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Review

Ambient Air Quality in the Czech Republic: Past and Present

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Received: 7 January 2020; Accepted: 14 February 2020; Published: 20 February 2020

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Abstract: Based on an analysis of related core papers and reports, this review presents a historical perspective on ambient air pollution and ambient air quality development in the modern-day Czech Republic (CR) over the past seven decades, i.e., from the 1950s to the present. It offers insights into major air pollution problems, reveals the main hot spots and problematic regions and indicates the principal air pollutants in the CR. Air pollution is not presented as a stand-alone problem, but in the wider context of air pollution impacts both on human health and the environment in the CR. The review is arranged into three main parts: (1) the time period until the Velvet Revolution of 1989, (2) the transition period of the 1990s and (3) the modern period after 2000. Obviously, a major improvement in ambient air quality has been achieved since the 1970s and 1980s, when air pollution in the former Czechoslovakia culminated. Nevertheless, new challenges including fine aerosol, benzo[a]pyrene and ground-level ozone, of which the limit values are still vastly exceeded, have emerged. Furthermore, in spite of a significant reduction in overall emissions, the atmospheric deposition of nitrogen, in particular, remains high in some regions.

Keywords: air pollution; air quality; 1950–2018; Czechoslovakia; emissions; aerosol; ground-level ozone; atmospheric deposition; health outcomes; environmental issues

1. Introduction

The modern-day Czech Republic (CR), one of the two succession countries of the former Czechoslovakia post 1993, is a Central European country with an infamous environmental pollution history, including heavy air pollution with serious impacts in the past. These were mostly due to emissions from burning poor-quality lignite of local provenience with very high contents of sulphur used both for coal-powered thermal power plants and local, domestic heating systems. Extremely high SO_2 emissions affected the health of the inhabitants adversely and resulted in serious environmental damage, including the decline of spruce forests. Furthermore, emissions from high stacks of large power plants added substantially, due to long-range transport, to acid rain and the acidification of ecosystems in other European regions, such as Scandinavia. The infamous 'Black Triangle', a border region situated between the former Czechoslovakia, East Germany and Poland, belonged to the most polluted areas of Europe at that time.

As a consequence of fundamental socioeconomic changes triggered by the Velvet Revolution of 1989, the introduction of new legislation, application of effective countermeasures in emission reduction and modernisation of energy production and industry, alongside extensive gasification of local heating systems, the overall situation in ambient air quality has improved substantially. An unprecedented reduction in SO_2 emissions of some 90% has been recorded, accompanied by reductions in TSP (total suspended particles) and NO_x (nitrogen oxides). Nevertheless, new challenges have emerged in air pollution, such as fine aerosol particles, ground-level ozone, and benzo[a]pyrene (BaP), pollutants of which the ambient air concentration currently extensively exceeds the legal limit values, affecting a substantial part of the population and vast geographical regions, and the concentrations of which seem to be very difficult to decrease.

This review paper aims to address ambient air pollution in the CR in its historical perspective, collating and summarising the essential information on ambient air pollution and changes thereto, in context with its relevant negative impacts on the environment and human health over the last 70 years, i.e., from the 1950s to the present. The review consists in three main parts covering the three principal time periods: (1) the period until the Velvet Revolution of 1989, (2) the transition period between 1989 and 2000 and (3) the modern period after 2000.

2. Air Pollution in the Former Czechoslovakia (Prior to 1989)

2.1. Emission Sources and Source Areas

Czechoslovakia's economy from the Second World War through the early 1980s grew at the expense of severe degradation of its natural sources and environment [1–3]. At that time, Czechoslovakia was a centrally planned economy under communist rule, with an emphasis on the massive development of heavy industries [4]. Ambient air pollution has been considered a major environmental threat since the 1950s. At this very time, large coal-combustion power plants were put into operation [5,6], emitting large quantities of sulphur dioxide (SO_2), TSP, NO_x and other pollutants [7]. These large emission sources with high stacks (Figure 1) were concentrated in the northwest region of Bohemia (NWR, location in map in Figure 2), in the Podkrusnohori region, adjacent to the German and Polish borders in particular, where their operation was driven by local poor-quality lignite coal with extremely high sulphur and ash content [8–10].

Figure 1. Prunerov coal power plant (photo by the author).

The sulphur content in the local coal varied widely according to the individual coal deposits. Coal mined in the North Bohemian Lignite Basin averaged about 1.2–3.5%, with a maximum total sulphur content as high as 15.8% and an ash content ranging between 2.6% and 69.9% [11]. Some 50–95% of sulphur compounds in the coal were emitted into the air [12]. The emissions were highly dependent on the applied technology and leading of the burning process [13–15]. Moreover, other trace elements potentially harmful for the environment, such as As, Be, Pb, V, F, Cr, Cu and Se were found in elevated concentrations in North Bohemian coal and released into the atmosphere while burning. The highest concentrations of As (387 ppm), Sb (7.5 ppm) and W (108.5 ppm) were reported from the Czechoslovak Army Mine (abbreviated ČSA in Czech) quarry [11]. This coal was mined in open cast mines, the operation of which devastated the originally scenic landscape and caused the end of numerous small settlements as well as the environmental, social and moral decline of the entire region [16–18].

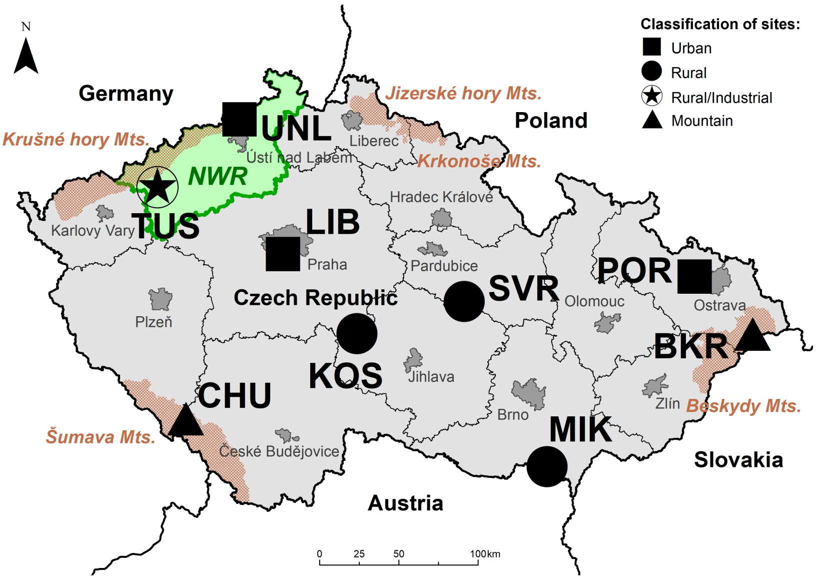

Figure 2. Map showing the areas and places mentioned in this review.

