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Who should measure air quality in modern cities? The example of decentralization of urban air quality monitoring in Krasnoyarsk (Siberia, Russia)

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ABSTRACT

Researchers have warned that the paradigm about who should measure air quality (AQ) in cities can change as low-cost commercial sensors for monitoring atmospheric composition gain global popularity. The new paradigm implies the expansion of the traditionally governmental responsibilities for AQ monitoring (to collect, interpret, and explain the data) to previously uninvolved actors. This study reports a first practical example of such changed AQ paradigm that occurred in a large industrial city of Krasnoyarsk (Russia). We describe how severe problems with urban AQ and a limited access to the AQ data from governmental sensors triggered decentralization of the AQ monitoring in the city. The decentralization is manifested by the fact that both governmental network and crowdfund-based activist AQ network, are being used for scientific and, to some extent, advisory purposes. The decentralization was foremost established due to the ambiguous quantitative information about AQ provided to users by the governmental network, exacerbated by efficient alternatives for alleviating this gap, offered by the activists. The unique decentralization of AQ monitoring in Krasnoyarsk can transform into the synergy between the government and citizen action aimed on easing air pollution as the governmental organizations can efficiently reinforce the resources (funds and manpower), and provide legal and technical support, while civic action groups with established audience can consolidate targeted groups of citizens for formulating efficient city-wide strategies in AQ management. Such synergy can become an inspiring example for the cities with degraded AQ, where the official monitoring is plagued by financial or technological limitations.

1. Introduction

Air pollution in cities has been traditionally measured by expensive, bulky instrumentation (Chow, 1995) and governmental organizations have been responsible for both monitoring air pollution and providing information and advice quality (Kuklinska et al., 2015). However, low-cost sensor technology opened new prospects in urban air quality (AQ) monitoring considering the accessibility, simplicity and dramatically lower prices of cheap nodes, compared to conventional AQ monitoring instrumentation (Morawska et al., 2018). Thousands of low-cost sensors have been deployed worldwide and, as the Morawska et al. (2018) review showed, a myriad of studies published since the spread of low-cost sensor technology worldwide. Indicatively, at the dawn of the low-cost approach some researchers had suggested that cheap sensors

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would change the paradigm of the AQ monitoring based on complex stationary equipment (Snyder et al., 2013). Therein, the low-cost technology was also incorporated in the large-scale AQ projects, thus confirming such prognosis (Morawska et al., 2018). As low-cost sensor technology is becoming a commonly used approach for urban AQ monitoring, another prediction of Snyder et al. (2013) about the public engagement in collecting and recording observations ("citizen science") is being realized. Non-expert groups of citizens can fund the projects to become the major stakeholders in such monitoring and, theoretically, to contribute to the AQ solutions based on individual knowledge (Ermolaeva et al., 2020). Although more than ten crowdfunding-based projects on investigating AQ based on low-cost technology were initiated in the 2010s (Thompson, 2016), it is unclear whether such initiatives can change the current paradigm of AQ monitoring by shifting traditional governmental responsibilities in AQ monitoring to third parties, as indicated by Snyder et al. (2013).

If a crowd-funded network for AQ monitoring is introduced in a technologically advanced city, stakeholders can shape environmental agenda by using such observations to increase people's awareness or empower civil pressure groups by such information (Van Brussel and Huyse, 2019). In this way, the low-cost AQ observations offer an optional technological upgrade (or extension of existing network) which helps in transforming the urban area to a smart city where information about the environment is automatically collected, potentially used for supporting decisions, but not necessarily used for traditional regulatory purposes (Mehta et al., 2016). More interestingly, a second potential scenario might occur when such network is introduced in a less technologically-developed city with poor and limited information about AQ. In this case, especially in low-to-mid income countries, public may have little or no access to data related to the conditions of the AQ (Pinder et al., 2019a, 2019b), which would decrease the possibility of immediate evaluation of the environmental agenda's progress. Under these circumstances, the traditionally governmental function for monitoring urban AQ can be potentially eroded, whereas the resulting gap can be alleviated by third parties (Wesseling et al., 2019), who can collect, interpret AQ data and giving public advice based upon this data due to low cost and accessibility of cheap AQ nodes.

It is plausible that the change of conventional paradigm of urban AQ monitoring might occur in Siberia. Most Siberian cities were planned as industrial hubs (Rodionova and Krejdenko, 2014) and ultimately evolved in large industrial or production centers. Thereafter, thousands of citizens of large Siberian cities were exposed to the bad AQ because most such cities had been developed around, usually, a vast industrial enterprise (Kryukova et al., 2015) and are notably smaller (in area) than cities with similar population numbers in North America (Schneider et al., 2009). As Musina and Neucheva (2018) put it, such urban areas planned during Soviet times are "*the cities built for industry, not for people*". Notably, the Russian government recently launched the federal project "Clean Air", aimed to improve the AQ in industrial cities of Russia with the worst AQ, where 11 out of 12 targeted cities are in Siberia (Clean Air Project, 2018). Perhaps, a large industrial city of Krasnoyarsk, suffering from the three-fold excess of PM2.5 concentration, compared to World Health Organization guidelines (Lin et al., 2020) is the most striking example of the AQ problem in urban Siberia. The bad AQ in Krasnoyarsk has attracted exceptional attention outside academia from such renown international outlets as the Independent (2018) and Bloomberg (2020). Despite this, the studies about urban AQ in Krasnoyarsk are scanty in the international peer-reviewed literature. Indicatively, two recent studies about AQ in Krasnoyarsk used aerosol observations from a network of cheap ground nodes (Lin et al., 2020; Mikhailuta et al., 2020), originally developed, installed and maintained by local activists, concerned about AQ in the city.

We suspect that the traditionally governmental functions of urban AQ monitoring (to collect, interpret, and explain the data) were possibly complemented by participatory monitoring in Krasnoyarsk (Siberia, Russia). This situation, denoted as "decentralization" of AQ monitoring, was analyzed in this study to evaluate the prediction of Snyder et al. (2013) about the transformative role of public engagement (collecting and recording observations) for the established practices of urban AQ monitoring. We (a) analyze unique societal and environmental factors around the urban AQ issue in Krasnoyarsk, (b) examine how the decentralization with the AQ monitoring in the city was formed and (c) explore why the system of governmental AQ monitoring has been unable to timely and efficiently respond to the problem of deteriorated AQ.

