapid economic expansion also contribute significantly to environmental degradation through emissions.

With the escalation of pollution concerns, access to AQ monitoring data has become more readily available through governmental platforms such as Krasecology, Roshydromet (The Russian Federal Service for Hydrometeorology and Environmental Monitoring), and ecological reports from the Ministry of Ecology. In Krasnoyarsk, a total of seven automated monitoring posts (AMP) can be found, as illustrated in Figure 3.1, namely: Kubekovo, 2 – Solnechniy, 3 – Severny, 4 – Berezovka, 5 – Vetluzhanka, 6 – Pokrovka, 7 – Cheremushki, 8 – Kirovskiy, 9 – Sverdlovskiy. They record concentrations for pollutants and aerosols every 20 minutes.

The AQ monitoring sensors deployed across Krasnoyarsk have been touted for their innovative technical specifications, designed to provide the public with real-time updates on the severity of air pollution within the city, as affirmed by the regional minister of ecology, Chasovitin V.A. (Labzovskii et al. 2023).

However, as soon as the pollution episodes became longer and more repeated, the interest of the population in the issue grew. After 2016 the google searches for the Krasnoyarsk air became more frequent, as described by Labzovskii et al. (2023). Higher interest of the population led to the formation of the eco-activist group/network “Nebo” in 2017, funded by people. Founders of “Nebo” proceeded to establish four low-cost sensors around the city. They measured aerosols, PM1, PM2.5, PM10.And soon enough, the government AMPs were considered to be expensive and inefficient, compared to the sensors installed by “Nebo” in 2017.The network of “Nebo” quickly became a more reliable source of information to the public, not only because of their sensor’s efficiency, but also because of the reliability of the available data (Labzovskii et al. 2023). Example of that is illustrated in the Figure 3.2.

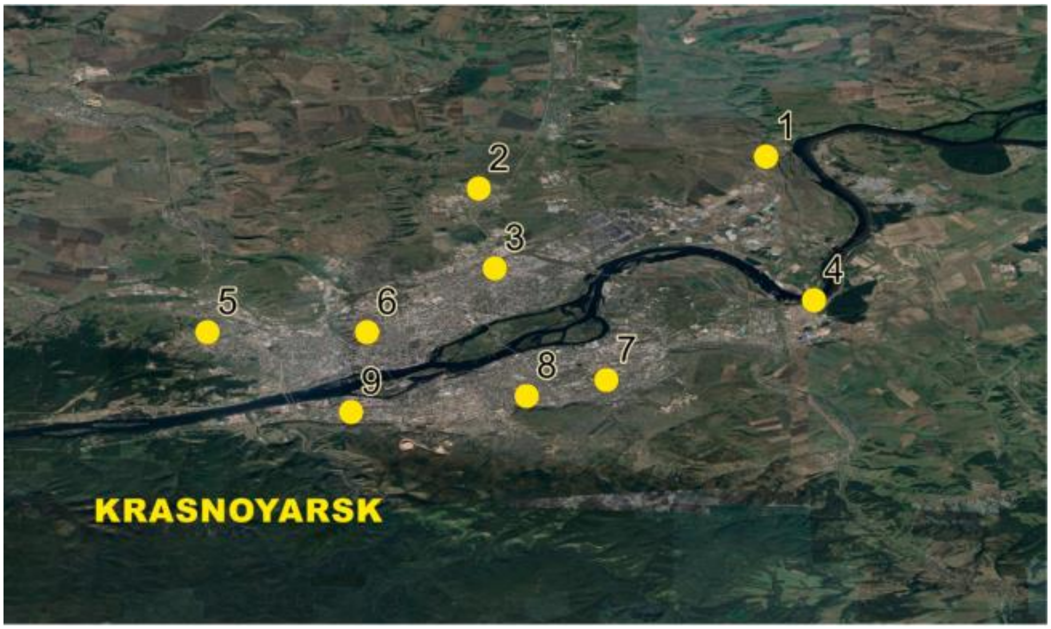

Figure 3.1 Governmental system of AQ monitoring, all 9 stations and their location (Labzovskii et al. 2023).