Furthermore, other industries, such as chemical, metallurgical, textile, cellulose paper mills, and glass and ceramic manufacture, added to the overall emissions [19]. The accumulation of numerous large emission sources in the poorly ventilated Podkrusnohori valley in Northwest Bohemia resulted in a poisonous air mixture, in particular during winter thermal inversions, when the ambient air pollutant levels reached extremely high values [20]. Under the communist regime, however, information on environmental, including ambient air, pollution was not available to the general population, and half-classified materials were intended exclusively as reports for experts [21]. The SO_2 annual mean concentrations ranged in the order of hundreds of $\mu g\ m^{-3}$, whereas the SO_2 daily mean concentrations ranged in the order of thousands of $\mu g\ m^{-3}$. The measurements at that time recorded in the unpublished internal reports of the Czech Hydrometeorological Institute (CHMI) in the above region, in particular in the adjacent Krušné hory (Mts.) (Erzgebirge, the Ore Mts.) reached up to 130 $\mu g\ m^{-3}$ of SO_2 in annual means during the 1970s (Figure 3). A daily mean of 1590 $\mu g\ m^{-3}$ of SO_2 (Figure 4) was recorded on 16 January 1982 [20]. For comparison, current ambient SO_2 concentrations measured in the same region are up to 10 $\mu g\ m^{-3}$ of SO_2 in the annual mean [22]. The Podkrusnohori region ranked amongst the most polluted parts of the entire country [19]. Apart from the North Bohemia region, other emission source regions included the major urban areas, such as Prague (the capital), Ostrava, Pilsen, Hradec Králové and Brno, with numerous industrial enterprises and local heating systems operating on brown coal and lignite, deteriorating the ambient air quality.

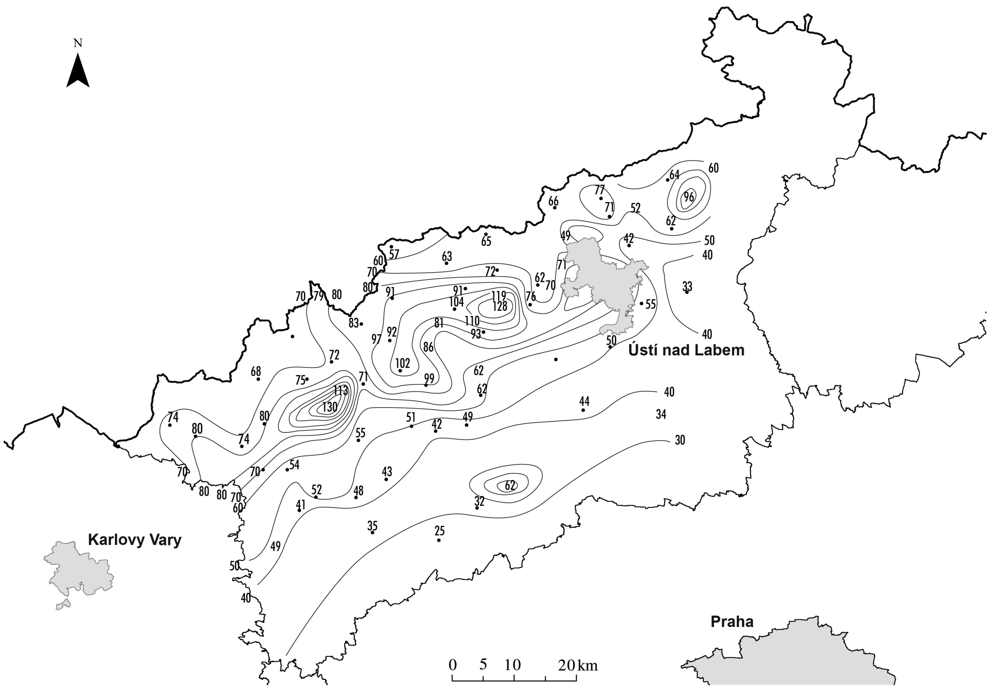

Figure 3. Map of Northwest Bohemia (NWR in Figure 2), showing the SO_2 annual means in µg m^{-3} in 1971–1980, the lines represent the isoconcentrations (redrawn according to [20]).

With 3150 kilotons in 1985, i.e., a full 203 kg per person per year in 1985, SO_2 emissions in the Czech-Slovak Federal Republic (CSFR) were the highest in Europe, 2.48 times higher than in Western Europe per unit of gross national product (GNP) [23]. Further, the total NO_x emissions (expressed as NO_2) were estimated to be 1200 kilotons annually, i.e., 57 kg per person per year; hence Czechoslovakia took an infamous first place in NO_2 emissions in Europe [23].

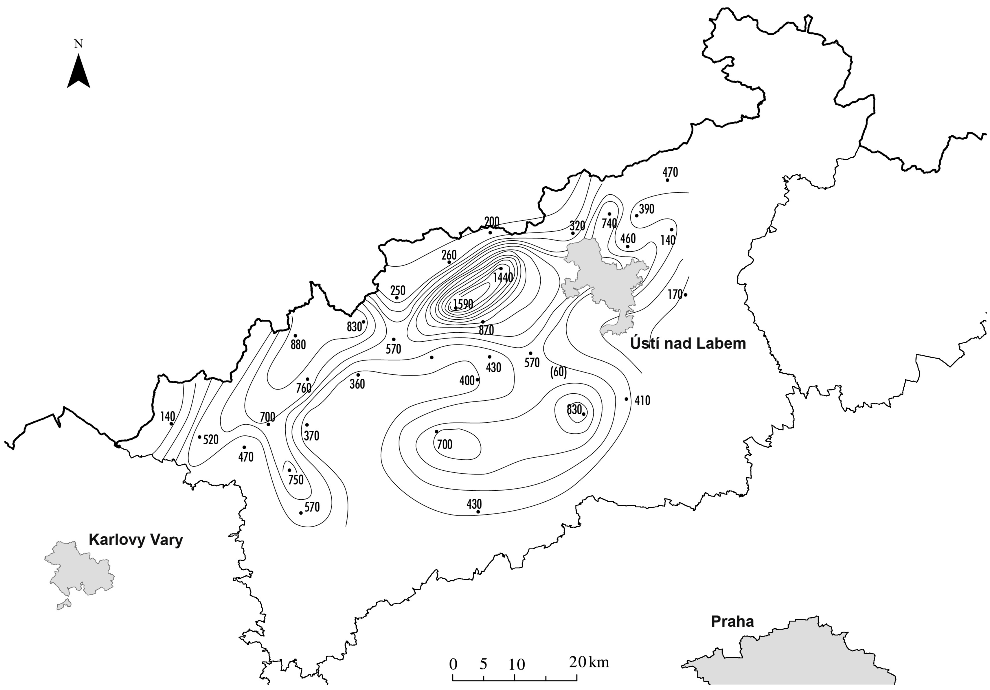

Figure 4. Map of Northwest Bohemia (NWR in Figure 2), showing the SO_2 daily mean in µg m^{-3} on 16 January 1982, the lines represent the isoconcentrations (redrawn according to [20]).

2.2. Ambient Air Quality Monitoring

The first measurements of ambient air pollution addressed sulphur dioxide (SO_2) and total suspended particles (TSP)—the then measured total sample of aerosol without particle fraction distinction—and date back to the 1950s. The measurement activities at that time focussed on industrial and highly populated areas and ambient air pollution was observed by the Public Health Service with respect to serious human health impacts [24,25].

Regular ambient air quality monitoring has been in operation since the 1960s and individual networks were aimed at the most polluted areas. The Czech Hydrometeorological Institute (CHMI) has been responsible for nationwide ambient air quality monitoring since 1964. The first monitoring sites were situated in the Podkrusnohori region in 1968. In 1969, the network expanded to the Ostrava region and in 1970, to the Brno region [26]. Gradually, a fairly dense network was set up for monitoring SO_2 in particular. Smog regulation and warning systems were built, the first was put in operation in North Bohemia in 1973 [27].

