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ENVIRONMENTAL ASSESSMENT OF THE STATE OF WATER BODIES IN THE ACCIDENT-IMPACTED ZONE USING INTEGRATED SPATIAL INDICATORS

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Abstract. In order to enhance the level of environmental safety at potentially hazardous enterprises, plans for the localization and elimination of emergency situations and accidents (PLEA) are developed. The PLEA governs the actions of enterprise personnel, population and authorities. However, under current regulations, it does not govern the procedures for monitoring the state of environmental components that may be affected in the event of an accident. This is particularly relevant to the monitoring of a water body into which accidental discharges of chemical pollutants may occur. The aim of this study is to provide a scientific justification for the use of integral (spatially interpreted) indicators of the state of water bodies in the course of post-accident remediation activities following pollution of natural water resources. Unlike simple concentration values, these indicators characterize the state of an extended part of the water body. It is proposed that the values of the integral indicator before and after the accident be compared. The usage of integral indicators is demonstrated through an analysis of retrospective data concerning the mitigation of a major man-made accident at the wastewater treatment facilities in Kharkiv. The assessment of the effectiveness of post-accident response measures using integral indicators, unlike simple concentration-based indicators, revealed incomplete restoration of the affected section of the Siverskyi Donets River following the emergency water release from the Oskil Reservoir. A distinguishing feature of integral quality indicators, compared to simple or composite water quality indicators at individual points of a water body, is their higher informational value.

Keywords: water body, monitoring point, accident**,** integral indicators, wastewater.

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1. Introduction

In Ukraine, for potentially hazardous enterprises, plans for the localization and elimination of emergency situations and accidents (PLEA) are developed in order to enhance their level of environmental safety. The development of PLEA is regulated by Order No. 112 of the Ministry of Labor and Social Policy of Ukraine, dated June 17, 1999. (Ministerstvo Ukrayiny z pytan nadzvychaynykh sytuatsii, 1999) According to Clause 4.1, the purpose of the PLEA is to plan the actions (and coordination) of enterprise personnel, specialized units, the population, central and local executive authorities, and local self-government bodies in the localization and elimination of accidents and the mitigation of their consequences. From the standpoint of environmental safety, the most critical scenario is a Level B accident, which is characterized by its progression beyond the boundaries of the enterprise, the potential impact of the accident's damaging factors on the population of nearby residential areas and other enterprises (or facilities), as well as on the environment. However, the PLEA does not regulate the procedure for monitoring the condition of environmental components that may be affected in the event of an accident. This specifically applies to the monitoring of a water body into which an accidental discharge of chemical substances may occur. Therefore, the development of proposals for organizing monitoring of the state of water bodies in the event of an accident at potentially hazardous enterprises is a relevant and pressing task.

There are various approaches to assessing the quality of natural water. The most basic one involves comparing the concentrations of pollutants (contaminants) with the maximum allowable concentration (MAC) standards, depending on the category of water use: household (Ministerstvo okhorony zdorovia Ukrainy, 2022) or fishery purposes (Ministerstvo ahrarnoi polityky ta prodovolstva Ukrainy, 2012). In European countries, the Water Quality Index (WQI) is increasingly being used as a tool for characterizing water quality. This index is based on physical, chemical, and biological factors, which are combined into a single value ranging from 0 to 100 (Chidiac et al., 2023). In the study (Nguyen Van et al., 2022), a modification of the WQI was proposed, which involved expressing the indicator in exponential rather than linear form—meaning the weighting coefficients functioned not as multipliers of the base parameters but as exponents. However, the WQI does not convey information about the condition of an extended section of a water body. Additionally, the approach of assessing water quality based on a composite indicator that considers salinity, tropho-saprobiological, toxic, and radiological properties of water at specific points of the water body has also been found to be insufficiently informative (Mats, 2023).

The application of the WQI was also described in study (Cicerone et al., 2025). A distinguishing feature of this work was its investigation of one of the most water-rich regions in Latin America and the Caribbean.