Figure 3.2 provides a visual representation of the comparison between the Krasecology AQ monitoring website and the non-profit independent AQ monitoring website Waqi.info. The waqi.info platform utilizes governmental AMPs along with "Nebo" sensors to gather information on air quality. The data recorded was acquired on the very same date, and the highlighted points on the graph correspond to the government-operated monitoring stations. Upon examination of the illustration in Figure 3.2, it becomes evident that all the stations featured on the Krasecology website do not display the specific numerical values of pollution levels; instead, they assert that the air surrounding those stations is clean (green color). Conversely, the waqi.info website presents precise numerical data obtained from these identical stations, revealing two instances where the air quality index is measured at 111 (orange color - considered unhealthy for sensitive groups) and 143 (red color - categorized as unhealthy). The network used the Environmental Protection Agency AQ indices (EPA AQI) for comparing their observations, instead of the outdated Soviet MPCs regulations used by the governmental AQ websites.

The dissemination of such inaccurate information, particularly from an authoritative government source asserting the absence of air pollution hazards in a given area, can pose significant risks.

On the example of PM 2.5 (a cause of premature mortality worldwide), the study by Labzovskii et al. (2023) compared the difference of thresholds for hazardous concentrations between the governmental AQI and the EPA AQI.

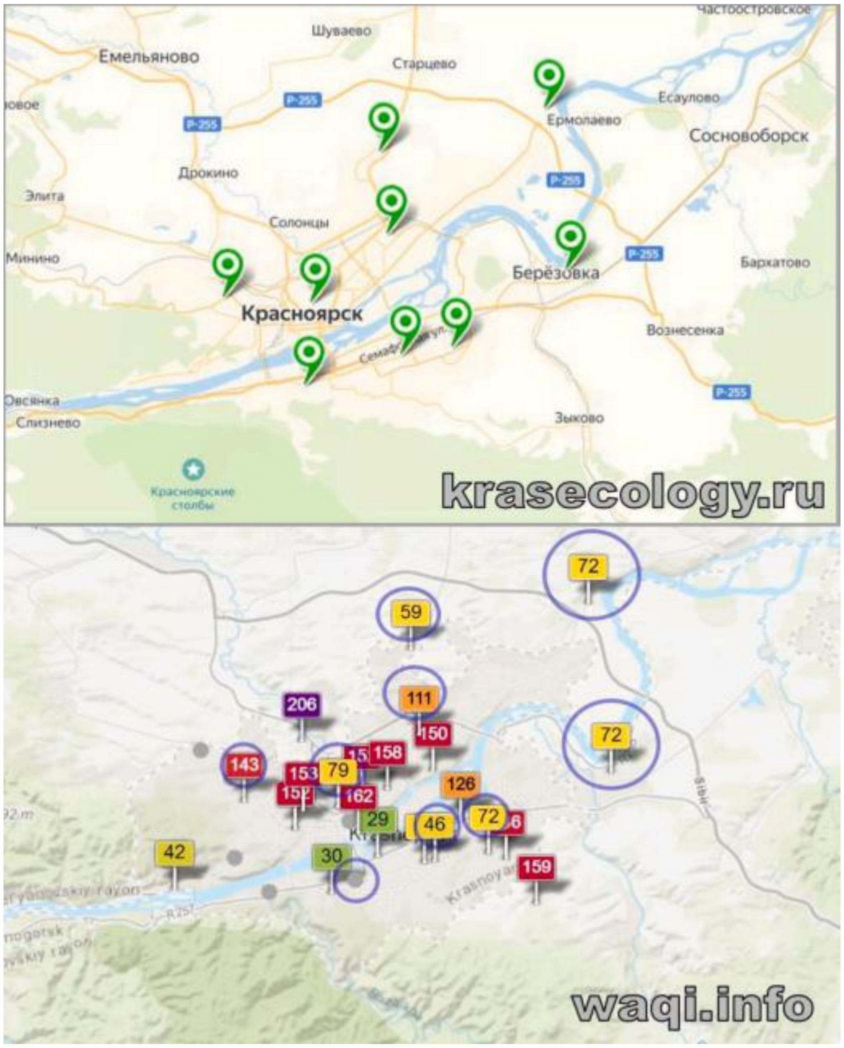

Figure 3.2 Visual comparison of the AQ data from two monitoring websites. On top: data taken from the governmental website, that differentiates only two pollution levels good(green) and bad(red). On the bottom, independent monitoring website waqi.info that differentiates six regimes of air pollution: good (green), moderate (yellow), unhealthy for sensitive groups (orange), unhealthy (red), very unhealthy (purple), hazardous (maroon; not observed during that day). The circles on the bottom picture represent the governmental monitoring stations. Date of the screenshots:12.02.2021 (Labzovskii et al. 2023).