After covering the most heavily impacted regions, measurements also began in relatively unpolluted areas, far from the major emission sources, in order to gain information on regional background air pollution. The Svratouch site in the Czech-Moravian Highlands has supplied data on air quality to the worldwide Background Air Pollution Monitoring Network (BAPMON) since 1972 and to the EMEP (European Monitoring and Evaluation Programme) since 1977 [28]. In the 1980s, the Košetice site (KOS in Figure 2) was set up for environmental monitoring on a regional scale [29,30]. The air quality monitoring was supplemented by observations of precipitation chemistry, with the first site established at Hrádek u Pacova in 1974 [31].

Apart from the CHMI, several other organisations were involved in ambient air quality measurements for their own purposes, such as the Public Health Service (abbreviated in Czech as HS), Organization for the Rationalization of Power Plants (abbreviated in Czech as ORGREZ), Czech Geological Survey (abbreviated in Czech as ČGÚ, and later as ČGS), Forestry and Game Management Research Institute (abbreviated in Czech as VÚLHM), Water Management Research Institute (abbreviated in Czech as VÚV) and the Research Institute of Plant Production (abbreviated in Czech as VÚRV).

Air pollution in Czechoslovakia culminated in the 1970s and 1980s. The monitoring results from 1971–1982 for the eight most heavily impacted regions defined by the then government (i.e., North Bohemia, Mělnicko-Neratovicko, City of Prague, Hradecko-Pardubicko, Brno, West Bohemia and Pilsen) were collated by the CHMI's internal reports [20,32–38]. The incorporation of a certain area into the impacted regions was based on the annual SO_2 mean concentration above 30 $\mu g\ m^{-3}$ (Figure 5). Based on monitoring and dispersion modelling results, the above regions were categorised into three different air pollution levels: (1) the most polluted, which were the North Bohemia and Prague regions, (2) medium air pollution level—the West Bohemia, Ostravsko-Karvinsko and Mělnicko-Neratovicko regions and (3) the lowest air pollution level—the Hradecko-Pardubicko and Brno regions. Interestingly, the two most polluted regions, i.e., North Bohemia and Prague, showed similar air pollution levels, though these originated from completely different emission sources. In North Bohemia, the problem arose from large emission sources, whereas in Prague the local heating systems were the culprit. Furthermore, with respect to distinct geomorphology, both Prague and the Podkrusnohori region have been prone to frequent thermal inversion occurrence preventing pollutant dispersion [39–41].

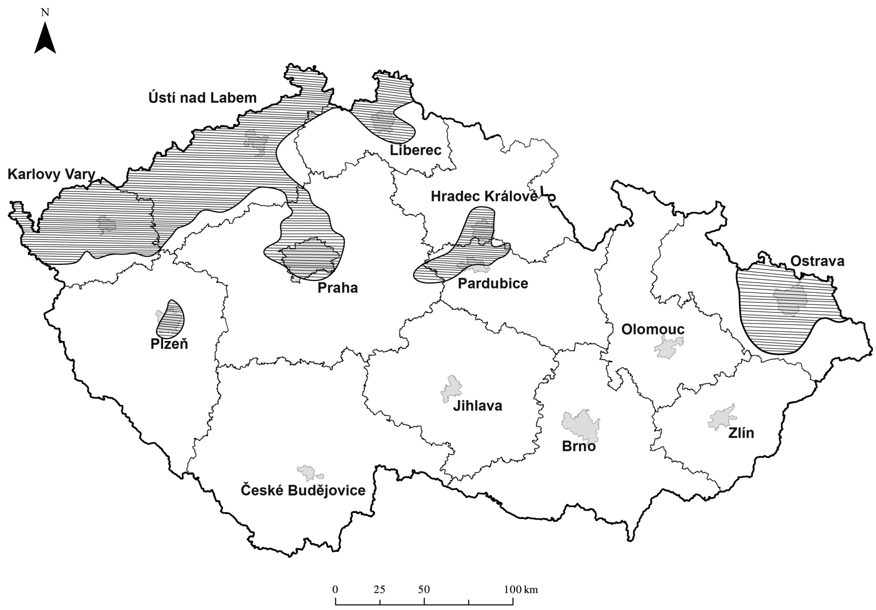

Figure 5. Map indicating the formerly impacted regions (in the 1970s and 1980s) with respect to air pollution delimited by annual SO_2 mean concentration above 30 $\mu g\ m^{-3}$ (redrawn according to [41]).

2.3. Human Health Outcomes

The first information on measured ambient air pollutant concentrations in the then Czechoslovakia, available only in Czech, originate from as early as the 1950s. They cover some industrial regions and are related to local inhabitant health outcomes [24,25]. Children living in areas with high air pollution were somewhat retarded in growth. Furthermore, they evinced significant changes in their red blood cell counts. It was recognised that children responded to elevated SO_2 concentrations in similar way as to rather lower O_2 pressure, such as in the high mountains: an increase in the total surface of erythrocytes ensured the transfer of O_2 to tissues easier [42]. It was demonstrated that a stay of 1–3 months in a clean atmosphere had favourable effects on such children, especially with respect to the haemoglobin, and that this reaction continued for about three months after the children returned to the region with polluted air. Hence children used to be sent to an open-air school, where the air was relatively clean [42]. Air pollution belonged amongst the factors not only impairing human health but contributing even to all-cause mortality. According to Bobak and Marmot [43], an estimated 2–3% of the total mortality could be attributed to air pollution in the CR in 1987. Bobak and Leon [44], in a study examining infant mortality and air pollution in 1986–1988 for 46 of the 85 districts of Czechoslovakia, reported a weakly positive association between neonatal mortality and ambient TSP and SO_2 concentrations.

A comprehensive Teplice programme aimed at a thorough study of the impacts on human health caused by ambient air pollution, including aerosol, genotoxic organic compounds and toxic trace elements in one of most heavily impacted districts of North Bohemia [45]. A significantly higher prevalence of adverse respiratory symptoms and decreased lung function were indicated as compared to the relatively clean Prachatice district in South Bohemia [46]. Moreover, a study of the effects of exposure on pregnancy and birth revealed an excess prevalence of low birth weight and premature births [47]. Furthermore, within this study, it was indicated that air pollution may alter early childhood susceptibility to infections [48]. Exposure to intermittent air pollution in the North Bohemian Teplice district was shown to cause sperm DNA damage resulting in an increase in rates of male-mediated infertility, miscarriage, and other adverse reproductive outcomes [49].