2. Data and methods

We describe the data and methods in this section. Section 3 relies on the publicly available information about the governmental network for AQ monitoring in Krasnoyarsk from the Regional Ministry of Ecology (http://krasecology.ru/), regional meteorological services (http://meteo.krasnoyarsk.ru) and regional government of Krasnoyarsk (http://www.mpr.krskstate.ru/nmy). Section 4 relies on the scientific literature, legal documents, and regular reports form the Ministry of Ecology and Resources. Moreover, we applied the analysis of Google trends, which had been shown as a relatively reliable tool for expressing the public interest in environment-related topics (Nghiem et al., 2016). We calculated the summarized internet search points from Google trends per year for the keyword combination 'Krasnoyarsk air' in Russian ("Воздух Красноярск"). We used the original combination of words in Russian language, thus implying that our Google search was region-specific. Section 5 relies on the analysis of legal documents and academic literature. We also used open access information about the participatory monitoring network in Krasnoyarsk from their website and social networks (https://nebo.live/ru/krs, https://www.instagram.com/nebo.community/?hl=en), the information from the AQ aggregator (https://waqi.info) and system of monitoring of the Scientific Center of Russian Academy of Sciences of Krasnoyarsk (http://air.krasn.ru/) The information about the technical characteristics of cheap nodes and governmental sensors from the manufacturers was used (AirVisual node – https://www.iqair.com/air-quality-monitors/airvisual-series, BAM – https://metone.com/products/bam-1020/). The Russian legal and policy documents were accessed in Russian language from various official websites including the website of the Ministry of Resources and Ecology (https://rpn.gov.ru/) or the open access database about legal documents in Russia (http://pravo.gov.ru/) and translated to English if necessary.

3. Governmental system for air quality monitoring in Krasnoyarsk

Krasnoyarsk is one of the largest cities of Siberia (> 1 million population) and heavily industrialized economy (the city produces 3 % of world's aluminum). The governmental system of AQ monitoring in Krasnoyarsk (the Krasnoyarsk AQ network hereafter) was created in 1998 by the Ministry of Ecology of Krasnoyarsk. The Krasnoyarsk AQ network consists of several ground-based instruments (9 are located within the Krasnoyarsk urban area) that measure several AQ-related species and aerosol parameters (CO, SO_2, NO, NO_2, H_2S, NH_3 and particles of PM2.5 and PM10) every 20 min. Fig. 1 shows the locations of the stations. The aims of the governmental network for atmospheric monitoring are (a) to monitor the level of air pollution for better understanding spatio-temporal distribution of air pollutants, (b) to support governmental institutes/agencies and the population with systematic and emergency information about the dynamics of air pollution and (c) to supply stakeholders with the information required for providing recommendations with regards to conservation and environmental policy, including for sustainable use of resources and for outlining economic development plan which considers environmental conditions.

The AQ is estimated according to the RD 52.04.667.2005 ordinance based on a set of AQ indices. This set includes (a) the Standard Air Quality Index (SAQI, "СИ" in Russian) based on the maximum concentration at a given time divided by the maximum allowed concentration

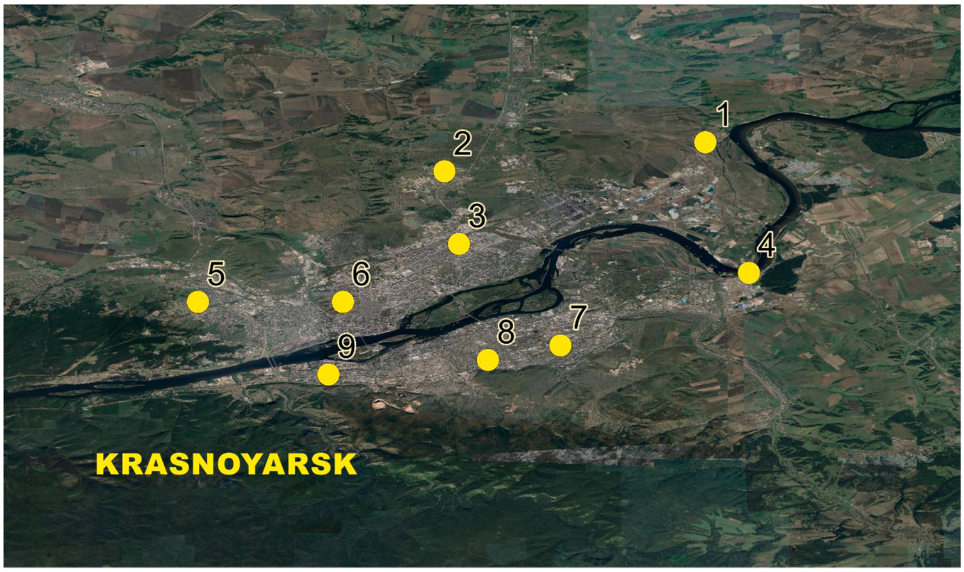

Fig. 1. The governmental system of AQ monitoring in Krasnoyarsk urban area according to the data from http://krasecology.ru/. 1 – Kubekovo, 2 – Solnechniy, 3 – Severny, 4 – Berezovka, 5 – Vetluzhanka, 6 – Pokrovka, 7 – Cheremushki, 8 – Kirovskiy, 9 – Sverdlovskiy. The background map is provided by the Google services (Google satellite imagery).

MAC, (b) combined AQ index (CAQI$_5$ or "ИЗА$_5$" in Russian) of five targeted pollutants (benzopyrene, formaldehyde, PM2.5, NO2 and NH$_3$ for Krasnoyarsk) that accounts the ratio between the averaged concentration of each type and the MAC of each type being and (c) HRMAC ("НП" in Russian) that simply expresses the Highest Repeatability of Maximum Allowable Concentration. Moreover, most indices originate from Soviet era regulatory documents that suggested that all pollutants produce the most adverse health effects on human at the MAC level and their effects at the same MAC level are nearly identical. The modern management decisions and the limits depend on the regulatory emission limits, listed in the online document (Russian Emission Limits, 2017). Since 2017, the PM2.5 concentration has been monitored by BAM-1020 dust analyzers manufactured by Met One Instruments (Tokarev et al., 2020). Several studies have been published about AQ in Krasnoyarsk which used the data from these stations (Badmaeva and Tsimmerman, 2015; Shaparev et al., 2019; Yakubailik et al., 2019; Chernykh et al., 2020; Tokarev et al., 2020) but it is hard to find any information about the validation of these instruments.

The Krasnoyarsk AQ network provides the data for research purposes, and, to inform the public. It also uploads the data on their website (http://krasecology.ru). There, a map with the short-term (1 day) SAQI estimates based on ground-based observations is available for the aforementioned species. More comprehensive information about AQ is uploaded by the Krasnoyarsk AQ network is in the form of monthly reports to one of the websites of Krasnoyarsk Hydrometeorological (Hydromet) Services (http://meteo.krasnoyarsk.ru). By August 2022, the latest report is by some reason available only for January 2020. Based on the data from the Krasnoyarsk AQ network, the Regional Ministry of Ecology issues alerts under meteorological conditions, conductive for air pollution episodes (so-called "Black Sky" regime). The "Black Sky" was enacted by the ordinance N112 from 01.03.2011 by the Federal Agency for Environmental Control of Russia. The "Black Sky" regime signifies the adverse meteorological conditions favorable for trapping the air pollutants in the planetary boundary layer. Interestingly, according to some studies, the "Black Sky" regime implies the "adverse" wind direction (bringing air from a high emission area to the city), a lack of strong wind, haze and stable atmospheric inversion. However, the range of meteorological parameters based on which this regime is introduced is lacking in both legal documents and in scientific sources. There is more concrete information about three stages of the "Black Sky" alert at which 30 major regional industrial emitters should decrease their emissions by 15–20 % (stage 1 "Black Sky"), 20–40 % (stage 2) and 40–60 % (stage 3) following the ordinance 19 of the Federal Law "About the protection of air" (Federal Law, 1999). All major metallurgical, cement, chemical plants and all coal power plants in Krasnoyarsk, mentioned in the special document (http://www.mpr.krskstate.ru/nmy) from the ministry, have to comply with this regulation.