The Krasnoyarsk AQ monitoring system (Krasecology ©2012) provides the indices data for the MPC for 1-h individual concentrations (160 $\mu g/m^3$) and MPC for 24-h averaged concentrations (35 $\mu g/m^3$). According the Krasecology system there are just three regimes of pollution including “low”, “high” (levels lower than MPC for individual 1-h measurements, levels higher than MPC in 24-h average respectively) and “very high” levels (levels higher than MPC for 24-h average) (Labzovskii et al. 2023). According to that logic, the one-time concentration of 159.9 $\mu g/m^3$ would be considered as a “low” level of pollution (Labzovskii et al. 2023). Whereas the standards for EPA AQI would evaluate such concentration as “very unhealthy”.

The hourly PM 2.5 concentrations of 159.9 μg/m^3 was compared by Labzovskii et al. (2023) to the weekly averages in two highly polluted cities of Dhaka (183 μg/m^3) and Delhi (140 μg/m^3). Such concentrations greatly exceed the WHO guidelines or even Russian national thresholds. The discrepancy between the governmental and independent AQ monitoring website discussed before prompts an inquiry into the potential causes for the disparity in reported data, raising suspicions of either malfunctioning equipment or deliberate underreporting of AQ levels on the governmental sites.

The suspicion is further expressed, when in 2017 the supervisors of "Nebo" were notified about recourse to a court. They were claimed by the regional attorney to use sensors that disagreed with the official monitoring stations. Even though the government has not imposed a fine, its reaction to the efforts of the service aiming to deliver precise air pollution information and safeguard the public is indicative of a feeble administration that struggles to accept any form of critique directed towards its governance. This response underscores a lack of accountability and transparency within the regulatory framework.

Even thought there was an action policy "Clean Air" that was accepted in 2018 by the government in order to reduce emissions of the pollutants in the air by at least 20% by 2024, the episodes of severe air pollution still remain as a reoccurring instance in the city of Krasnoyarsk. Under this policy, the total amount of financing allocated for implementing the plan in Krasnoyarsk is 68.7 billion rubles ($1 billion). Of these, almost 20 billion rubles ($308 million) are to be spent on measures to reduce emissions from transport, and 46.5 billion rubles ($715 million) will be spent on reducing emissions from heat and power generating enterprises and the private sector (Shaparev et al.2019).However, with such massive amounts of money spent, the media speculates that results of the policy were somewhat underwhelming, with a result of the insignificant reduction of the air pollution emissions by 2022,according to the Court of the Accounts(SprKrk , © 2022).Additionally, the concentrations listed in table 2.3 for the year 2022(4 years after the implementation of the policy) are still high and exceeding the safer concentrations.

One of the most obvious solutions is of course a major change in the legislation, policies and regulation levels established in the last century. The government needs to use the WHO guidelines as a frame of reference. Even though, this solution seems relatively easy, there is a concern for the willingness of the authorities to promote such actions, the legislation in Russia is extremely complex, corrupt, and inefficient.

Henry & Douhovnikof (2008) argue that the environmental policies, such as the Environmental Doctrine (2002), a Water Code (2006), and a Forest Code (2007) that were put into effect, contained a number of commendable aspects, yet were also plagued by numerous inconsistencies and oversights that hindered their practical implementation. Ecologists have pointed out that these policies were overly idealistic and faced significant challenges when it came to being applied in real-world scenarios. Moreover, the research conducted by Henry & Douhovnikof (2008) highlighted the issue of discrepancies existing between the strict environmental protection regulations documented in official legislation and the subpar execution of these rules in practical application. In addition to this, it is important to note that Russia operates as a federation, implying that certain regional laws may hold precedence over national statutes, particularly concerning matters related to environmental conservation. As emphasized by Henry & Douhovnikof (2008), the absence of clear-cut oversight from the central government has led to a scenario where both levels of authority evade accountability and fail to uphold their obligations in safeguarding the environment. Clearly defined guidelines are essential for nationwide implementation, tailored to the unique characteristics of each region. A streamlined, straightforward procedural framework can facilitate practical application. Furthermore, rigorous enforcement of these regulations, along with diligent monitoring of fees and inspections, is crucial for ensuring compliance and effectiveness in safeguarding public welfare (Hoffmann 2019).