2.4. Environmental Issues

Severe air pollution affected both human health and the environment. Mismanaged forest ecosystems were susceptible to additional stresses [50–57]. A substantial part of forest areas (more than 60%) were damaged in various degrees by air pollution, namely SO_2 acting either directly or indirectly via acid deposition and subsequent soil changes. The outcomes included increased mortality and decreased increments in forests, loss of valuable ecotypes, impact on water management and overall decrease in stability of the landscape [58–60]. Damaged forests were the most visible and best-known symptoms of acid rain [61,62]. Losses on forest wood attributable to air pollution in the then Czechoslovakia were estimated at 9.5 million m^3 $year^{-1}$ by the International Institute for Applied Systems Analysis (IIASA); this estimate being reckoned conservative, as exclusively SO_2 was accounted for, whereas NO_x and NH_3 were not considered [63]. Unprecedented forest decline, namely in the Krušné hory Mts., Jizerské hory Mts. and Krkonoše Mts., in the 1970s and 1980s were of major concern for the then foresters and forest management [64] and attracted infamous attention from scientists all over the world. The Krkonoše National Park (KRNAP) was cited—together with the adjacent Polski Park Narodowy—by the International Union for Conservation of Nature and Natural Resources (IUCN) as the world's most threatened protected natural area [65].

Though Czech environmental studies at that time were practically non-existent [21], some papers on ambient air pollution impacts on the environment can still be mentioned. Air pollution was reported to influence the nesting ecology of the house martin (*Delichon urbica*) in 141 villages and towns in Czechoslovakia, including a significant reduction in nesting density, colony size and occupancy [66]. Fluoride pollution in wild deer assessed in North Bohemia showed significantly decreasing exposures from the mid-1990s, attributed largely to the implementation of emission control devices on coal-fired power plants [67].

Emissions were also blamed for the contamination of crops. Ustyak and Petrikova [68] reported that the results of their study for North Bohemia in 1987–1992 indicated very high contamination of agricultural crops by heavy metals and As. Specifically, 3–16% of fodder crop samples and 49–86% of food crop samples were contaminated (i.e., they showed higher heavy metal contents than was permissible at that time) in spite of a low degree of soil contamination. The main pollutants of fodder crops were Hg, Cd, Pb and Co, whereas the main pollutants of food crops were Cd, Cr, Hg, As, Pb, Ni and Zn [68].

Air pollution also affected precipitation chemistry, and consequent atmospheric deposition and stream water chemistry was observed [69]. The long-term effects of atmospheric pollution by metals and acids were documented even on sediment cores from Čertovo Lake in the Šumava Mts., situated in a relatively unpolluted region [70].

2.5. Air Pollution in the Context of the Former Communist Countries

The problem of severe ambient air pollution and consequent human health and environmental impacts was not limited exclusively to the former Czechoslovakia, but involved other Central European communist countries, such as the former GDR (Eastern Germany or the Democratic Republic of Germany) and Poland [71–73]. These three countries ranked among the worst polluters due to emissions from the power generation systems as well as heat production both for industry and municipalities. These sources accounted for about 90% of total SO_2 emissions and about 60–70% of emissions of dust and NO_x [74]. Fly-ash emission in Eastern Europe was greater than in any other industrial region in the world [65]. The heavily industrialised 'Black Triangle' (sometimes also called the 'Dirty Triangle') region encompassing Northern Bohemia, Silesia and adjacent portions of Eastern Germany was infamous for its heavily impacted environment and the high frequency of winter smog occurrence causing an adverse effect on the health of local inhabitants and on the environment [74].

2.6. Long-Range Transport

A few decades ago, air pollution was considered entirely a local problem. The acceptable solution seemed to be building high stacks to disperse the emissions and thus reduce ground-level air pollutant concentrations. Due to long-range transport, however, the previously local-scale problem developed into a regional-scale issue [75]. Consequently, towards the end of the 1960s, due to the long-range transport of air pollutants, namely SO_2 and NO_x, a substantial decrease in pH of precipitation and subsequent acidification of both terrestrial and aquatic ecosystems was observed over large portions of

Europe, including areas distant from major emissions sources, such as Norway and Sweden [76]. The problem, popularly called 'acid rain', resulted in important negative changes in chemistry and biota in lakes, running water and forests and triggered hot debates among both scientists and the general population [77–80]. The then Czechoslovakia, as a major emitter country, also contributed substantially and was blamed for air pollution export and consequent acidification problems elsewhere [23,81].

3. The Period after the Velvet Revolution, the 1990s

Some positive trends, such as a decrease in ambient air pollution by several pollutants can be tracked back as far as the 1980s [82]. The improvement in the state of the environment, including the ambient air quality, however, has been clearly visible only since the transition from the communist past triggered by the Velvet Revolution in November 1989. In the beginning, this was due mainly to industrial decline, then later as a result of economic restructuring and privatisation [62,83]. In fact, the environmental issues, including the vast dissatisfaction of a considerable part of the population over the then ambient air pollution, contributed substantially to the collapse of the old regime in Czechoslovakia [84–87]. From the very beginning, a strong emphasis was therefore placed on solving environmental problems, including air pollution and the adoption of relevant countermeasures to improve the poor state of the environment [88].

As for the emissions, an unprecedented reduction in SO_2 of some 90% was achieved via a combination of newly adopted strict legislation measures, considerable investments into desulphurisation remedies installed at large emission sources and a transfer from burning lignite to gas in residential heating. For comparison, the reduction in SO_2 emissions in most European countries at the same time accounted for approximately 60% [89]. At the same time, TSP emissions also decreased substantially [90], whereas NO_x emissions decreased considerably less [91]. An important motivation for improvements was also the preparation of the CR for accession to the EU [92]. The CR became a candidate for accession in 1993 and made all efforts to implement the EU legislation, including the Air Quality Law, well in advance.

The most pronounced improvement in a dynamic decrease in air pollutant emissions was seen in the period between 1989 and 1998 [93–95], the impetus to this favourable development being the newly set up strict emission limits to be met in 1998 (Figures 6 and 7). The existing major emission sources were forced to modernise or close up, without the exceptions abundantly permitted so far. Residential heating systems switched from burning coal to gas in many places, including Prague. A substantial reduction of residential coal consumption in the CR from 1990 to 2014 was achieved, by a factor of 6.2 [96].

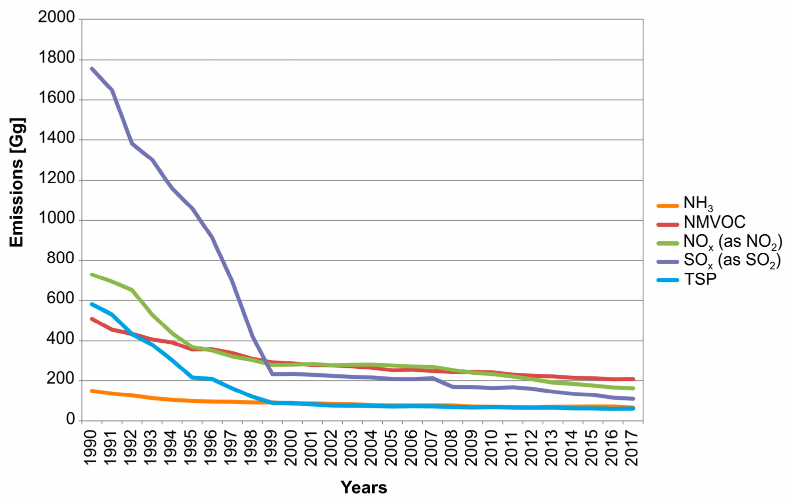

Figure 6. Overall emissions of SO_2, NO_x, NH_3, NM VOC and TSP in the Czech Republic (CR), according to European Monitoring and Evaluation Programme (EMEP) data [97].

