CHAPTER 4

Information technologies in scenario-based modeling of post-conflict territory remediation: from express sanitation to sustainable recovery

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Abstract

The study presents a comprehensive analysis of the application of information technologies in scenario modeling of remediation of post-conflict territories, within the sample of three regions of Ukraine, affected to different degrees and scales by military activity (Kherson, Zaporizhzhia, Kharkiv regions), as a practical case. A hybrid integrated model has been developed by the author and proposed for implementation, combining geographic information systems (GIS), machine learning (ML), optimization algorithms, and other tools of modular deployment of digital infrastructure. The developed remediation model is based on the principle of complementarity, combining traditional and green methods depending on the scenario. Such flexibility ensures the adoption of the most well-founded managerial decisions and accelerates the transition to sustainable recovery. In the study, gradient boosting algorithms and Online ML were used for the purpose of providing predictive modeling and dynamic response in real-time mode. A comparative analysis of remediation scenarios was carried out using digital modeling, KPIs, and predictive algorithms. The results of the modeling confirm the high relevance and practical significance of the triad ML + GIS + IoT, and also demonstrate the viability of the modular remediation system. The author proposed using matrices of validity of digital components and heat maps, which will allow the justified selection of digital solutions; forecasting the risks of their implementation, as well as forming strategies for their phased implementation.

Keywords

Digital management, traditional remediation (TR), green remediation (GR), complementarity, invasion, scenario modeling, geographic information systems (GIS), machine learning (ML), multi-criteria analysis (MCDA), optimization algorithms, express sanitation, sustainable recovery.

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4.1 Introduction

As one can be convinced based on the events of recent years, armed conflicts cause large-scale damage to the environment, creating acute and long-term ecological problems on territories affected by military activity. Thus, for example, the result of military-type activity of the aggressor in Ukraine was damage (in some cases irreparable) estimated at more than 56.4 billion USD, characterized by large-scale pollution of air, water, and soil [1]. About 30% of the territory of Ukraine is littered with unexploded ordnance and mines, and approximately 160 thousand km² of land were subjected to intensive bombardments, in turn forming zones of ecological pollution from destroyed industrial facilities and infrastructure. Tens of thousands of hectares of land require the elimination of contaminants polluting it and remediation of millions of tons of soil. The consequences for ecosystems are acquiring a catastrophic character: soil degradation, pollution of water resources, loss of biodiversity – represent a threat to the health of the population and largely complicate the return of displaced residents to their native lands and the subsequent restoration of economic activity. Thus, sustainable recovery of post-conflict territories becomes an urgent task, on the solution of which depends, above all, national ecological security, as well as the complete revitalization of the regions [2].

The full-scale war in Ukraine caused unprecedented environmental destruction, leading to the contamination of territories requiring both emergency sanitation and long-term remediation. Traditional approaches (such as excavation of soils, thermal treatment, chemical restoration, etc.) often disrupt the ecosystem and can result in negative consequences for it. This determines the need for in-depth comprehensive study of all possible options for the use of available and expedient methods of remediation of soil, water, and air, as well as the creation of digital scenario models capable of adapting and ensuring the transition from express response to long-term sustainable recovery.

This study responds to the modern challenge regarding the necessity of digitalization of environmental recovery programs in zones of armed conflicts.

The aim of the study is the development of a digital scenario model of remediation of post-conflict territories using modern information technologies, ensuring the transition from express sanitation to sustainable recovery.

In accordance with the aim, the following research tasks were identified: in-depth analysis of the theoretical and methodological foundations of remediation of contaminated territories; identification of the features of various remediation scenarios based on the analysis of various types of contamination and based on the prioritization of goals; design of an integrated digital model based on GIS, IoT, ML, and optimization algorithms; evaluation of digital tools using multi-criteria validity matrices and heat maps; development of strategic recommendations for modular deployment of digital infrastructure and replication of the model.

4.2 Theoretical and methodological basis of the research

First of all, it is necessary to outline the contours of the concept "green remediation" (*Green Remediation*, *GR*), by which the author means the use of a set of environmentally sustainable approaches to the cleanup of contaminated territories (soil, water, and air), which minimize the impact on the environment and at the same time contribute to the restoration of natural resources.

The term Green Remediation was first proposed and developed by the Environmental Protection Agency (EPA) in the USA as part of efforts to integrate environmental principles into the processes of cleanup of contaminated lands [3].

Next, the results of an in-depth analysis of the differences of GR from traditional remediation (*Traditional Remediation*, *TR*) will be presented and its key aspects verified. So, a panoramic review of the scientific literature on the specified problem made it possible to identify traditional remediation as a set of technologies and methods aimed at the cleanup of the contaminated environment (soil, water, air) using physical, chemical, and engineering processes.