4. Change of the paradigm in AQ monitoring of Krasnoyarsk: prelude, climax and triggered decentralization

4.1. Prelude of AQ problems in Krasnoyarsk. Unique societal and environmental factors, conductive for deteriorated AQ

To understand the current situation with AQ in Krasnoyarsk, it is instructive to discuss how the problem with bad AQ has been historically shaped in the city and became a challenge for the governmental system of AQ monitoring. As mentioned, Krasnoyarsk is an industrial Siberian city, which implies that the (a) civic urban infrastructure of the city was evolved around the industrial enterprises, (b) most population densely reside in close vicinity to these enterprises, (c) harsh climate necessitates substantial warming, which generates additional pollutants during winter. Moreover, Krasnoyarsk suffers from some environmental unique conditions, conductive for AQ deterioration.

Economically, vast production of aluminum was initiated in the 1960 s at the Krasnoyarsk Aluminum Smelter. The smelter stood out with its production capacities (1 million tons) and unprecedented amount of outdated technologies concentrated at one vast facility (Litovchenko et al., 2020). The Soviet government anticipated AQ problems in cities like Krasnoyarsk and introduced the standard (17.2.3.01-86) that obligated installation of 10–20 stationary and mobile stations for AQ monitoring in cities with populations of > 1,000,000 people (National Committee of USSR, 1987) in 1986. However, as seen from Fig. 1, there are fewer stations of the governmental AQ monitoring in the urban area of Krasnoyarsk even today. The current stage of the problem with AQ in Krasnoyarsk was likely triggered in the early 2000 s when the Russian economy experienced the unprecedentedly rapid growth (6.4–10 % of GDP growth in 1999–2005), compared to the 1990s (−15.7–1.4 % in 1992–1998) (Goldman, 2008). The revenues from this economic growth were massively invested in the cornerstones of the Russian economy including the production of raw materials, chemicals and heavy machinery (these three together generating more than 20 % of Russian exports) that are mostly produced in industrial cities such as Krasnoyarsk. As a result, Krasnoyarsk has turned into one of few so-called “islands” of prosperity in Russia of the 21st century (Kinossian, 2014) that concentrated economic activities around their urban cores, while its industrial emissions have been also steadily increasing on 5 %, 6 % and 7 % in 2009, 2010 and 2013, respectively (Badmaeva and Tsimmerman, 2015). This is a considerable increase given the cumulative annual amount of pollutants (629 kT of pollutants) emitted from the industrial and vehicular sources in Krasnoyarsk (Shaparev et al., 2019). Today, the largest emitters of the city are aluminum producer ‘RUSAL Krasnoyarsk’ (~ 56 kT) and Krasnoyarsk Thermal Power Plants (~ 40.6 kT) (Shaparev et al., 2019). Moreover, the contribution of a considerable portion of emissions from Krasnoyarsk was not included in the aforementioned estimates. Romanov et al. (2020) only recently estimated these previously unaccounted emissions from private households heated by coal (~ 3,5 kT) and small boiler houses distributed throughout the city (~ 8–9 kT), which exceed the emissions from all three thermal power plants. As the necessity of winter heating has been exacerbated with the growth of the urban population, the energetically inefficient power plants run on lignite have also allegedly exacerbated AQ problems in the city during winter (Chernykh et al., 2020).

Climate conditions were always conductive for deteriorated AQ in Krasnoyarsk because it is located on the Yenisei River in the valley, surrounded by mountains (the valley-like relief of the terrain), and experiences frequent low wind speed regimes. Due to this, frequent temperature inversions driven by the unfreezing river (> 70 % days during the year) often cap the pollution within the boundary layer of the atmosphere (Hrebtov and Hanjalić, 2017; Romanov et al., 2020). During stagnant atmospheric conditions with prevailing thermal inversions, the concentration of pollutants can be increased up to 200 times in the boundary layer (Mikhailuta et al., 2020). Moreover, the city is surrounded by the vast spaces of Siberian forests and is vulnerable to frequent exposure of the strengthening summer wildfires under global warming (Lin et al., 2020; Gosteva et al., 2020). As a result, the “Black Sky” adverse meteorological conditions were reported at least 111 times in the period of January 2019–February 2020 (Dergunov and Yakubailik, 2020).

4.2. The climax of air quality problem in Krasnoyarsk: 2006–2019

4.2.1. Available information about air quality in Krasnoyarsk

Quantitative information about AQ in Krasnoyarsk has been available since the mid-2000s when, the problem with bad AQ has intensified. The Federal Service for Hydrometeorology and Environmental Monitoring of Russia (Roshydromet) reported a prominent growth of NOx and benzopyrene (a very toxic pollutant emitted predominantly from aluminum production) in the atmosphere of Krasnoyarsk in 2006 (Roshydromet, 2008). Since 2007 the Regional Ministry of Ecology has been uploading reports about environmental conditions in Krasnoyarsk with SAQI annual estimates. These estimates represent the most trustworthy information about AQ in Krasnoyarsk because scientific literature about AQ in Russian cities is scanty, and most information about AQ is taken from the governmental reports (Henry and Douhovnikoff, 2008). As SAQI expresses the air pollution level (low 0–1, medium 2–4, high 5–10 and very high > 10), the air pollution was likely very high in 10 out of the 12 years (except 2011 and 2012) in Krasnoyarsk (Table 1). Also, Table 1 illustrates that AQ in Krasnoyarsk has been degrading from 2007 to 2010 whereas a temporarily reduction of unknown nature occurred in 2012–2013 and then the AQ problem reached its two-decadal climax in 2016 (Table 1). The latest Report of the Ministry of Ecology and Resources of Krasnoyarsk Region in 2019 classified the AQ in the city as “very bad”, and Krasnoyarsk is regularly listed among the most polluted urban areas in Russia (Krasnoyarsk Region Report for 2018, 2019). Moreover, a remote sensing-based study showed that AQ in Krasnoyarsk is far below WHO international annual average guidelines (35 μg/m^3 vs recommended 5 μg/m^3) and ~ 63 % higher than the national annual average PM2.5 level in Russia (Lin et al., 2020).