In the study (Odnorih et al., 2020), water quality was investigated using environmental monitoring data, based on the case of the Southern Bug River. The research primarily focused on the dynamics of changes in the river's condition, the suitability of its water for use, and the identification of key pollution factors. However, the simultaneous assessment of the river's condition based on measurements from various monitoring points was not part of the study's objectives.

The paper (Arabameri et al., 2025) presents a study aimed at optimizing the long-term spatiotemporal assessment and forecasting of river water quality using intuitive Python-based modules: 1) PyOD: A toolkit for scalable outlier detection and the classification of deviations from expected water quality norms; 2) Statsmodels: A module for decomposing river time series data into trend, seasonal, and residual components; 3) AutoTS: An automated time series forecasting model for predicting the state of river water quality. The Karun River in southern Iran served as the case study. While the developed software framework enables complex statistical analysis of the raw data, the criteria for establishing control points are not specified in the paper.

Study (Biedunkova et al., 2025) investigates various approaches to assessing organic water pollution, using the Styr River (Ukraine) as a case study with data spanning from 2018 to 2022. The statistical analysis included Pearson correlation, multiple linear regression, principal component analysis (PCA), and network analysis. The results demonstrated variations in OPI levels depending on the methodology employed. Consequently, pollution classifications ranged from 'clean' to 'moderate.' Seasonal trends were observed, characterized by higher pollution levels in the summer and lower levels in the winter. Key parameters contributing to pollution were identified. However, as in study (Arabameri et al., 2025), the rationale for selecting control points was not described.

In study (Di Fluri et al., 2024), a forecasting methodology based on the Biochemical Quality Index

(BQI) was developed. This methodology holds potential as an auxiliary tool for managing monitoring efforts (for instance, in river sections where poor water quality is expected) and for developing local preventive water conservation strategies. This is particularly relevant for small watercourses where monitoring is typically limited or entirely absent. However, the proposed method does not allow for an integrated assessment of the watercourse's status.

Study (Grzywna et al., 2024) investigated changes in the water quality of the Vistula River following an accidental discharge of untreated sewage. The paper presented an analysis of the environmental impact caused by the accidental release of untreated municipal wastewater from the Warsaw sewage system. Notably, cluster analysis methods were used to examine only specific local river sections within the incident's impact zone.

Study (Hassan et al., 2023) examined the influence of seasonal fluctuations and wastewater discharge on river water quality, along with the associated human health risks. The research focused on the northwestern part of Dhaka, Bangladesh. Wastewater samples were collected from five outfalls. Surface water was assessed using the Water Quality Index (WQI), the Entropy Water Quality Index (EWQI), and the Irrigation Water Quality Index (IWQI). However, the methods described are more suitable for ecological risk assessment than for evaluating the consequences of a technological accident.

Article (Mudrak et al., 2022) presents an assessment of the ecological status of small rivers in Eastern Podillia (Ukraine). The study addressed the issue of water availability in small rivers, as well as river water pollution based on specific chemical and biochemical parameters. However, studies of this nature are aimed at planning long-term environmental protection measures, rather than developing operational response plans for mitigating the consequences of technological accidents.

It appears reasonable to apply the concept of strategic environmental assessment – previously proposed in relation to subsoil use in the study (Karabyn et al., 2022) – to the evaluation of surface water conditions. In particular, the development of proposals for the use of integral (in the spatial sense) water quality indicators is highly relevant. Unlike simple concentration measurements, these indicators characterize the condition of an extended section of a water body.

The aim of this study is to provide a scientific justification for the use of integral (spatially interpreted) indicators of the state of water bodies in the course of post-accident remediation activities following pollution of natural water resources.

