EEET ECOLOGICAL ENGINEERING
& ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology 2023, 24(2), 11–18
https://doi.org/10.12912/27197050/156963
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Received: 2022.10.22
Accepted: 2022.12.08
Published: 2023.01.01

Development and Practical Testing of the Zonal-Indicative Methodology for Assessing the Impact of Industrial Enterprises on the State of Atmospheric Air Pollution

Volodymyr Bakharev[1], Angelina Chugai*[2], Iryna Soloshych[1], Olena Kortsova[1]

[1] Educational and Scientific Institute of Mechanical Engineering, Transport and Natural Sciences, Kremenchuk Mykhailo Ostrohradskyi National University, 20 Pershotravneva Str., Kremenchuk, 39600, Ukraine

[2] Nature Protection Faculty, Odessa State Environmental University, 15 Lvivska Str., Odessa, 65106, Ukraine

* Corresponding author's e-mail: avchugai@ukr.net

ABSTRACT

The article provides the general provisions and features of the application of the zonal-indicative methodology for assessing the impact on the state of the atmospheric air of enterprises from local industrial complexes and its practical approbation. A unified approach to determining the zones of negative influence of industrial objects and their groups on the state of atmospheric air is proposed. Analytical dependencies have been established to determine the physical and linear dimensions of the influence zones. The peculiarities of the method of determining "marker" substances for the conditions of formation of the level of atmospheric pollution due to the activity of local industrial complexes are characterized. An algorithm for implementing the method is proposed, which includes procedures for selecting marker substances of the first order (impact), second order (basic), and third order (specific). Significant parameters for the selection procedure of marker substances and the conditions for differentiating emission sources are substantiated, which allows to ensure the effectiveness of the practical implementation of the method. Approbation of the proposed zonal-indicative methodology was carried out on the example of the Kryukiv Carriage Plant, which is part of the local industrial hub in the southern part of Kremenchuk. The calculation of zones of probable influence and other parameters necessary for the application of the indicative evaluation method was carried out. The inverse problem "technological process – marker substance" has been solved. Measurement points of the maximum one-time surface concentrations of pollutants have been determined. Analytical processing of the results of calculation studies and laboratory (including field) observations was carried out. The obtained calculated values of surface concentrations made it possible to determine the substantiated maximum possible contribution of the object to the formation of the general level of atmospheric air pollution in the southern microdistricts of Kremenchuk. In particular, it was established that the level of acceptability of the possible negative impact should be determined based on the results of calculations of the dispersion of marker pollutants in atmospheric air without taking into account background concentrations.

Keywords: air pollution, marker substance, industrial complex, zonal-indicative methodology.

INTRODUCTION

In order to prevent negative technogenic impact on the environment, the following issues are important, such as cleaning emissions (discharges) of pollutants (Malovanyy et al., 2020; Malovanyy et al., 2021), monitoring pollution of natural environments, disposal of wastewater treatment waste at sewage treatment plants (Tymchuk et al. al., 2020), introduction of environmentally safe strategies for handling household (Popovych et al., 2020) and industrial (Plyatsuk et al., 2018) waste. In terms of air pollution, systematic exposure to pollutants in significant concentrations directly affects the health of the population. Therefore, there is an urgent need to create effective systems of monitoring and control of the activity of industrial facilities.

Numerous studies have been devoted to solving problems within the framework of the problem of assessing and forecasting the impact of industrial facilities on the state of atmospheric air. A significant number of assessment methods are known, which can be conditionally divided according to three principles: calculation, zonal and indicative. The use of the zonal approach is usually limited to the definition of only one sanitary protection zone (SPZ); the indicative one is the definition of pollution markers from a specific production according to the sectoral principle. The application of the indicative approach does not give the expected result today. The reason lies in the identity of the nomenclature of pollutants entering the atmospheric air from emission sources on the territory of industrial facilities belonging to the industrial complex (IC). Therefore, the reasoned proof that the contribution of this very object as part of IC to the formation of an increased level of atmospheric air pollution is decisive. This task is currently relevant for ensuring the environmental safety of technogenic urban systems, such as the city of Kremenchuk.

Kremenchuk has a significant number of technogenic objects (the main ones are petrochemical, machine-building and metalworking, thermal power and transport enterprises) and covers an area of about 10,000 hectares, of which 37% are industrial enterprises. The nature of placement of technogenic objects on the territory of the district allows conditionally to distinguish 5 technozones: northern, southern, avtozavodska (car factory), eastern, central. Four of them are located on the left bank of the Dnipro River, and one is on the right bank.