Table 1
Standard Air Quality Index in Krasnoyarsk by years according to the Regional Ministry of Environment and Resources reports in 2007–2019 (Krasnoyarsk Region Report for 2007, 2008; Krasnoyarsk Region Report for 2008, 2009; Krasnoyarsk Region Report for 2009, 2010; Krasnoyarsk Region Report for 2010, 2011; Krasnoyarsk Region Report for 2011, 2012; Krasnoyarsk Region Report for 2012, 2013; Krasnoyarsk Region Report for 2013, 2014; Krasnoyarsk Region Report for 2014, 2015; Krasnoyarsk Region Report for 2015, 2016; Krasnoyarsk Region Report for 2016, 2017; Krasnoyarsk Region Report for 2017, 2018; Krasnoyarsk Region Report for 2018, 2019; Krasnoyarsk Region Report for 2019, 2020).

Year	SAQI
2007	12.8
2008	18
2009	10.4
2010	20.4
2011	20
2012	6.4
2013	7
2014	30.2
2015	18.5
2016	40.6
2017	20.1
2018	30.6
2019	22

4.2.2. Strong demand about explicit air quality information in Krasnoyarsk

Since 2016, alarming evidences about the increase of air pollution-driven diseases in Krasnoyarsk started to emerge in the research literature. High health hazard risk (according to the “MR 2.1.10.0156-19” ordinance) (Popova et al., 2019), twofold underestimation of the obstructive pulmonary disease diagnosed (Artykhov et al., 2015) and substantial increase in benzopyrene and formaldehyde-induced types of cancer (Meshkov et al., 2018) were reported in this period. At the same time, the interest about air pollution in Krasnoyarsk clearly increased among the citizens of the city. Google trend analysis can reflect this interest (Fig. 2), where we used the keyword combination ‘Krasnoyarsk air’ in Russian language ("Воздух Красноярск" in Russian), as shortly mentioned in the methodology. Indicatively, the interest in AQ in Krasnoyarsk was evidently associated with the AQ conditions in the city. For instance, the interest in the air was gradually declining in the 2010–2013 period (Fig. 2) when the SAQI was generally decreasing in Krasnoyarsk (correlation coefficient between the interest and SAQI is 0.78 in this period). After 2013, SAQI exhibited considerable interannual variability but also showed prominent growth, compared to the previous period. At the same time, the internet searches based on a keyword “Krasnoyarsk air” (in Russian) rapidly grew to reach the first peak in 2017 and then, the second and largest peak occurred in 2019. Note that in the latest period (2016–2019; see Fig. 2), the highest agreement was found not between the internet searches and SAQI, but between the internet searches and SAQI of the previous year. This pattern is potentially attributed to a salient peak in the internet searches about air that was detected in the first months of a year (January,

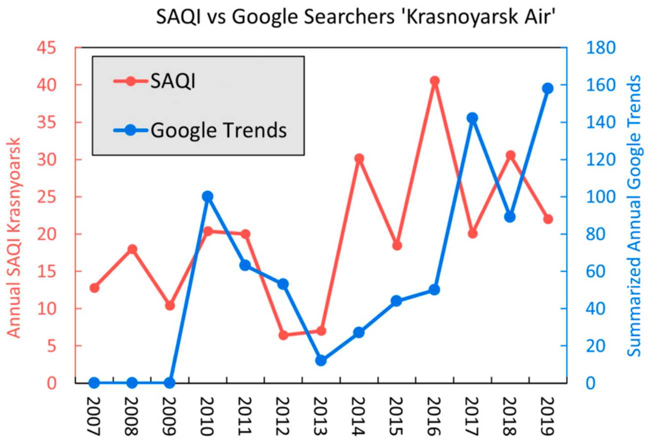

Fig. 2. Standardized Air Quality Index (SAQI) for year *i* (x-axis) for Krasnoyarsk (red) versus summarized google points based on Google trend analysis (blue).

February), but had been caused by bad AQ events in the end of a previous year (December), when most air pollution episodes occur in Krasnoyarsk (Lin et al., 2020).

5. Decentralization of air quality monitoring in Krasnoyarsk

5.1. The role of participatory air quality monitoring in Krasnoyarsk in 2017–2021

To respond to the problem with AQ in Krasnoyarsk and to the growing demand to address it, several activists in Krasnoyarsk established the crowd-funded network for monitoring the AQ in Krasnoyarsk called "Nebo" ("Sky" in Russian). The network was created in 2017 when the first peak of the people's interest about the conditions of the air in Krasnoyarsk spiked, as confirmed by the data from Fig. 2. The Nebo website states that "*We started our project as a group of enthusiasts who were faced with severe air pollution and a lack of up-to-date data*", thereby implying that the network was initially planned, created and ran by activists and volunteers (https://air.nebo.live/). By summer 2017, Nebo had installed four identical low-cost sensors for AQ registration (AirVisual Node based on the common registration of light-scattering at a particle) in Krasnoyarsk. Among aerosols, the sensors measured PM1, PM2.5 and PM10 whereas meteorological parameters are registered simultaneously by the sensors. The primary interest of the Nebo network was to measure PM2.5; an indicator of premature mortality worldwide (Evans et al., 2013). This was a sensible choice as 91% of air pollution in Krasnoyarsk is formed by PM2.5 (Shaparev et al., 2019). The sensors were installed in relatively similar environmental conditions, being set up at the floor above ground level of the residential buildings of a similar type. By January 2018, the Nebo network had increased the number of sensors. By August 2022, Nebo had installed 74 sensors around Krasnoyarsk (the details about their sensors are regularly updated at https://nebo.live/ru/krs). For illustration, Table 2 compares the technical characteristics of the Nebo sensors (AirVisual) and the instruments, deployed by the government (BAM-1020). A good ratio between affordability and the efficiency indicates that the deployment of the cheap nodes was beneficial (price = ~ 1/42 of BAM price, size = ~ 1/2 of BAM, weight = ~ 1/46 of BAM; 0–0.5 mg/m^3 is the measurement range in the same meteorological range of conditions as for BAM), compared to BAM. Due to this, the activists quickly covered a large area of Krasnoyarsk by these simple sensors. Most importantly, instead of utilizing MAC-based indices of Soviet times (Bespamyatnov et al., 1975), used for most regulatory purposes by governmental agencies in Russia, the activists have been converting their observations to the widely-recognized Environmental Protection Agency AQ indices (EPA AQI; Federal Register, 1999), that is calculated as a piece-wise function (Mintz, 2016). The importance of this choice is further explained in one of the following sections.

Table 2
Comparison of basic characteristics between AirVisual sensors (deployed by the activists) and BAM instrument (deployed by the governmental network) Only those characteristics available in the open access and provided for both sensors are shown, while the detailed technical characteristics of the Nebo sensors are provided in Appendix A.