2. Materials and Methods

Methodological principles for assessing the state of water bodies based on observations at various monitoring points were developed in Ukraine during the 1980s. One example of such an integral indicator in this context is the water pollution index (Proskurnin et al., 2022):

$$I = \frac{1}{K \cdot N} \sum_{i}^{N} \left(\sum_{k}^{K} \frac{1}{V_{kj}} \sum_{v}^{V_{kj}} u_{kjv} \right), \tag{1}$$

where $$u_{kjv} = \begin{cases} C_{kjv} / MAC_j, & C_{kjv} > MAC_j, \\ 1, & C_{kjv} \le MAC_j, \end{cases} \tag{2}$$

where N is the number of pollutants present in the water; j, k, and v are indices corresponding to the pollutant, monitoring point, and measurement, respectively; K is the number of monitoring points; $V_{j,k}$ is the number of measurements of the j-*th* parameter at the k-*th* monitoring point; and $C_{k,j,v}$ is the concentration of the substance in the water.

Later, an indicator of the state of the water body that takes into account the distances between monitoring points was introduced (Vasenko et al., 2015):

$$I = \frac{1}{L} \sum_{k=1}^{K-1} p_k \cdot l_k , \tag{3}$$

where p_k is the water quality assessment (either composite or simplified) at the k-*th* monitoring point; l_k is the length of the river section between the k-*th* and (k +1) monitoring points; and L is the total length of the river section under consideration.

As can be easily observed, formula (3) represents a value of the integral calculated using the rectangle method (Lytvynov, 2022):

$$I = \int_L p(l)\,dl . \tag{4}$$

Despite the informational value of integral indicators, their practical application remains minimal. They are not used to assess the quality of natural water in such important applied tasks as regulating the discharge of pollutants with wastewater or evaluating the environmental impact of enterprises. Nor are they employed in the planning of post-accident remediation measures. Furthermore, there are no established standards for the acceptable values of integral indicators. As a result, their use is currently limited to theoretical research.

It appears reasonable, in planning post-accident remediation measures, to use integral indicators calculated according to formula (3), i.e., with consideration of the distances between monitoring points. As a measure of water quality at an individual point, it is possible to use the sum of pollutant concentrations normalized to their maximum allowable concentrations (MACs):

$$p = \sum_{j=1}^{N} \frac{C_j}{MAC_j} . \quad (5)$$

Since the current water protection legislation does not include established standards for the values of integral indicators, the following approach is proposed. In the event of an accident that leads to pollution of a water body, the measured (or forecasted, in the case of implementing remediation measures) value of the integral indicator should be compared with the integral indicators calculated from retrospective data prior to the accident. Given that the focus is on potentially hazardous enterprises, such measurements should be carried out regularly as part of environmental auditing (Odnorih et al., 2024). This would allow the integral indicator value I to be treated as a random variable, and to define the bounds of a confidence interval $[I^-, I^+]$ with a specified level of confidence. For instance, a 95 % confidence level may be used.

Since the integral indicator I is inversely related to water quality (i.e., the worse the water quality, the higher the value of I), the criterion for acceptable water quality based on the integral indicator should be formulated as the condition:

$$I_a \le I^+ , \quad (6)$$

where I_a is the value of the integral indicator (measured or forecasted) after the accident.

3. Results and Discussion

The demonstrative example is based on an analysis of retrospective data related to the remediation of the accident at the Dykanivka wastewater treatment facilities in Kharkiv, Ukraine, which occurred on June 29, 1995. As a result of heavy rainfall lasting approximately three hours, around 90 mm of precipitation fell, which incapacitated the treatment facilities and led to the discharge of a large volume of untreated municipal and industrial wastewater into the Siverskyi Donets River. The pollution of the river was primarily associated with elevated levels of biogenic substances. The area affected by the accident included, in particular, an industrial section of Donetsk Oblast downstream from the confluence with the Oskil River. As part of the post-accident remediation measures, water was released from the Oskil Reservoir (known at the time as the Chervonooskil Reservoir) via the Oskil River. The effectiveness of these measures was assessed by comparing pollutant concentrations in the Siverskyi Donets River downstream of the Oskil confluence with their maximum allowable concentrations (MACs). However, since this section of the Siverskyi Donets River is subject to anthropogenic pressure not only from the accident site but also from the wastewater discharges of industrial and municipal enterprises, it is more appropriate to evaluate the effectiveness of remediation measures using an integral indicator. In this case, monitoring points should be established at distances of 500 meters downstream from the wastewater discharge points. This distance is determined by methodological regulations in force in Ukraine, both at the time of the accident and currently, for the placement of monitoring points when calculating discharge limits for substances in wastewater. A hydrological diagram of the relevant industrial section is presented in Fig. 1.