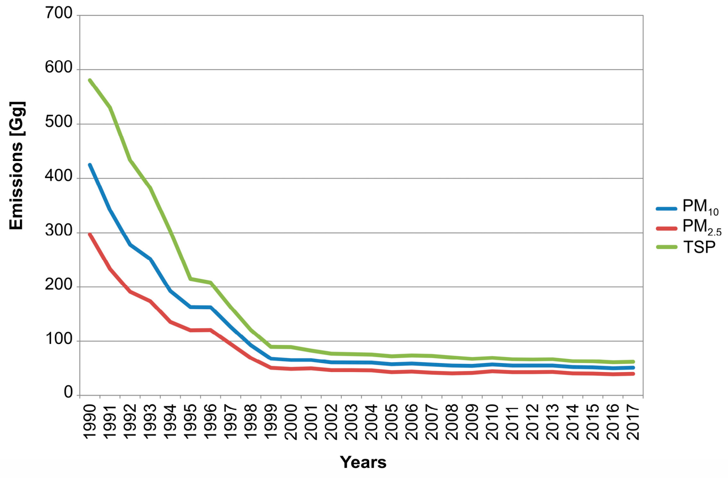

Figure 7. Overall emissions of TSP, PM_{10} and $PM_{2.5}$ in the CR, according to EMEP data [97].

The extent to which the changes in emissions were reflected in changes in ambient air quality is shown for several sites representing different environments, altitudes and geographical regions (Table 1, location in map in Figure 2). The trends in annual mean concentrations of SO_2, NO_x, PM_{10} and O_3 from the 1990s to the present time are presented in Figures 8–11. The individual annual means are missing in cases where the requirement of a sufficient number of measured values was not fulfilled [22]. The most impressive decreases, most obvious in the presented diagram for the UNL and TUS sites (both in NWR) and the Prague site LIB were recorded for SO_2 (Figure 8). The ambient NO_x concentrations (Figure 9) show decreasing trends, though much milder than for SO_2, with the highest concentrations for the LIB site reflecting clearly the impact of a nearby main road, and somewhat lower concentrations for the NWR sites (UNL and TUS) under influence of large thermal power plants. Fairly large differences (as compared to SO_2 and PM_{10}) between NO_x concentrations at different types of sites are evident. Ambient PM_{10} concentrations (Figure 10) also show overall decreasing trends with peaks at the beginning of the 2000s. Annual means of ambient O_3 concentrations (Figure 11) are not decreasing and show contrasting patterns to the above pollutants (Figures 8–10). In accordance with the general assumption, the highest values were recorded at the CHU and BKR mountain sites, whereas the lowest values were measured at the Prague LIB site.

Table 1. Measuring sites (location in map in Figure 2), the long-term records of which are presented in Figures 8–11.

Station	Code	Altitude [m a.s.l.]	Classification [1]	Region
Ostrava-Poruba	POR	242	B/S/R	Ostrava
Mikulov-Sedlec	MIK	245	B/R/A-REG	South Moravia
Praha4-Libuš	LIB	301	B/S/R	Prague
Tušimice	TUS	322	B/R/IA-NCl	NWR [2]
Ústí n.L.-Kočkov	UNL	367	B/S/RN	NWR [2]
Svratouch	SVR	735	B/R/N-REG	C-M Uplands
Bílý Kříž	BKR	890	B/R/N-REG	Beskydy Mts.
Churáňov	CHU	1118	B/R/N-REG	Šumava Mts.

[1] Classification according to the European Commission EC Decision EoI 97/101/EC: B/S/R—background/suburban/residential, B/S/RN—background/suburban/residential, natural, B/R/IA/NCI—background/rural/industrial, agricultural/near city, B/R/A-REG— background/rural/agricultural-regional, B/R/N-REG—background/rural/natural-regional, [2] NWR—Northwest region.

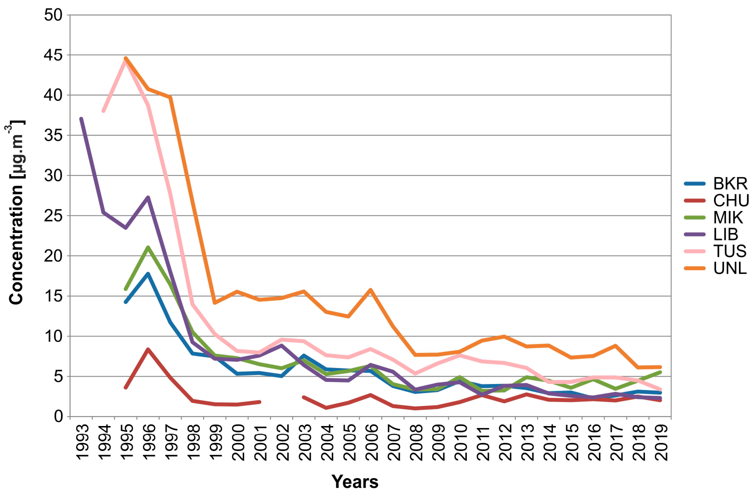

Figure 8. Trends in ambient annual mean SO_2 concentrations at selected sites (see Table 1, Figure 2), 1993–2019, based on Czech Hydrometeorological Institute (CHMI) data.

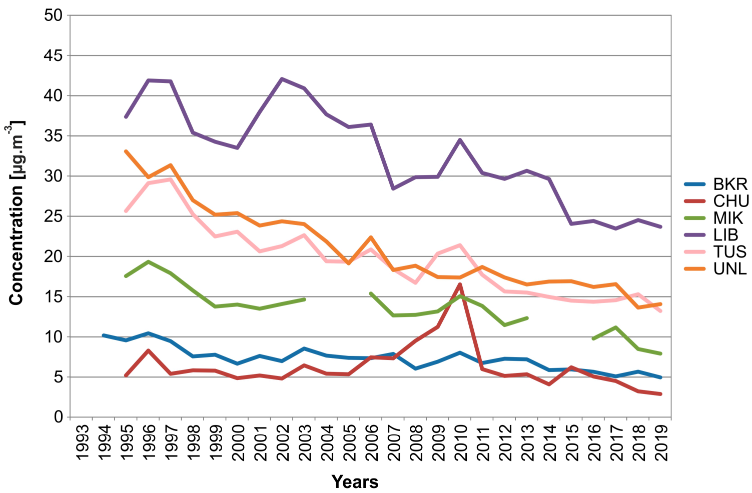

Figure 9. Trends in ambient annual mean NO_x concentrations at selected sites (see Table 1, Figure 2), 1993–2019, based on CHMI data.

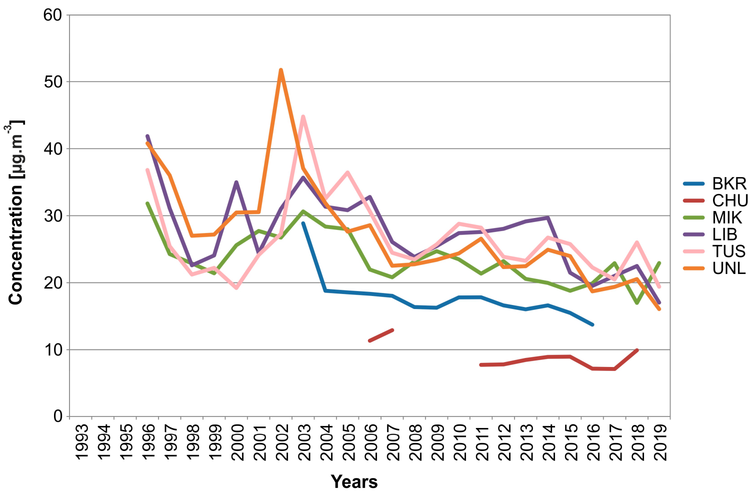

Figure 10. Trends in ambient annual mean PM_{10} concentrations at selected sites (see Table 1, Figure 2), 1993–2019, based on CHMI data.