MATERIALS AND METHODS

The purpose of the study is to develop methodological approaches for assessing the impact of individual industrial enterprises as part of IC on the air basin. In general, the concept of "IC" in the interpretation of "territorial-production complex as part of an industrial agglomeration" is considered by us as a group of enterprises connected by a complex interaction of complex-forming factors. In fact, it is an industrial agglomeration as a specific form of territorial organization of an industrial complex, which has a complex multi-component functional structure and is characterized by a high level of economic efficiency of functioning (Gladky, 2010). It is worth noting that the practical assessment of the impact of such complexes on the state of the atmospheric air is significantly complicated by the similarity of the list of pollutants entering the atmospheric air, as well as by the imposition of conditional zones of emissions influence of individual sources from the range. In such conditions, a complex scientific and practical task needs to be solved – the definition of the list of "substances-sources-industrial processes", the impact of which on the state of atmospheric air pollution can be reasonably considered to be significant.

To solve this problem, it is advisable to use the method of determining marker substances (Bascom et al., 1996; Behrendt et al., 1997). In the studies of foreign authors, the concept of "marker substance" in relation to atmospheric air pollution of urban systems is mainly used in the aspect of marking the negative impact on the health of the population due to the spread of diseases of certain nosological groups (Calderon-Garciduenas et al., 2002; Hong et al., 2002). The results of research by a number of authors (Johnson et al. 2010; Oikonen et al. 2003) confirm the validity of such an approach, which gave reason to use it for practical purposes (Tsai et al., 2003; Wellenius et al., 2005; Yorifuji et al., 2011). The application of both methodological approaches – zonal and indicative – will allow to determine both the predominant sources and priority polluting substances for more effective control of the negative impact of industrial facilities.

Thus, the goal of the work is to develop a complex zonal-indicative approach to assessing the impact on the state of atmospheric air of industrial facilities from the composition of local ICs with practical testing on the example of microdistricts of the technogenically loaded urban ecosystem of Kremenchuk.

RESULTS AND DISCUSSION

We assume that marker substances (MS) are substances that characterize production technologies, reflect their features, are essential and key for evaluating the factors of influence of production processes on the state of environmental components. In the conditions of the overlap of the territories of SPZ of objects belonging to a certain group, the actual superimposition of conditional flares from emission sources, as well as the determination of marker substances based on traditional approaches are impossible. Therefore, a unified approach to determining the zones of negative influence of industrial facilities is proposed (Table 1).

Significant parameters for the selection procedure of marker substances: SPZ, ZAP, x_{cont}, x_{max} – definitions are given in the Table 1. The maximum calculated concentration fulfils the condition $C_{max\ calculated} \geq MPCms$. The minimum calculated concentration fulfils the condition $C_{min\ calculated} \geq$ the lower concentration limit for the control device. Surface concentration at a control point is the value of the concentration of a pollutant at a point on the terrain, usually within the residential development zone of an adjacent settlement, in which the $C_{calculated\ in\ \text{controlled spot.}} \geq C_{min\ calculated}$ condition is met. Surface concentration at the point of sampling fulfills the condition of $C_{в.п.} \geq Cp_{min}$. Distances for sampling: $x_{infl.}$ is the distance from the source of influence to the point of sampling. Conditions for differentiation of emission sources:

1. $L_{ZAP} = 50h_{max}$ (L_{ZAP} – the size of the zone of active pollution; h_{max} – the height of the highest source of pollutants entering the atmospheric air on the territory of the industrial facility, m).
2. If $L_{ZAP} > L_{SPZ}$, it means high sources of emission (potentially possible negative impact outside the SPZ).
3. If $L_{ZAP} \leq L_{SPZ}$, it means low sources of emission (the distribution of significant concentrations occurs within the limits of SPZ, beyond which the fulfillment of the condition $C_{max\ calculated} \geq MPC_{ms}$ is impossible).

The MS selection algorithm includes: selection of MS (I) of the first order (influence); selection of MS (II) of the second order (basic); selection of MS (III) of the third order (specific). In general, the following scenario is implemented: "industrial node → superimposition of SPZ and ZAP of individual objects that are part of it → a set of emission sources → a general assessment of the impact of MS (I) → determination of high sources → determination of MS (II) → assessment of the impact of a set of low sources → selection of a set of MS (III) → priority sources → specific technological process."