Parameter	Network: Government	Network: Participatory (Nebo)
Sensor Type	E-BAM-1020	AirVisual Node
Range	0–65 mg/m^3	0–0.5 mg/m^3
Measurement Cycle	Hourly: 1, 5, 10, 15 or 30 min	Real-time: every 2 min
Detector	Scintillation probe	Laser Sensor
Humidity Range Inlet	0–90 % RH* (non-condensing)	0–90 % RH* (non-condensing)
Humidity Control	Actively controlled inlet heater module	Moisture evaluation sensor with input heater connection
Flow Rate	16.7 liters/min (adjustable)	0.5 liters/min
Sample Pump	Dual diaphragm type (DC powered, 4000 h rating)	Built-in-fan
Input Power	12 V DC @ 48 Watts max	5 V DC @ Watts max
Operating Temperature	-25 to + 50 °C	-35 to + 60 °C
Enclosure	41 cm × 36 cm x 20 cm, 14 kg	15 cm × 8 cm × 3 cm, 0.3 kg
Price	10,000 $	140 $

* RH – Relative Humidity.

The Nebo network has set three main goals: (a) to alert the public about air pollution based on meaningful AQ indices, (b) to collect AQ data for research, and (c) to determine the main pollutants in the city (the personal correspondence with the Nebo network supervisors). All these goals clearly overlap with the traditionally governmental functions to collect and interpret AQ data, to provide advice for sensitive groups of the population and to associate atmospheric composition anomalies with meteorology and the underlying emissions in the city. Most likely, Nebo effectively pursued their goals at least in two aforementioned aspects. Regarding alerting the public about air pollution, they started using their website and thereafter provided dozens of recommendations based on EPA AQI for Krasnoyarsk citizens. These recommendations are popular in Krasnoyarsk according to the strengthening trust between the Nebo network advisory and its numerous followers in social networks. While, Lin et al. (2020) previously reported that > 25,000 people follow Nebo activities in April 2020, the number increased on 52 % in two years (> 38,000 followers) (Nebo, 2022). From research perspective, the PM2.5 data from the Nebo sensors (combined with satellite data) were used for the first multiyear study that reported the spatially-resolved distribution of PM2.5 and the average PM2.5 estimates for Krasnoyarsk (2017–2018) with clear method-driven uncertainties (Lin et al., 2020). Moreover, Mikhailuta et al. (2020) successfully used their data for attributing pollution sources in Krasnoyarsk.

Besides the main goals, public can participate in discussing and evaluating the AQ monitoring results as the Nebo activists provided such platform on their social networks, where the public advisory about AQ is being uploaded on nearly daily basis and commented by many visitors. In this light, the activists used social networks and started (d) reporting the cases of repeated pollution in the region to authorities (e) collecting and redistributing the video and photo materials from the local community about detected pollution (f) opening public discussion of emission reduction plans, politicians' statements about the pollution control policy and emission reduction strategies. On top of that, (g) some volunteered Nebo activists have already participated in the discussion with the regional officials and politicians about the fate of AQ monitoring and environmental agenda in Krasnoyarsk (discussion about the adequacy of the existing AQ indices, AQ monitoring in the city and the commitment of industry in reducing dangerous pollutants). This means that citizens can shape the environmental agenda in Krasnoyarsk through the provided opportunities. Specifically, they can install a cheap node sensor at their home, thereby contributing to AQ monitoring routines or by participating in online or public discussion on key environmental decisions in the city, thus affecting the environment-related agenda in the city, as previously observed by Van Brussel et al., (2019). This, in turn, indicates that the AQ monitoring has become decentralized in Krasnoyarsk. The decentralization is manifested by the successful contribution and even replacement of traditionally governmental functions of AQ monitoring by civic action and activism in Krasnoyarsk. The activist network for monitoring AQ in Krasnoyarsk is a set of cheap sensors that had been initially bought, installed and thereafter maintained in similar environmental conditions by third-party users without any centralized maintenance, where only the data collection and visualization were coordinated.

5.2. *Challenges and prospects of decentralization of AQ monitoring in Krasnoyarsk*

One of the most illustrative examples of such decentralization is https://waqi.info (accessed by > 750,000 visitors per month by January 2021 according to sitechecker.pro); one of the largest AQ aggregators worldwide. It currently shows AQ information from the Nebo stations alongside the stations from the Krasnoyarsk AQ Monitoring network operated by the Regional Ministry of Ecology (Fig. 3). Moreover, two more AQ networks including AirKrasn (http://air.krasn.ru/) by the Scientific Center of Russian Academy of Sciences in Krasnoyarsk (Zavoruev et al., 2020) and Department of Hydrometeorology and Environmental Monitoring AQ sensors around the city, but the information from these networks was not uploaded to the waqi.info platform, further perplexing the issue of accessibility of information about AQ in Krasnoyarsk.

The governmental system of AQ monitoring in Krasnoyarsk was equipped by state-of-the art sensors, arbitrarily labeled as the best AQ monitoring system in Russia by then regional minister of ecology, Chasovitin (Nebo, 2017), was also described as a system that is able to provide clear knowledge about the spatial dynamics and the sources of pollution by the governor of the Krasnoyarsk region (Krasnoyarsk Region Portal, 2019). Thus, it is instructive to understand why such system in Krasnoyarsk was unable to adequately respond to the growing social concerns about AQ and the alternative monitoring activities emerged in the city.

5.2.1. *Methodological driver of decentralization: uninformative AQ indices by governmental agencies*

The decentralization of AQ monitoring in Krasnoyarsk was foremost driven by a debatable choice of AQI for informing broad public about hazardous AQ in the governmental system. The thresholds for hazardous concentrations of PM2.5 were unreasonably high for the Krasnoyarsk AQ monitoring system. This does not mean that the thresholds were initially established beyond the recommended value; the AQ indices were rather not reflective of internationally accepted levels of health risk. In particular, the Krasnoyarsk AQ monitoring system (http://krasecology.ru/Air) provides information as a set of various MAC-based AQ indices expressed as individual hourly ($\mathrm{MAC} = 160\ \mu\mathrm{g/m^3}$) and 24-hour averaged concentrations ($\mathrm{MAC} = 35\ \mu\mathrm{g/m^3}$). There are just three regimes of pollution including “low”, “high” ($\mathrm{SAQI} < 10 \cdot \mathrm{MAC}$ for individual 1-h measurements; $\mathrm{SAQI} > \mathrm{MAC}$ in 24-h average) and “very high” ($\mathrm{SAQI} > 10 \cdot \mathrm{MAC}$ for 24-h average; not existent for 24-h average) levels. Such high thresholds for individual measurements of most pollutants, including PM2.5, correspond to conditions hazardous to human health that sensitive groups can immediately experience. For instance, a one-time SAQI-based PM2.5 concentration of $159.9\ \mu\mathrm{g/m^3}$ ($< 160\ \mu\mathrm{g/m^3}$) is classified as “low” pollution according to such approach, while for EPA AQI such pollution would be in the middle of “very unhealthy ”category. More specifically, the hourly PM2.5 concentration of $159.9\ \mu\mathrm{g/m^3}$ is between the weekly average of PM2.5 in two highly polluted cities of Dhaka ($183\ \mu\mathrm{g/m^3}$) and Delhi ($140\ \mu\mathrm{g/m^3}$) (Rodríguez-Urrego and Rodgríudez-Urrego, 2020). Such levels are rarely registered in the atmosphere of urban areas and greatly exceed both the WHO guidelines of $25\ \mu\mathrm{g/m^3}$ (WHO, 2018) and the Russian national guidelines of $35\ \mu\mathrm{g/m^3}$ (Dergunov and Yakubailik, 2020). While 24-h averages can reasonably express air pollution in general, the implementation of this parameter into the regularly updated online interface is somewhat questionable. Oddly, the 24-h averages can express only two conditions of air pollution including “low” and “high” pollution (high when $\mathrm{SAQI} > 35\ \mu\mathrm{g/m^3}$) and the averages are not visible on the online map, provided by the governmental AQ monitoring system in Krasnoyarsk. The 24-averages are only shown in the table visible only after scrolling down past the one-time SAQI table (taken from hourly observations) that plagues the accessibility of this information.