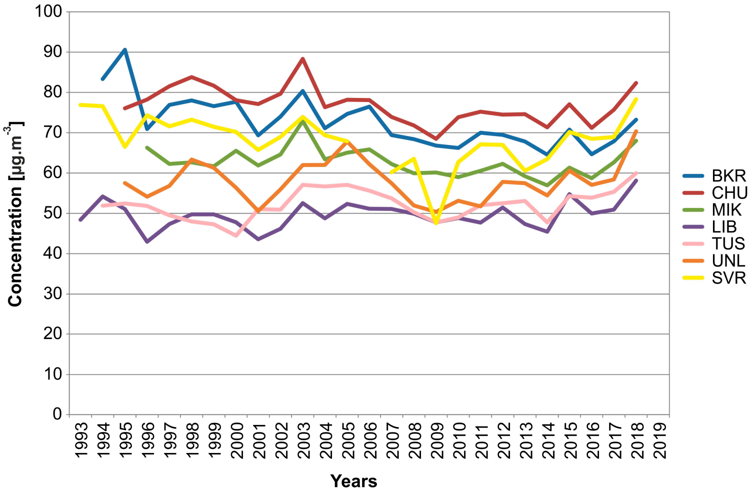

Figure 11. Trends in ambient annual mean O_3 concentrations at selected sites (see Table 1, Figure 2), 1993–2018, based on CHMI data.

During the 1990s, Czechoslovakia started to be involved in various international activities, including individual studies, projects and programmes bringing numerous interesting results (e.g., [98–103]). For example, within a CAESAR (Central European Study on Air pollution and Respiratory health) study encompassing 25 study areas in six Central and Eastern European countries (Bulgaria, the Czech Republic, Hungary, Poland, Romania and the Slovak Republic), high PM_{10} and $PM_{2.5}$ levels were indicated, with large changes between seasons, likely due to local heating. The measured PM levels were hypothesised to contribute to the observed reduced life expectancy in the region [104]. For the first time, the environment including ambient air pollution of the Czech Republic was assessed in the context of Europe's environment in the comprehensive report published by the European Environmental Agency (EEA) [105].

4. Air Pollution in the Modern-Day Czech Republic (after 2000)

The number of ambient air quality monitoring sites has changed continuously since 1969, the highest number of stations was in operation in the 1980s and 1990s. The optimisation of the monitoring network in the 2000s resulted in a reduction in the number of sites and the replacement of others. Currently, 198 stations in the Czech Republic monitor the air quality, 127 of which are operated by the CHMI. Of these 127 stations, 80 are automated [22].

Even though Czech ambient air quality improved substantially after 2000, the levels for some ambient air pollutants are still not satisfactory [22]. Aerosol/suspended particles, ground-level ozone and benzo[a]pyrene are considered the major problems, similarly to elsewhere in Europe [106].

The national legislation on air quality management evaluation in the Czech Republic is based on European legislation. The basic legislative norm in the CR is Act No. 201/2012 Coll., on air protection as amended ('Air Protection Act'). The ambient air quality is observed and monitored by a nationwide long-term monitoring network operated by the Czech Hydrometeorological Institute (CHMI) [22]. CHMI, an institute designated to monitor and assess the ambient air quality in the CR, focusses its activities mainly on covering the criteria pollutants, i.e., the pollutants for which limit values were set up on the basis of WHO recommendations [107,108] by relevant national legislation. In accordance with EU legislation [109], these are in particular SO_2, NO_x, PM_{10}, $PM_{2.5}$, CO, benzene, benzo[a]pyrene, and toxic metals in aerosol (Pb, Cd, As, Hg), monitored on a regular basis. Currently, due to historic reasons, the CR belongs to the countries with the densest monitoring networks [110]. Nevertheless, in accordance with legislation, the major regular monitoring activities are focused primarily on highly populated major urban agglomerations, whereas monitoring in smaller towns and communities is scarce, in spite of the fact that there are strong indications that they are highly polluted in particular due to local heating emissions, and in reality they are inhabited by a considerable share of the Czech population [111–113].

CHMI runs two types of stations: automated and manually operated. The automated stations measure continuously and give 1 h mean concentrations, whereas the manually operated stations give 24 h mean concentrations. Precipitation chemistry is sampled on a monthly or weekly basis by automated wet-only samplers. All the measured air quality data are stored in a central nationwide ambient air database, ISKO (the Czech acronym for the Air Quality Information System) [22]. In addition, a supersite observatory, Košetice, is run by the CHMI, participating in numerous international activities, including long-term programmes and scientific projects [114]. The regular annual reports providing detailed information on air quality are available and can be downloaded at the CHMI website [115] in Czech and English versions. The results of continuous monitoring are summarised and presented in user-friendly colour maps indicating the hotspot areas and problem regions. The results are interpreted in the context of both human health and environmental effects. Apart from these annual graphic yearbooks, long-term analyses are also available [116–118].

Furthermore, in addition to the nationwide ambient air quality monitoring run by the CHMI, numerous other measuring activities are operated by other institutes and organisations for different purposes. These include, e.g., the monitoring of persistent organic pollutants (POPs), which are not explicitly included among the criteria pollutants but are widely recognised as extremely harmful substances (due to their persistency and bioaccumulation) on human health [119–123]. In addition to direct measurement, tree needles and mosses were proven to be useful monitors giving similar information on POPs as high-volume air monitoring [124,125].

With regard to aerosol, not only lawful mass concentration, but also particle number concentration (particle number size distribution) is measured, suitable in particular for aerosol dynamics and source apportionment studies [126–128]. In addition, the main fractions of carbonaceous aerosols, i.e., organic carbon (OC) and elemental carbon (EC) are measured in both urban and rural areas [129,130].

4.1. Aerosol

Aerosol, or suspended particles, is considered to be a major air pollution problem in the CR, similarly to elsewhere [106]. According to the latest annual report [22] providing an assessment of ambient air quality based on established limit values [109], in 2018, the daily limit value of 50 μg m^{-3} for PM_{10} was exceeded over 3.2% of the entire territory of the CR (in a grid of 1 × 1 km) inhabited by approximately 14% of the population; the annual limit value of 40 μg m^{-3} for PM_{10} was exceeded at 0.1% of the entire territory of the CR with approximately 0.3% of the population. The annual limit value of 25 μg m^{-3} for fine fraction of $PM_{2.5}$ was exceeded in 1.2% of the entire territory of the CR inhabited by approximately 6.1% of the population. The annual limit value of 1 ng m^{-3} for benzo[a]pyrene, an established human carcinogen [131,132] related to $PM_{2.5}$ aerosol fraction and indicator of polycyclic aromatic hydrocarbons (PAHs) exposure, was exceeded in a number of cities and municipalities, on 12.6% of the entire CR territory inhabited by an astounding 35.5% of the country's inhabitants [22]. The trends in BaP based on long-term monitoring by the CHMI at several suburban sites, representing the exposure in residential areas of Czech cities in 2004–2018 are presented in Figure 12.