Having determined a specific technological process, it is possible to provide reasoned recommendations on environmental protection. It should be noted that the selection of control points is carried out in the direction of the location of residential development zones, regardless of the wind direction for the settlement. The following are also separate requirements:

1) systematic and episodic control with the help of stationary and mobile control points – the priority of choosing a control point at the points of intersection of the SPZ of industrial objects that are part of the industrial node – x_{SPZ};
2) operational and regime control using mobile observation points – the priority of choosing a control point under the conditions of $x_{controlled\ spot}$ as close as possible to the calculated $x_{\mathbf{max}}$ for a certain high source (Kortsova, 2018).

Therefore, the method implements an algorithm for the practical determination of marker substances under conditions of influence on the state of the atmospheric air of enterprises of the local IC. The proposed approach with the complex application of zonal and indicative methods

Table 1. Definition of concepts related to the zonal method

Name	Characteristics of the influence zone	Marking
Zone of overturning of the emission flare	The distance between the emission source (H ≥ 10 m) and the point of contact of the emission flare in the surface layer of the atmosphere ($x_{cont} = 0.16\ x_{max}$)	Point of contact, x_{cont}
Sanitary protection zone	The distance between the emission source and the point on the terrain at which the values of the surface concentrations of any substances present in the emissions of this source do not exceed the *MPCms*	SPZ
Zone of active pollution	The zone of the maximum possible dispersion of pollutants with a significant concentration ($C \geq 0.05\ MPCms$)	ZAP
Zone of maximum surface concentrations	The distance between the emission source and the point on the terrain at which the value of the surface concentrations of substances present in the emissions of this source is maximum	The point of maximum concentration, x_{max}
Zone of possible (maximum possible) pollution	The zone of the maximum possible dispersion of pollutants, taking into account the influence of meteorological conditions and parameters of emission sources. This zone has radiuses ; $r_{internal} = 2 \cdot \varphi \cdot H$, M; $r_{enternal} = 20 \cdot \varphi \cdot H$, M	ZPC

was tested on the example of the Kryukiv Carriage Plant (KCP), which is located in the southern technozone of the city of Kremenchuk. The Kremenchug Steel Plant is located next to the KCP. It is worth noting that the SPZ boundaries of these objects intersect, which creates conditions for the organization of a local IC. The territory of the KCP industrial site is located in an area with a developed transport network, represented by public roads and railways. The situational map of the area where the enterprise is located is presented in Figure 1.

It was established that the composition of all technological processes of the main production of KCP includes the application of soil and painting of surfaces. From the list of the most common pollutants, the main contribution to the formation of the volume of gross emissions is made by SO_2, CO, $[NO + NO_2]$. However, the priority substance is the amount of nitrogen oxides due to being a more dangerous substance. Xylene has the largest contribution to the formation of gross emissions of specific substances of the object.

For all sources of KCP emissions, with the exception of unorganized ones, the calculation of probable zones of influence and other parameters necessary for the application of the indicative assessment method was carried out (Table 2). It was found that the maximum parameters of the possible zones of negative influence of the object on the state of the atmospheric air are determined by the emissions of the combustion plant < 50 MW (boiler units).

Analysis of the results of the calculations shows that for the vast majority of emission sources of the object, taking into account the insignificant size of the SPZ; the conditions $L_{ZAP}>L_{SPZ}$ and $\boldsymbol{x}_{max} \geq L_{SPZ}$ are fulfilled. In general, the application of the zonal method made it possible to determine points on the terrain to control the concentration levels of pollutants. This is the basis for the application of the indicative evaluation method, taking into account the preliminary theoretical selection of the MS of the object, carried out as a result of the analysis of the features of the implementation of the main technological processes of

Fig. 1. Situational map of the area where the enterprise is located

Table 2. Maximal sizes of probable zones of harmful influence of KCP

Name	Marking	Value, *M*
Zone of overturning of the emission flare	Point of contact, x_{cont}	237
Sanitary protection zone	SPZ	100
Zone of active pollution	ZAP	5000
Zone of maximum surface concentrations	The point of maximum concentration, x_{max}	1578
Zone of possible (maximum possible) contamination (outer radius)	ZPC	6835

production. Benz(a)pyrene was identified as MS (I). However, this substance is not present in the emissions of KCP, and the most likely source of the above-standard value of the surface concentration of benzo(a)pyrene is road transport.