As posited by Hoffmann (2019), the potential exists for the elimination of pollutants from certain types of vegetation, including mosses, plants, and trees. These natural elements can serve as a reservoir for pollution, effectively removing harmful substances from the environment. Moreover, it is worth noting that larger parks and forested areas have the capacity to function as a cooling mechanism, thus mitigating the adverse impacts of the urban heat island effect, as highlighted by Hoffmann (2019).

Furthermore, there was an anticipation that the establishment of the Krasnoyarsk metro system would play a crucial role in reducing the levels of automobile emissions, which are identified as a significant contributor to environmental pollution. This optimistic outlook was primarily derived from the decision made by the governor to initiate the construction of the metro in 2012, coupled with the allocation of a substantial amount of one billion rubles from the national budget to support its progress. However, despite these initial steps, it is noteworthy that the metro project has yet to reach completion and is currently non-functional (NewsLab©2024).

Consequently, there is a pressing need for the enhancement of public transportation services in the forthcoming years as a means to combat air pollution stemming from the use of private vehicles, commencing with the metro system, and extending towards the adoption of sustainable practices commonly observed in Europe (Hoffmann 2019). These sustainable measures may involve the integration of low-emission hybrid or electric buses into the public transport fleet, as well as the establishment of restricted zones within the city limits where personal vehicles are prohibited from entering, thereby promoting a shift towards eco-friendly modes of transportation. It is imperative to acknowledge that the implementation of such strategies should be tailored to suit the unique characteristics and requirements of each city (Hoffmann 2019).In the case of Krasnoyarsk, it could prove beneficial to enforce stricter regulations pertaining to private vehicles, such as imposing limitations based on the age of the vehicles (considering the prevalence of older cars exceeding 10 years in the city) or regulating their environmental impact by restricting the usage of petrol and diesel-powered cars. The introduction of bike and walking lanes within a city's infrastructure has the potential to significantly encourage its residents to opt for more eco-friendly and sustainable modes of transportation. By providing designated lanes for cyclists and pedestrians, cities can not only promote physical activity and reduce traffic congestion but also contribute towards a cleaner environment by decreasing the dependence on cars. Furthermore, the utilization of car sharing applications in urban areas such as Prague can also play a crucial role in promoting sustainable travel practices among citizens. These apps enable individuals to access shared vehicles conveniently, thereby reducing the overall number of private cars on the roads and encouraging a shift towards more efficient and environmentally friendly transportation options (Hoffmann 2019).

Moreover, the fundamental strategy to improve the air quality in Krasnoyarsk is centered around the transition from the utilization of coal as a primary fuel source to the utilization of gas. A comprehensive plan for the supply of gas and the implementation of gasification projects in the Krasnoyarsk region has been officially sanctioned. Currently, two potential scenarios are under careful examination: the initial scenario involves the construction of a dedicated pipeline originating from the nearby oil fields situated within the boundaries of the Krasnoyarsk region itself, with an estimated cost of 248-250 billion rubles or $2.7 billion. Conversely, the second scenario proposes linking the pipeline to the pre-existing systems in Tomsk, with a projected cost of 178 billion rubles or $1.9 billion, these systems are interconnected with the Kemerovo region as well. Nevertheless, it is essential to note that these are still in the preliminary planning stages according to the research by Shaparev et al. (2019). Additionally, the comparative cost of coal per ton ranges from 0.8 to 1.0 thousand rubles, whereas the cost of gas could potentially reach up to 4.5 thousand rubles, taking into consideration the expenses associated with the construction of the pipeline. As highlighted in the study by Vlasov et al. (2020), there exists a promising opportunity to transition away from the reliance on brown coal by CPPs in Krasnoyarsk towards a more environmentally friendly alternative referred to as "smokeless coal," which is produced by subjecting brown coal to a heating process under controlled air conditions. Moreover, the adoption of this innovative technology would negate the necessity of erecting new power plants, as emphasized by Vlasov et al. (2020).