Due to this, the governmental stations upload the information about AQ the governmental website with one-time SAQI on the map whereas

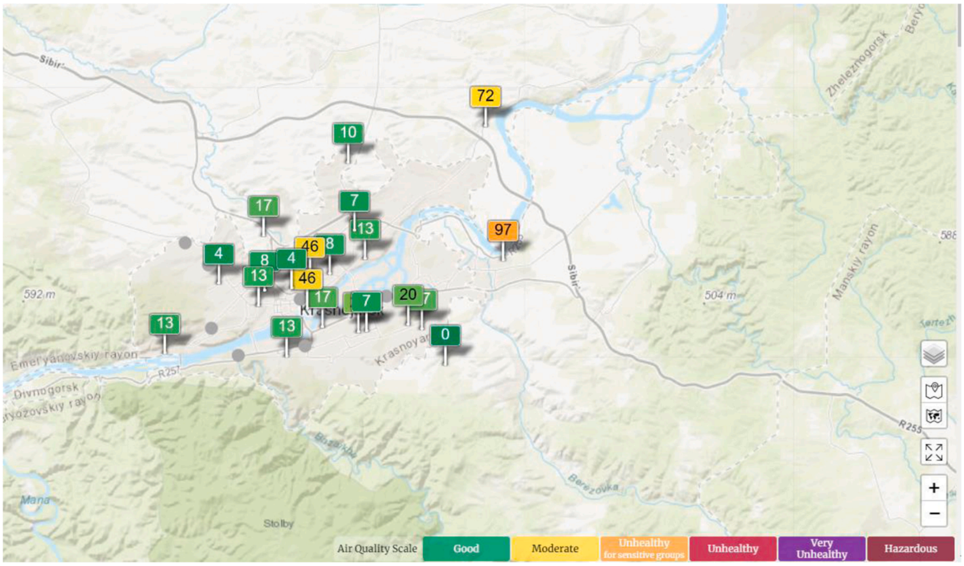

Fig. 3. A screenshot from https://waqi.info/ website which collects AQ information from AQ sensors around the world (made on 07.02.2021, 15:05 UTC). Data from the governmental monitoring is shown alongside the Nebo network data without any distinctive marks. Note that by summer 2022, the total number of stations, deployed by Nebo and various branches of government increased, but it is difficult to estimate the exact number of sensors. The full list of sensors we found in the open access by August 2022 is shown in the Supplementary material (Fig. S1).

the air pollution is nearly always good. However, the same data uploaded to the aggregator waqi.info after conversion to EPA AQI somewhat indicate bad AQ during some days. Such a paradoxical, but not uncommon example of one day is shown in Fig. 4 where the AQ is good according to the governmental system and bad according to the online AQ website waqi.com, despite both platforms used the same data from the same sensors. Needless to say, such disagreement between these websites noted by users may undermine the trust towards the system of AQ monitoring, whereas the exact reason of disagreement would remain unclear and can be even exaggerated by a user (malfunctioning instrumentation or underreporting of AQ by purpose).

5.2.2. Communicational driver of decentralization: data provision and transparency policies

The time-series of the governmental monitoring data is not publicly available (only the last 24-h observations can be downloaded from the monitoring website). Access is only given only upon request by organizations affiliated with air pollution-related projects. Simultaneously, information about AQ in Krasnoyarsk from the scientific literature is rather fragmented and suffers from the lack of details about the instruments used, their technical features, validation and potential uncertainties. Despite the promising results, most studies that used either of the AQ governmental networks (the Krasecology system or the Air-Krasn system) to estimate AQ or the concentration of hazardous pollutants in the city lacked the description of instrumental imperfections or error bars in the expressed concentrations of pollutants (Badmaeva and Tsimmerman, 2015; Shaparev et al., 2019; Zavoruev et al., 2020; Dergunov and Yakubailik, 2020; Tokarev et al., 2020). Most critically, there is no holistic work about AQ in Krasnoyarsk using state-of-the art instrumentation where both technical characteristics of the used instruments and long-term spatio-temporal characteristics of most important pollutants could be explicitly analyzed.

In such conditions civic action partly not only introduced the alternative AQ monitoring, but also assimilated modern digital information technologies into their activities. The activists have widely used their own online platforms to provide a ground for AQ alerts from their users that could be uploaded in the form of an instant message, a photo or video evidence of the suspected pollution. This strategy facilitated the use of Nebo online advice primarily targeting a younger audience (< 40 years old) as they strongly prefer this type of communication (Curtis