Nitrogen oxides, such as MS (III) – the specific substance xylene, are determined as markers of the second order. The main conditions for the selection of MS (III) of the order of the indicative evaluation method are fulfilled. An additional confirmation of the correctness of the MS selection is the analysis of the fulfillment of the condition – the distance between the low sources in the group must meet the condition: $x_{source1} - x_{source2} \leq x_{max}$, where $x_{source1} - x_{source2}$ is the distance between the sources on the terrain. To finally confirm the correctness of the selection of MS (II) and MS (III), an analysis of the fulfillment of the condition $Cpmax \geq MPCms$ is necessary, which can be carried out by calculating the dispersion of pollutants in the surface layer of the atmosphere.

The calculation of the dispersion of pollutants was performed using the EOL+ software package version 5.3.8. The calculation was carried out without taking into account residential buildings and values of background concentrations of harmful substances. The results are given in the Tables 3–4. As evidenced by the results of the calculations, the condition for the application of the indicative evaluation technique $Cpmax \geq MPCms$ is fulfilled. However, the maximum surface concentrations of the specified substances at the specified control points and at the boundary of the SPZ of the object do not exceed the established standards of atmospheric air quality.

In order to verify the model calculation of scattering, the KCP laboratory carried out a series of field observations of the NO_2 concentration at the same points (T.2 – T.5). The results are presented in the Table 5. As evidenced by the results of on-site measurements, the maximum surface concentrations of pollutants, including MS (II) *NOx* at the specified control points and at the boundary of the SPZ of the facility do not exceed the established quality standards. The final conclusion regarding the acceptable level of the impact of KCP on the state of the atmospheric air is made on the basis of an analytical study of the probable relationship between the results of modeling and field observations.

The results of determining the correlation coefficient, which characterizes the presence or

Table 3. The results of the MS (II) (NO_2) scattering calculation

Pollutant	Code	*MPCms*	The maximum value at the selected points, mg/m^3	
Nitrogen oxides (in terms of nitrogen dioxide [NO + NO_2]) [NO + NO_2])	301	0.2	T.2	0.078
			T.3	0.078
			T.4	0.072
			T.5	0.056

Table 4. Results of MS (III) (xylene) scattering calculation

Pollutant	Code	MPC	The maximum value at the selected points, mg/m^3	
Xylene	616	0,2	T.2	0.088
			T.3	0.088
			T.4	0.082
			T.5	0.062

Table 5. Generalized results of in-situ observations of the KCP laboratory at control points in the zone of probable influence

Set control points	Wind speed, m/s	Wind direction	Pollutant	*MPC*, mg/m^3	Concentration, mg/m^3
T.3	0.9	North-West	NO_2	0.2	0.037
T.4	1.1	North-West	NO_2	0.2	0.01
T.5	1.4	North-West	NO_2	0.2	0.02
T.3	2.0	East	NO_2	0.2	0.03
T.4	4.0	South-East	NO_2	0.2	0.01
T.2	4.0	South-East	NO_2	0.2	0.037
T.5	4.0	South-East	NO_2	0.2	0.02

absence of a relationship between the maximum single values of surface concentrations obtained by calculation, and the results of the calculation are given in the Table 6 and Figure 2. According to the Chaddock scale, the correlation is significant. The closeness of the connection between trait Y and factor X is noticeable and direct. However, to establish the presence of a linear relationship between the series of measurement results, it is necessary to calculate the significance (reliability) of the correlation coefficient: $- r_{xy} = t_{cnocm} = 0.539$.

We put forward hypotheses:

- H0: $r_{xy} = 0$, there is no linear relationship between the variables;
- H1: $r_{xy} \neq 0$, there is a linear relationship between the variables;

According to Student's table, $t_{critical}$ is obtained at the level of significance $\alpha = 0.05$ and degrees of freedom k=2: $t_{critical}$ $(n - m - 1;\ \alpha / 2) = t_{critical}$ $(2;\ 0.025) = 6.205$, where $m = 1$ is the number of variables. If $|t_{observ}| > t_{critical}$, then the obtained value of the correlation coefficient is significant (the null hypothesis confirming the value "0" for the correlation coefficient is rejected). Since $|t_{observ}| < t_{kritical}$, then we accept the hypothesis that the correlation coefficient is equal to "0". That is, the correlation coefficient is not statistically significant.

In our case of paired linear regression, testing the hypotheses about the significance of the correlation coefficient is equivalent to testing the hypothesis about the significance of the linear regression equation, that is, the linear relationship.