Regular monitoring of the water quality of the Siverskyi Donets River in the section under consideration was carried out only downstream of the Oskil confluence (i.e., at Monitoring Point 0). Therefore, when calculating the integral indicator, the concentrations of substances at other monitoring points can be approximately estimated using a recursive formula:

$$C_k = \frac{C_{k-1} \cdot Q_{k-1} + S_k \cdot q_k}{Q_{k-1} + \cdot q_k} , \quad (7)$$

where k is the index of the monitoring point (MP); C is the concentration of the pollutant at the MP; Q is the flow rate of river water at the MP; q_k, and S_k are, respectively, the flow rate of wastewater and the concentration of the pollutant in the wastewater discharge upstream of the k-th MP.

The data on the concentrations of biogenic substances in the area of the Oskil River confluence prior to the accident are presented in Table 1.

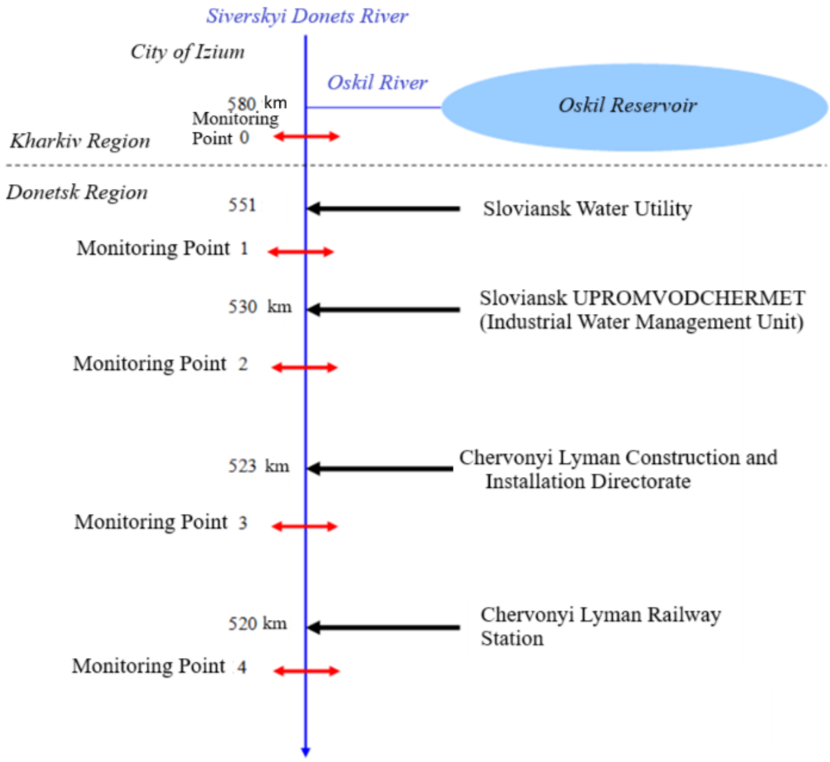

Fig. 1. Diagram of the industrial section of Donetsk Region located within the accident-affected zone (the indicated distances are measured from the river mouth)

Table 1

Results of Water Quality Measurements of the Siverskyi Donets River by Biogenic Indicators in the Area of the Oskil Confluence Prior to the Accident