With respect to PAHs as a group, a study [133] measuring 15 PAHs (including seven which are carcinogenic) in PM_1 in the winters of 2013 and 2017 in industrial, urban and rural sites indicated values ranging between 60.8 ng m^{-3} (in the city of Ostrava) and 11.7 ng m^{-3} (in the small town of Čelákovice). The burning of biomass and coal used for residential heating in old-style boilers emits high PaH concentrations in particular [134]. PAH concentrations linked to local heating, as one of the important sources, were also found at the National Atmospheric Observatory Košetice (NAOK), a rural background site in the CR [135]. Particle-bound carcinogenic PAHs concentration may be applied as an indicator for estimation of the biologically active (mutagenic, genotoxic, embryotoxic) components used for epidemiological studies of the effects of air pollution on human health [136].

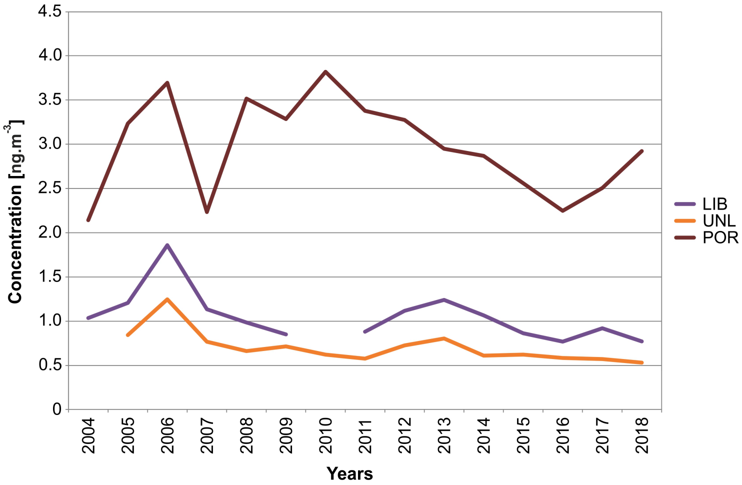

Figure 12. Trends in ambient annual mean BaP concentrations at selected sites (see Table 1, Figure 2), 2004–2018, based on CHMI data.

Due to long-term monitoring results, the Moravian-Silesian region/Ostrava region is recognised not only as a Czech hotspot for PM and BaP, but also truly as a European hotspot [22,106]. Ambient BaP concentrations frequently exceed the limit value of 1 ng m^{-3} at some sites of this region by seven to nine times [22]. The Ostrava region, with its concentrated heavy industry was in the past nicknamed the steel heart of the country. The heavy air pollution in this region results from several major sources, such as traditional steel and coke plants, local heating (with common burning of waste or coal powder) and traffic and, last but not least, by regional transport of polluted air masses from industrial parts of Poland [137–143]. Industry is apparently the major source of ultrafine particles (UFP) [144,145], the aerosol fraction which is blamed for the strongest effects on human health [146].

The local heating systems in Czech towns and villages burning either coal or wood also contribute substantially to PM exposures [111–113,147–149]. It is estimated that nearly 20% of the households in the CR are heated individually by the combustion of solid fuels [150]. That wood burning might be a dominant source of PM_{10} mass followed by coal combustion was somewhat surprisingly demonstrated even for the residential section of Mladá Boleslav, an industrial town famous for its large Skoda automotive factory [151]. Moreover, an incorrectly led combustion process [152], including the co-combustion of fuel with municipal waste, which is a common (though banned) practise in some regions (in particular with low-income residents who use this practise due to economic reasons), adds substantially to both PM and BaP emissions [153]. Currently, a programme subsidising the change of old types of manually operated boilers, which do not meet the emission requirements of European legislation [154] is under way, promoted and supported by the Ministry for the Environment.

All kinds of transport add substantially to this pollution and road vehicles in some places might even be the principal source of aerosol, such as in Prague, with a still unfinished city bypass and the major roads crossing the very centre of the city [155,156]. The hotspots are to be found in particular at places along the main roads, as was shown, e.g., in a study aimed to quantify the UFP exposure in the breathing zone in residential neighbourhoods of streets [157].

Serious health outcomes, including genotoxicity, due to the permanent high ambient PM and BaP exposures were reported for the Ostrava region by several studies conducted recently [158–163]. Furthermore, a moderately strong association between air pollutant concentrations and respiratory difficulties among asthmatic children and adolescents was reported [164]. The association between particle number and $PM_{2.5}$ concentrations and daily hospital admissions due to cardiovascular and respiratory diseases was reported for Prague [165]. A long-term study of the health impacts of air pollution on children in heavily polluted parts of the CR revealed that air pollution significantly affected children's health and resulted in increased respiratory morbidity [166,167].

4.2. Ground-Level Ozone

Ground-level O_3, recognized as an air pollutant only recently, has been monitored in the CR since 1993. Though emissions of O_3 precursors have decreased substantially (NO_x, VOC and CO by approximately one half and CH_4 by one quarter in the CR and in neighbouring countries), no corresponding decrease in O_3 ambient levels has been observed. In a thorough time trend analysis of continuous data from 26 long-term monitoring sites of various types (urban, mountain, rural) reflecting different environments in 1994–2015, statistically significant decreasing trends were recorded only at about one-half of these [117]. The fact that O_3 concentrations show high year-to-year variability due to their strong dependence on meteorological conditions of the specific year [168–170] was demonstrated also on the Czech data [171]. Both meteorology and air pollution (precursor emissions) are responsible for day-to-day variability in O_3 concentrations. This was shown for five Czech rural sites representing middle-elevated forests in Central Europe, where daily O_3 levels were significantly associated with air temperature, global solar radiation, relative humidity and ambient NO_x concentrations, the association being highly non-linear [172]. The phytotoxic potential of O_3, expressed by exposure index for forests AOT40F—a measure of potential effects as used throughout Europe [173]—is high for most of the CR [110,174,175]. The highest AOT40F values observed reached 38–39 ppm h; and the critical level for forest protection of 5 ppm h is usually exceeded early in the growing season, generally in May, at most of the measuring sites [176]. The O_3 spatial exposure pattern correlates strongly with the map showing global solar radiation across the CR [177]. The highest O_3 exposures are found in the relatively unpolluted, with respect to other pollutants, southern portions of the CR [172]. The O_3 concentrations increase with the altitude, whereas the increase of AOT40 with rising altitude is less clear [178].

Apart from long-term monitoring sites, measuring pollution continuously using the reference method as declared by the EU, as well as standard Quality Assurance/Quality Control (QA/QC) procedures (EC, 2008), for developing more detailed O_3 spatial patterns in more detailed scales, diffusive (passive) samplers were used. According to recommendations given by Krupa and Legge [179], these were used for indicative measurements within environmental studies conducted in protected natural areas (the Jizerské hory Mts., Orlické hory Mts., Novohradské hory Mts. and České Švýcarsko National Park), in complex, less accessible terrain in forested mountain areas without electricity available for standard measurements, and proved very successful, offering high precision and accuracy [180–183].