Table 6. The results of the correlation calculation

Definitions of lines	Control points				The value of the correlation coefficient, r_{xy}
	T.2	T.3	T.4	T.5	
Row 1. The value of the results of laboratory measurements	0.037	0.0335	0.01	0.02	0.539
Row 2. Results of scattering calculation	0.078	0.078	0.072	0.056	
Row 3. Value of *MPC* of nitrogen oxides (in terms of nitrogen dioxide [NO + NO_2])	0.2	0.2	0.2	0.2	–

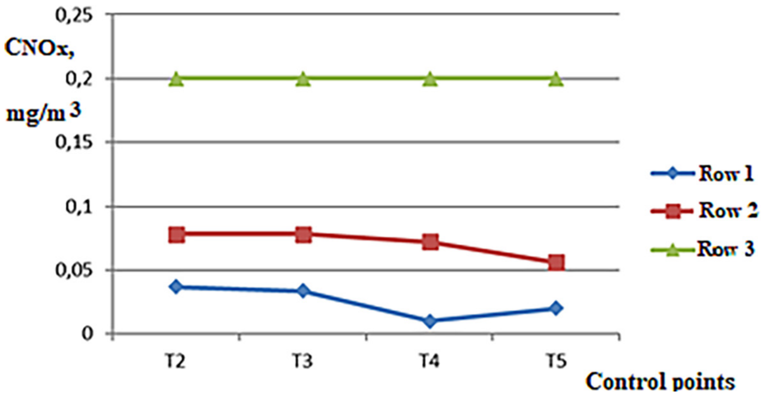

Fig. 2. Relationship between the results of laboratory measurements (field observations) and the results of scattering calculations

So, we have a significant correlation between the results of field observations and the model calculation of scattering, but there is no statistical confirmation of the reliability of the linear relationship between the data. The obtained results of analytical processing show that the reliable relationship between these variables is polynomial, that is, it depends on a number of unaccounted factors of influence. On this basis, it is possible to put forward a well-founded assumption that the man-made influence of KCP on the state of atmospheric air in the micro-districts of the southern part of Kremenchuk is not decisive.

Thus, taking into account the above statements, it can be objectively established that the reasonably acceptable level of the negative impact of KCP on the state of atmospheric air in the adjacent residential areas in accident-free mode of operation should not exceed the values given in the table 3 and 4. In general, this made it possible to determine the justified maximum possible contribution of the object into the formation of the general level of atmospheric air pollution.

CONCLUSIONS

The work is devoted to solving the actual scientific and practical issue of developing a complex zonal-indicative method for assessing the impact on the state of atmospheric air of industrial facilities from the composition of local ICs for technogenically loaded urboecosystems. The results obtained during the performance of the tasks set in the work are as follows. A unified approach to determining the zones of negative influence of industrial objects and their groups on the state of atmospheric air is proposed. Relevant zones of influence are highlighted, namely: overturning of the emission torch, sanitary protection, active pollution, maximum surface concentrations, possible (maximum possible) pollution. Analytical dependencies have been established to determine the physical and linear dimensions of the influence zones.

The method of determining "marker" substances for the conditions of formation of the level of atmospheric pollution due to the activity of local ICs is given. An algorithm for the implementation of the method is proposed, which includes procedures for selecting MSs of the first order (influence), second order (basic), and third order (specific). The significant parameters for the procedure for the selection of MS and the conditions for the differentiation of emission sources are justified, which allows to ensure the effectiveness of the practical implementation of the method.

The proposed zonal-indicative method was tested on the example of a powerful industrial facility of the KCP from the local industrial hub in the southern part of the city of Kremenchuk. The calculation of zones of probable influence and other parameters necessary for the application of the indicative evaluation method was carried out. An indicative method of assessing the object's impact on the state of atmospheric air is applied. The inverse problem "technological process – marker substance" has been solved. Measurement points of the maximum one-time surface concentrations of pollutants have been determined. MS (II) determined as nitrogen oxides (in terms of nitrogen dioxide $[NO + NO_2]$). This substance is typical for emissions from "high" sources, including thermal installations, the parameters of which primarily determine the size of potential negative impact zones. A specific substance in the object's emissions – xylene – was determined as MS (III). This substance is present in the emissions of groups of sources in all the main technological links of production at KCP. Analytical processing of the results of calculation studies and laboratory (including field) observations was carried out.

The obtained calculated values of surface concentrations made it possible to determine the substantiated maximum possible contribution of the object to the formation of the general level of atmospheric air pollution in the southern microdistricts of Kremenchuk. It was established that the level of acceptability of a possible negative impact should be determined based on the results of calculations of MS scattering in atmospheric air without taking into account background concentrations.

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