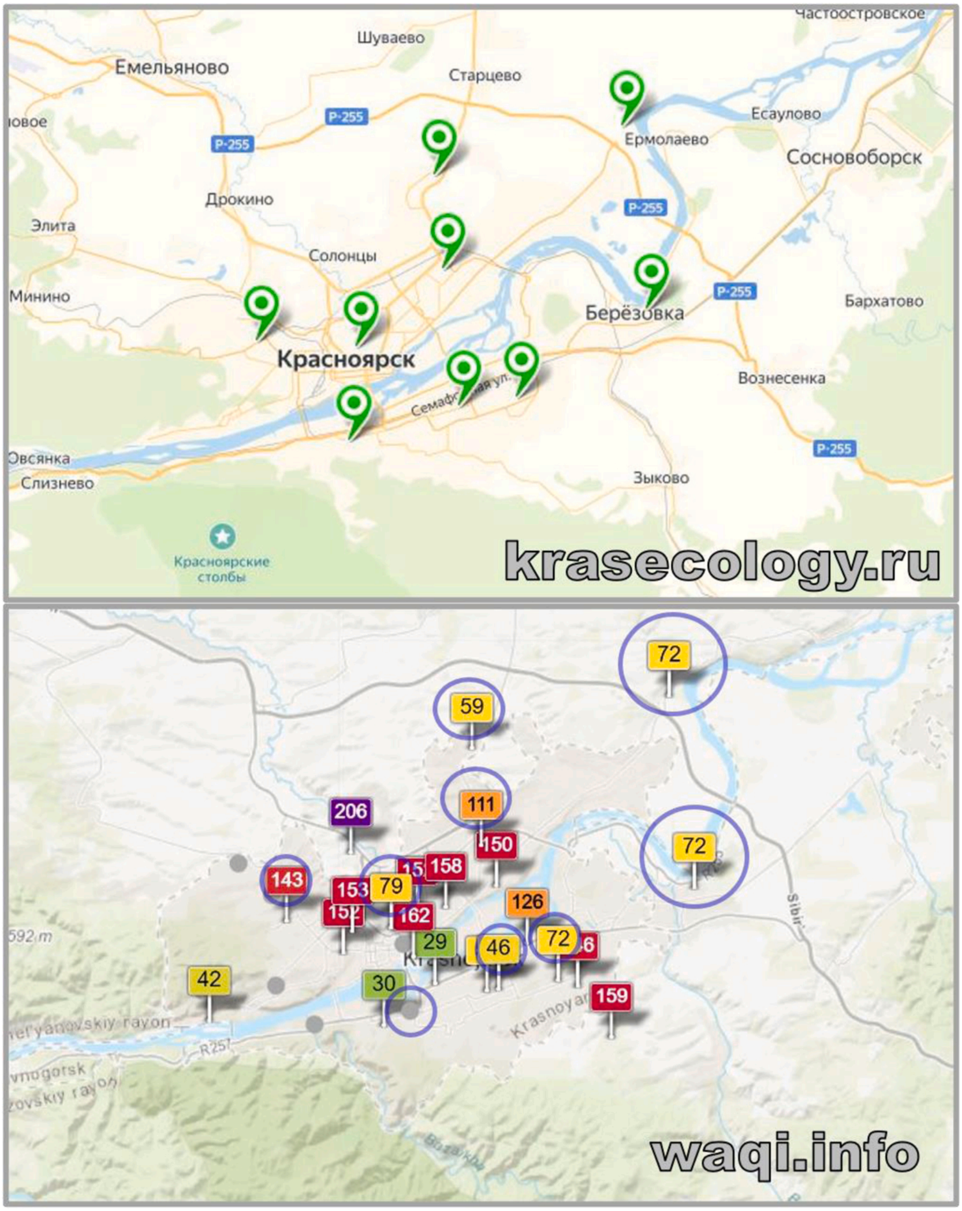

Fig. 4. Visual comparison between the assessment of AQ based on the website of the governmental system of AQ monitoring (krasecology.ru) on the top panel versus the website waqi.info on the bottom panel. Top panel: two regimes of air pollution: good (green) and bad (yellow) based on SAQI. Bottom panel: 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). Date: 12.02.21; 19:50 UTC. On the bottom panel, blue circles denote the stations of the governmental network (other stations belong to Nebo). The stations without numerical estimates on the map did not receive the measurement information during that particular day.

et al., 2019) rather than making calls with the complaints to a corresponding institution. For comparison, the records of responses of the Regional Ministry of Ecology to received AQ complaints are stored at the website of the network but available only up to 2019 (http://krasecology.ru/About/Hotline), thereby indicating a potential inefficiency of such feedback system. In this light, a decision to inform a broad audience about bad AQ by using modern media platforms was likely essential for the activists because modern users adequately understand the limitations of such information (Wesseling et al., 2019), and can therefore make reasonable conclusions from it. Moreover, Mullins and Bharadwaj (2014) have indicatively concluded that public alerts can contribute to reduction of air pollutant concentrations and reduction of hospitalizations (Mason et al., 2019). The activists have started uploading and discussing emission reduction plans, legal documents and statements of regional and federal officials on the same platform (Nebo, 2022). Moreover, the activists encouraged broad public, policy-makers and scientists to use their data.

5.2.3. Prospects of participatory air quality monitoring: legal and policy-making aspects

The legal status of the right on clear air and on how to tackle low AQ toward such goal is facilitated by legal documents, regulations and agreements in Russia and in Krasnoyarsk. Besides the constitutional right to the clean air for all Russian citizens (Article 42 of the Constitution), there are legal initiatives and goals aimed at improving the AQ in Russia and in Krasnoyarsk. At the national level, the Federal Targets of Sustainable Development urge authorities to "significantly reduce number of pollution-related deaths by 2030" (3.9, Target 3) and to "decrease $PM_{2.5}$ and PM_{10} in several cities" (11.65, Target 11) (Babenko et al., 2016). Additionally, there are tailored assignments to improve the AQ in Krasnoyarsk. At local scales, the Environmental Charter was signed by 111 members, including the largest industrial emitters alongside regional and municipal officials in the city (Environmental Charter of Krasnoyarsk Region, 2017). The Federal Government's ordinance (N1026-r, 23.05.2019) required allocation of quotas for air pollutants from major emitting industries (ORF, 2019a). Most importantly, there was an ordinance from the Federal Government of Russia (N1806 from 24.12.2019) to create a modernized AQ monitoring system in industrial cities with poor AQ, including Krasnoyarsk (ORF, 2019b). The Federal Project "Clean Air" aims to reduce the atmospheric pollutants in several industrial cities, including Krasnoyarsk, where the modernization of AQ monitoring was expected to be performed by 31.12.2021 (Clean Air Project, 2018). Although the legal foundation to control and to improve the situation with AQ was paved, the ambiguity remains on the role of citizen-based monitoring of AQ because most these legal documents were formulated without considering participatory monitoring. This situation is not unique for Russia as De Craemer et al. (2020) have previously concluded that the existing AQ legislation is not optimized to assimilate observations from participatory monitoring into legally defined practices.

In such situation, the Krasnoyarsk activists faced a notable counterstand from some regional agencies. In line with the previous suggestion that authorities are often concerned about illegal use of AQ sensors (Wesseling et al., 2019), the Department of the Federal Service for Meteorological and Environmental Monitoring of Russia in the Siberian Federal District notified the supervisors of Nebo in November 2017 about a recourse to a court (N 02-24/28 from 22.11.2017) by The Regional Ministry of Ecology and the public attorney office of Krasnoyarsk region. The supervisors of Nebo were suspected in the violation of the national regulation (1 of 19.20 from the Code of Russian Federation) due to conduction of meteorological monitoring by unlicensed instrumentation (the Federal Law N99 about "Licensing of certain types of civic activities"). The regional attorney expressed the primary complaint that the Nebo sensors disagreed with the official monitoring stations. The penalty was not imposed on the Nebo activists and later, the Ministry of Natural Resources and Environment of Russian Federation responded to the related request that *"Monitoring of the environment and air quality are not related to the responsibility of meteorological services and therefore licensing is not required"* (RBC, 2018). Moreover, the legal trial seemingly bolstered the popularity of Nebo and its activists via the so-called "Streisand effect" (popularization of event or activity as a result of the targeted censorship or muting) that had been already evidenced in Russia (Clark, 2014). Such initial reaction on the participatory monitoring is not surprising because environmental groups, once noticed, are often seen as "*threatening regime stability and exacerbating the problem of control*" by decision-makers in Russia, as Plantan (2018) put it. Therefore, the weak legal basis, which could formalize the role of participatory monitoring in regular governmental AQ monitoring and the lack of political will even to tolerate those who show themselves as environmental activists, are suggested as two main bottlenecks, constraining assimilation of cheap sensor technologies in AQ monitoring practices in Russia.