To date, published papers on the O_3 biological effects on Czech forests are ambiguous [183–188]. However, despite the fact that the recorded O_3 concentrations are fairly high, no serious harmful effects attributable to O_3 have been published so far. This conclusion, i.e., that there is no clear field evidence in forests under high O_3 concentrations in the CR, corresponds with similar reports from studies conducted throughout Europe (e.g., [189]).

In contrast to environmental studies, epidemiological studies indicated clear O_3 impacts on human health. In a five-year study (2002–2006) in Prague, including the 2003 and 2006 ozone abundant summer seasons, a statistically significant association between O_3 levels and daily mortality from respiratory diseases was revealed [187]. A relative risk of 1.080 (95% CI: 1.031–1.132) was observed for mortality from respiratory diseases per 10 $\mu g\ m^{-3}$ increase in 1 day lagged daily mean O_3 concentrations, which acknowledged that O_3 exposure in Prague, though lower when compared to many other European cities, is high enough to influence human health adversely [190]. This factor should be examined more with respect to climate change with an increasing frequency of extreme weather, including heat waves [191].

4.3. Atmospheric Deposition

Atmospheric deposition, as an important self-cleaning process of the atmosphere, removes air pollutants from the air on one hand, while on the other hand it acts as a contamination source for other spheres, such as the hydrosphere, pedosphere and biosphere [170]. The long-term monitoring results have shown a significant decrease in sulphur deposition at most measuring sites [94,116,192]. The spatial pattern of changes in sulphur deposition fluxes between 1995 and 2011 revealed a decrease over forested areas in a wide range of 18.1 to 0.2 g m^{-2} $year^{-1}$ with the highest improvement in the formerly most heavily impacted areas [116]. In contrast, nitrogen deposition has not improved much, and its spatial patterns are far more complex. The highest decrease in N deposition flux between 1995 and 2011 was a mere 2.5 g m^{-2} $year^{-1}$ in the formerly most heavily impacted areas, a stagnation in Southern and Northern Moravia and a mild increase of 0.4 g m^{-2} $year^{-1}$ in the Jizerské Mts., close to the Polish and German borders [116]. The trends in air pollutant emissions are reflected in changes in atmospheric chemistry and deposition, including changing proportions of the ion ratios of NO_3^-/SO_4^{2-}, NH_4^+/SO_4^{2-} and NH_4^+/NO_3- in precipitation [94,116,193].

Similarly as in other regions of Europe and US [194,195], it was demonstrated that in the CR, by not considering (1) deposition path via fog and (2) unmeasured constituents of dry deposition, such as NH_3 and HNO_3(g), the total sulphur and nitrogen depositions are likely to be underestimated substantially [196,197]. Although the chemistry of fog is regularly observed at only a few sites in the CR, and information on fog chemistry is scarce [198,199], it is widely recognised that fog in the CR is enriched as compared to rain, particularly in SO_4^{2-} and NO_3^- [103,104,200]. Moreover, the hydrological input of fog, namely in forested mountain areas, in the CR above 800 m above sea level might not be negligible [201]. SO_2 and NO_x, precursors of SO_4^{2-} and NO_3^- in fog, were shown to be (apart from the relative humidity) significant explanatory variables modelling the fog probability at Czech sites [202]. The fog pathway should definitely be accounted for in real deposition flux studies, although fog occurrence in the CR has decreased significantly over the last sixty years [203]. The chemistry of rime (as a part of horizontal deposition) has been studied recently at 10 regional mountain-top sites in the CR [204–207], nevertheless the contribution of rime to atmospheric deposition has been unclear thus far.

Improving ambient air quality and decreasing atmospheric deposition have also been demonstrated by long-term nationwide biomonitoring, including analyses of mosses and tree bark [208–213]. Furthermore, peat bogs proved useful for reflecting the history of heavy metal atmospheric deposition. An analysis of historical rates of Pb deposition over the past 150–200 years using ^{210}Pb dated in sphagnum-derived peat cores peaking in 1965–1992 confirmed a period of the highest production and burning of local lignite [214]. Peaks in Hg accumulation rates in peat cores were indicated between the 1950s and 1980s, reflecting the emissions from intensive coal burning in Central Europe [215]. Moreover, tree rings can be used as an archive for air pollution as was demonstrated for the Pb and $^{206}Pb/^{207}Pb$ ratio [216]. A decrease in arsenic deposition for the Orlické hory Mts. (Adlergebirge) near the Czech–Polish border in the winters of 1984–1986 and 2003–2015 was reported by Doušová et al. [217].

Recovery from acid deposition with respect to changes in soil, stream water and lake water chemistry was reported from numerous places in the CR after the SO_2 and NO_x emission reduction in Central Europe [218–222]. Nevertheless, in spite of a certain N deposition decrease, it was indicated that Czech forest soil horizons up to 20 cm in depth are still affected by a high N input [223], and in some regions elevated N deposition results in soil nutrient imbalances, in particular between nitrogen and phosphorus and nitrogen and magnesium [224]. Consequently, a higher proportion of nitrophilous species was detected in Czech forests during recent decades [225]. It was shown that a high acidic deposition, apart from geographical variables affects the climate–growth association of *Picea abies*, the most important tree species in the CR [226,227].

5. Conclusions

This review presents the ambient air quality development over the last 70 years in the territory of the modern-day Czech Republic. Major activities and achievements in ambient air quality management are indicated. The long-term nationwide monitoring results are supplemented by goal-directed one-time studies. Furthermore, apart from the air quality itself, the ambient air pollution impacts on both human health and the environment are collated.

It is obvious that much has been done in air pollution prevention, and that ambient air quality in the CR has improved substantially over the period under review due to newly introduced stringent legislation and technical countermeasures. Nevertheless, there are still activities which remain significant emission sources, such as local heating and vehicle transport travelling through communities, which are political issues that are hard to manage. The share of the population permanently exposed to PM and BaP concentrations above limit values remains considerable, and O_3 exposure for both humans and the environment is of high concern. Furthermore, despite significant emission reduction, atmospheric deposition, in particular of nitrogen, remains high in some regions.

Long-term ambient air quality monitoring has generated a vast database, which is still, in spite of numerous published studies, largely unexplored. This invaluable source of information should be examined more thoroughly. An association of historical and modern-day results might be one of the interesting goals for future analysis, offering a new perspective. Moreover, the ambient air quality data offer a unique input for large environmental studies and models, exploring in detail how air pollution affects the biosphere and hydrosphere, including forest, agricultural, natural and water ecosystems.

Funding: Open Access and Article Processing Charge was funded by the Czech Hydrometeorological Institute research project "Dlouhodobá koncepce rozvoje výzkumné organizace (DKRVO) Český hydrometeorologický ústav na období 2018–2022" financed by the Czech Ministry of Environment.

Acknowledgments: I would like to thank Petra Tichá and Jana Schovánková, both from the Czech Hydrometeorological Institute, for preparing Figure 2, Figure 3, Figure 4, Figure 5, Figure 6, Figure 7, Figure 8, Figure 9, Figure 10, Figure 11and Figure 12 and Erin Naillon for proofreading of this manuscript.

Conflicts of Interest: The author declares no conflict of interest.

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