Substance	Measurement number									
	1	2	3	4	5	6	7	8	9	10
Ammonium nitrogen	0.5	0.56	0.54	0.62	0.54	0.5	0.68	0.7	0.62	0.58
Nitrites	0.23	0.19	0.25	0.22	0.26	0.26	0.23	0.2	0.27	0.26
Nitrates	7.03	8.25	5.57	7.71	7.83	5.89	7.08	5.95	6.68	7.59
Phosphates	2.96	2.61	2.7	2.52	2.39	2.3	2.16	2.35	2.12	2.88
Petroleum products	0.05	0.05	0.06	0.04	0.05	0.04	0.05	0.05	0.05	0.06
Biochemical Oxygen Demand$_5$	3.2	4.19	3.46	3.46	4.36	3.71	3.53	3.19	3.26	3.6
Dissolved oxygen	9.44	7.85	7.05	7.54	9.05	8.38	7.87	10.04	8.69	9.28

Table 2

Quantitative and Qualitative Characteristics of Anthropogenic Pollution Sources of the Siverskyi Donets River Downstream of the Oskil Confluence

Indicator	Output			
	Sloviansk Water Utility	Sloviansk UPROMVODCHERMET (Industrial Water Management Unit)	Chervonyi Lyman Construction and Installation Directorate	Railway Station of Chervonyi Lyman
1	2	3	4	5
Discharge, m^3/c	0.0188	0.0968	0.0003	0.0524
Concentration, mg/dm^3				

Continuation of Table 2

1	2	3	4	5
Ammonium nitrogen	0.1	0.4	1.2	3
Nitrites	0.06	0.1	0.14	0.1
Nitrates	4.9	14.3	0.1	4.8
Phosphates	2.8	3.5	3.4	3.1
Petroleum products	0.07	0.28	0.09	0.02
Biochemical Oxygen Demand$_5$	3.5	8.5	0.1	4.9
Dissolved oxygen	4.1	4.5	4.3	5.1

Data on the volume and composition of wastewater are presented in Table 2.

Using the data from Tables 1 and 2, the sample of integral indicator values for the pre-accident period was calculated using formula (7) (Table 3).

Table 3

Calculated Values of the Integral Indicator for the Section of the Siverskyi Donets River in the Pre-Accident Period

Water quality measurement number of the Siverskyi Donets River in the Oskol River area	Integral water quality indicator
1	2
1	7.42
2	7.29
3	8.05
4	7.44
5	8.01

Continuation of Table 3

1	2
6	7.52
7	7.78
8	7.30
9	8.00
10	8.28
Average value I_{av}	7.71
Standard deviation ʃ	0.34

Assuming a normal probability distribution of the value *I*, the following confidence interval is obtained:

$$\left[I^-, I^+\right] = \left[I_{av} - z_{95\%} \cdot \sigma; I_{av} + z_{95\%} \cdot \sigma\right] = \\ = \left[7{,}06; 8{,}37\right], \quad (8)$$

where $z_{95\ \%}$ is the quantile of the standard normal distribution ($z_{95\ \%}$ H 1.96).

Fig. 2 shows the density distribution graph of the variable *I*.