The prevalence of occasional lack of awareness within specific government agencies and their staff members has led to growing concerns regarding the ongoing impact of severe air pollution on the city. It seems evident that the deeply ingrained and intricate legal framework in place is inadequately equipped or disinterested in tackling local challenges like the "black sky regime". Nonetheless, there remains a glimmer of hope as viable remedies have been proposed to address the air pollution crisis in Krasnoyarsk. It is posited that by mobilizing public interest and engagement, a significant influence can be exerted on the authorities to enact necessary changes.

4.Conclusion

In conclusion, the 'black sky regime' in Krasnoyarsk highlights the worldwide air pollution dilemma, exacerbating its environmental and public health consequences. The definition of “black sky regime” was provided and the main factors behind it explained.

Historically, Krasnoyarsk's fast rise as a major industrial hub aggravated air pollution issues, while simultaneously building the dependence of Russian economy on production of materials based in the city. The city's unique geographical conditions were described as one of the factors contributing to the air pollution in the city. The city represents a valley surrounded by hills on the western and northern sides, based on a big unfrozen river of Yenisei. The impact of dams built on Yenisei are detrimental to the air pollution as well, keeping it unfreezing in the winter and colder in the summer, process of which contributes to the production of the fog above the city, which is mixed with the present in the air pollutants. Additionally, the cold winter temperatures and warm summer season have an additional impact on the pollution. In the winter seasons, the air was said to have a heavier, denser quality making the pollutants mixed into it hard to disperse with the wind. Wind was additionally characterized to be weak or weaker on the territory of the city, proven to be not strong enough to successfully disperse the pollutants. The surrounding hills and tight urban build up are one of the reasons for the weaker winds.

Anthropogenic factors were identified to be the biggest contributor to the severity of the air pollution episodes in the city. Aluminum and metal factories based in the vicinity of the city were defined to contribute to the exceeding amount of benzopyrene emitted. Old school dependence of the city on coal heating, i.e., three coal power plants contributed to the production of sulfur, nitrogen dioxides and particulate matter. The city of 1.2 million people was characterized to have a high dependence on personal automobile transport, which was discovered to be one of the most impactful factors, producing excessive amounts of benzopyrene, formaldehyde and heavy metals in the atmosphere.

The present analysis formed an assumption that the collective force of all the factors brought together may have an impact on the immediate environment and people living in it. This was based on the definition of the main general effects of the pollutants typically present in the atmosphere of Krasnoyarsk: carbon monoxide, sulfur dioxide, nitrogen dioxide, particulate matter, benzopyrene and formaldehyde. It was followed by the determination of their concentrations. Which concluded to the realization that all of the above-mentioned pollutants are exceeding not only Russian national maximum permissible concentrations, but also the WHO guidelines. Consequently, the determination of the concentrations was followed by the research of possible correlation between them and the developments of diseases and health risks in the population.

It was determined that the population of Krasnoyarsk has been exposed to a dangerous level of carcinogenic elements, which accounted to a risk of cancer three times higher than the safe level and a 2.7% of annual increase of cancer cases per year since 2006.Additionally, research showed the extremely high risks of development of cardiovascular and respiratory diseases in population, which factors as pollution may be attributed to.

Effects of severe air pollution in the city have been noticed in the overall environment health status. The study determined that there were exceeding concentrations of heavy metals in the soils of the city, affecting the growth rate of crops and soil productivity. The same effect has been noticed in the river Yenisei, concentrations of some hazardous heavy metals were found to be exceeding permissible concentrations in the river too, posing a concern.

Finally, the thesis discussed the other aspects of the air pollution problem in the city. The reliability of the governmental AQ data was questioned, which lead to the assumption that the authorities are not only trying to diminish the issue, but even hide it. One of the reasons for this thesis being written was not only to present a descriptive depiction of the air pollution problem, but also to expose the data provided from the governmental reports, in a sense of its unreliability. Most of the literature analyzed tended to minimize the data and used a more positive approach in discussing the subject matter.

Nevertheless, it is believed that any future changes will likely originate from the city's residents themselves, akin to those who initiated the "Nebo" network. Thus, proper education, access to information, and ongoing awareness of the issue could potentially bring about significant changes.

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