6. Discussion

We summarized the existing information about AQ in Krasnoyarsk and concluded that the conditions for deteriorated AQ in Krasnoyarsk were established at the early stage of the urban planning (favorable location for capping temperature inversions, concentration of unprecedently intensive production of commodities around which the residential areas evolved in the Soviet-alike urban planning) and exacerbated in modern times (rebounded production of commodities, increased heating demand in winter supplied by highly-polluting lignite fuel, increased frequency of neighboring forest fires in summer). Nowadays, although appropriate infrastructure for AQ measurements is available in Krasnoyarsk, the corresponding data were not being best utilized for the public good. This gap in the governmental efforts for monitoring AQ was allegedly complemented by the crowd-funded participatory AQ monitoring system. The participatory monitoring data were already used for informing a broad audience about alarming AQ conditions in the city (mainly based on PM2.5 peaks compared to the background conditions), and utilized by researchers (Lin et al., 2020; Mikhailuta et al., 2020). Moreover, it is unclear whether inspired by participatory monitoring or not, but Zavoruev et al. (2019) reported that the Russian government already started implementing cheap sensors for monitoring AQ in Krasnoyarsk.

Overall, the civic involvement and broad utilization of the resultant data by users and scientists indicate that the current system of AQ monitoring in Krasnoyarsk is decentralized. This confirms the prediction of Snyder et al. (2013) about the transformative role of public engagement in the paradigm of urban AQ monitoring. The decentralization occurred because local activists in Krasnoyarsk quickly replaced those functions that were deficient in the governmental system of AQ monitoring and public advisory of Krasnoyarsk. In particular, (a) while the governmental network used somewhat ambiguous AQ indices with the thresholds, nearly unsensitive to daily adverse health effects on population, the activists introduced widely-used EPA AQ indices with the thresholds, more realistically reflecting the severity of AQ effects on human health. Crucially, the Krasnoyarsk activists already proposed to the Federal Service for Supervision of Natural Resource Usage ("Rosprirodnadzor") to create a new national air quality index that should realistically reflect long-term exposure of Russian citizens to AQ conditions, and Rosprirodnadzor has agreed to support this initiative (Rosprirodnadzor, 2021). Moreover, while (b) the governmental network provided only a fragmented access to official AQ data, thus making it somewhat unvalidatable by third parties, the activists provided their data in open access and actively encouraged broad public, researchers, industry and officials to use their data. Lastly, (c) while government relied on less flexible system for feedback about bad AQ, the activists used modern information technologies of communication, namely, social networks for exchanging the information about AQ among the citizens.

This decentralization of AQ monitoring in Krasnoyarsk is an illustrative example how civic activists can more efficiently reinforce their preferences for environmental quality using modern technologies and tools (and oppositely, to promote these technologies and tools through their demands and suggestions to the government). Although the onset of the participatory AQ monitoring in Krasnoyarsk brought certain benefits, there are challenges, hampering interplay between broad public, governmental AQ monitoring and civic activism, laying in legal and political dimensions. The lack of (a) legal basis for incorporating the participatory monitoring into existing observational practices for public good in Russia has been prominent, but is being alleviated. Russian government introduced the standard for involvement of citizens in the improvement of their urban environment and this involvement has risen on 45 % in 2020 (ASI, 2021). This is a sign of positive change because the current study and previous observation-based studies about Krasnoyarsk (Lin et al., 2020) and other cities like Antwerp (Van Brussel and Huyse, 2019) indicated that volunteers, activists and stakeholders can most efficiently integrate a set of cheap sensors into a functional network and information exchange platform by their collective efforts. However, even with the broad participation of third parties under the improved legal basis, (b) policy-makers can remain skeptical or even negative about participatory monitoring in Krasnoyarsk due to the concerns about political power of such monitoring and the collective citizen effort behind it. We strongly encourage policy-makers to deprioritize these concerns in Krasnoyarsk by benefiting from the combination of accessible technology (cheap sensors) and citizen engagement in environmental agenda.

7. Conclusions

Overall, the question "*Who should measure air quality in cities?*" can be answered in the following way – air quality should be measured by synergetic efforts between the government and civic action in Krasnoyarsk. In particular, the Russian government can effeciently reinforce the resources (both funds and manpower) for solving the problem with air quality monitoring. Meanwhile, civic action groups with established audiences can consolidate targeted groups of citizens for formulating efficient city-wide strategies in air quality management. The emerging signs of the synergy scenario are evident as the Minister of Ecology of Krasnoyarsk proposed to facilitate the licensing of low cost sensors installed by the activists. The related federal agencies are actively working with them to densely cover the city with low-cost sensors for future source attribution of air pollution (SSI, 2021). Such synergy can improve the existing models for predicting AQ in Russia, making the information more transparent and providing an opportunity to participate in shaping the environmental agenda of the city, thereby meeting the interests of government, population and activists, respectively. In this way, a potential eco-immigration from Krasnoyarsk that may be triggered by bad air (Lam et al., 2021) can be prevented.

In future, (a) the quality of the provided data by all air quality networks in Krasnoyarsk should be thoroughly scrutinized by local-oriented studies, while (b) the introduction of any new air quality index should be supported with scientific evidence. We identified association between degraded air quality and interest about air in the city, thus prompting that the (c) phenomenon of social media/civic activism in the countries suffering from bad air quality and their role in environmental policy-making should be elucidated. Globally, synergy between governmental and the civic groups can become an inspiring example on how to improve air quality management and potentially to reduce the monitoring costs by using the lessons from the citizen science. Future global studies can also (d) seek an extended selection of cities where a similar paradigm shift in air quality monitoring has happened and (e) develop a legal roadmap for a global-scale synergy between civic activism and governmental efforts for air quality monitoring.

CRediT authorship contribution statement

Lev D. Labzovskii: Original Idea, Conceptualization, Investigation, Writing – original draft, Visualization. **Joshua Vande Hey:** Supervision, Writing – review & editing. **Aleksey A. Romanov:** Visualization, Data curation, Writing – review & editing. **Polina Golovatina-Mora:** Writing – review & editing. **Dmitriy Belikov:** Writing – review & editing. **Azam Lashkari:** Writing – review & editing. **Samuel Takele Kenea:** Writing – review & editing. **Erik Hekman:** Writing – review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2022.11.016.

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