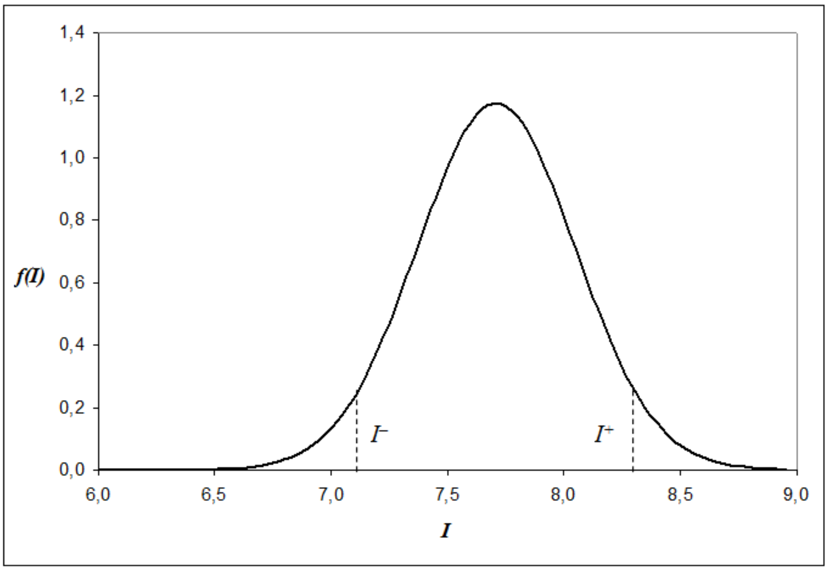

Fig. 2. Density distribution of the integral indicator during the pre-accident period

The discharge of untreated wastewater into the Siverskyi Donets River as a result of the accident at the Dykanivka wastewater treatment facilities led to significant pollution of the river. As part of the post-accident remediation measures, a controlled water release from the Oskil Reservoir was carried out at a rate of 50 m³/s. Table 4 presents data on river water pollution after the accident (before and after the reservoir release), as well as the concentrations of substances downstream of the Oskil River confluence during the release.

As shown in Table 4, the water release significantly improved river water quality across all indicators except for nitrites. However, it is not possible to conclude from the data in Table 4 whether the environmental situation stabilized along the entire section of the river under consideration. The effectiveness of the post-accident remediation measures was analyzed using the integral indicator. The result of the integral indicator value calculation based on data from Tables 2 and 4 is as follows: I_a = 8.52, which exceeds the upper bound of the confidence interval I^+ = 8.37. Thus, the release of 50 m³/s of water from the Oskil Reservoir did not lead to the stabilization of the environmental situation in the accident-affected zone.

A distinguishing feature of integral (spatially interpreted) quality indicators, compared to simple or composite water quality indicators at individual points of a water body, is their higher informational value. Specifically, integral indicators characterize the condition of an extended section of the water body. The presented example of assessing the effectiveness of remediation measures during the accident at the Dykanivka wastewater treatment facilities illustrates the advantage of the proposed approach for evaluating the condition of the affected part of the water body.

A limitation of the proposed method is the insufficiency of chemical water quality indicators when a protected section of a water body is affected by an accident. In such cases, the condition of the ecosystem must also be assessed using biological indicators.

Table 4

Water quality in the Siverskyi Donets River downstream of the Oskil confluence after the accident

Substance	Before the reservoir water release (50 m³/s)		After the reservoir water release (50 m³/s)	
	Concentration	Concentration normalized to MAC	Concentration	Concentration normalized to MAC
Ammonium nitrogen	1.2	3.08	0.93	2.38
Nitrites	0.15	1.88	0.18	2.20
Nitrates	47	1.18	24.45	0.61
Phosphates	5.4	1.73	3.03	0.97
Petroleum products	0.07	1.40	0.05	1.08
Biochemical Oxygen Demand$_5$	4.8	1.06	3.01	0.67
Dissolved oxygen	4.1	0.98	6.56	0.61

A drawback of the approach at its current stage of development is the uncertainty in determining the locations of monitoring points in the absence of clearly identifiable point sources of pollution.

4. Conclusions

To assess the effectiveness of remediation measures following an accident that resulted in the pollution of a water body, it is advisable to use the integral indicator. Unlike concentration values of pollutants or composite indicators at individual points, the integral indicator characterizes the condition of an entire section of the water body.

The practical significance of the obtained results concerning the justification for using integral water quality indicators in planning post-accident remediation measures lies in the absence of regulations governing the monitoring of environmental components that may be affected in the event of an accident.

A subject for further development of this research is developing recommendations for the placement of monitoring points in the presence of densely located pollution sources and significant diffuse sources.

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