The basic methods of traditional remediation of military contamination can include the following:

– physical methods, such as excavation of contaminated soil, filtration, sedimentation and flotation of water, as well as the use of barriers to prevent the spread of contamination;

– chemical methods, which include the application of chemical reagents for neutralization or adsorption of pollutants;

– biological methods, such as the use of bacteria, microorganisms, and plants for the decomposition or absorption of contaminants (for example, bioremediation and phytoremediation);

– thermal methods, based on the incineration or heating of contaminated soil or water for the destruction of toxic substances.

As is emphasized in the majority of studies on this topic, the unconditional advantages of the tools and methods of TR are:

– effectiveness and speed of impact, since with the help of traditional remediation tools, as a rule, the set goals are achieved faster, which makes them especially useful in situations requiring immediate intervention;

– predictability of results, which is justified by the better degree of study, and therefore predictability of consequences, and this facilitates the planning and management of remediation projects;

– versatility, which allows the use of TR methods for a wide range of military contamination on one territory, including heavy metals, organic and inorganic substances;

– wide availability of technologies, which is tested and proven in specific conditions, which simplifies the process of implementation of remediation.

However, as was identified by the author, the list of disadvantages of the tools of Traditional Remediation is more extensive than the above highlighted advantages, and this at the very least requires a thoughtful approach to their selection and application. The conclusion reached by the author of the monograph is that traditional methods of remediation, despite their effectiveness in the short term, can carry significant risks in the long term. These risks cover not only environmental consequences, but also affect genetic, social, economic, and medical aspects, which emphasizes the necessity of thorough analysis and planning before their application. It is about the so-called "*ecological footprint*", which means the totality of the negative impact of these methods on the environment in the process of elimination of military contamination.

Taking into account the scale and complexity of remediation activities carried out within the framework of the implementation of the remediation strategy of Ukraine, it is especially necessary to consider its *invasiveness*, by which the author of the scientific work means the type of anthropogenic intervention which, despite its focus on the restoration or improvement of the state of the ecosystem, can lead to deep and long-term negative changes, often of an irreversible nature.

Among the key disadvantages it is necessary to highlight:

– the high risk of irreversibility of changes in the ecosystem, which consists in the disruption first of the structure of the system, and then of the eco-balance, the process of restoration of which may take decades or even centuries, if this is possible at all [4, 5];

– high risks from the use of several TR methods simultaneously on one territory. For example, simultaneous chemical treatment and thermal neutralization of soil or water can lead to unpredictable chemical reactions, creation of secondary pollutants, and additional environmental threats [6, 7];

– risk of secondary contamination, which consists in that the application of chemicals can lead to the formation of by-product pollutants, and this, in turn, leads to the necessity of further treatment of secondary waste and an increase in remediation costs [8, 9];

– high cost and high energy consumption, since the use of specialized equipment with material costs in the process of its application can make traditional remediation very expensive, especially on large territories.

In scientific publications of recent times, as the author of the study has identified, publications still prevail that are focused on the application of sustainable and environmentally clean methods of remediation, such as "green remediation", which includes the use of natural processes for the cleanup of contaminated territories. For example, in a comprehensive study on the application of remediation of contaminated lands, the authors emphasize that the choice of technology is no longer based exclusively on the elimination of the source of contamination, but is aimed at the restoration of soil quality. Thus, "green remediation" can be the key to solving the problem of restoring contaminated sites, since it focuses on the quality of the environment, including the preservation of the biocenosis. Further developments in the field of green remediation reflect the goal of promoting cleanup strategies that also take into account the consequences of climate change [10].

In addition to the above-mentioned method, among the most popular methods of "green remediation" are: phytoremediation, bioremediation, the use of microalgae, biofiltration, air biofiltration, and others. Specifically, on each of the listed methods of GR a large number of publications has been published, which allowed the author to identify the main advantages of these methods in comparison with traditional methods of cleanup of contaminated territories. Here are the main ones:

– environmental friendliness, since in such natural processes as plant growth and microorganism activity the impact on the environment is minimal;

– economic efficiency, which is expressed in that plants and microorganisms can perform the cleanup work over a long period of time with minimal maintenance costs;

– improvement of the state of the ecosystem, since plants and microorganisms not only clean the soil or water, but also improve its structure, contribute to the preservation of biodiversity, and prevent erosion;

– generation of additional multifunctional ecosystem effects: plants and microorganisms used for the purposes of GR can realize, along with the main function, additional ones, such as compensation of the carbon footprint, enrichment of the lands with humus, destruction of complex forms of decomposable military activity waste, which brings additional benefit to the ecosystem and society as a whole [11].

The parametric comparative analysis of traditional remediation approaches and methods of "green remediation" is presented in **Table 4.1**.

According to the author's conviction, traditional remediation (TR) can be characterized as an "invasion" (from Latin *invasio*) due to its aggressive impact on ecosystems, including destruction of soil structure, change of hydrology, creation of secondary pollutants, destruction of the biocenosis. In contrast to this, green remediation (GR) acts as a "regenerative" approach, minimizing the ecological footprint and contributing to the restoration of ecosystems.

Table 4.1 Parametric assessment of methods of traditional and green remediation of soil, water, and air

Parameter	Traditional remediation	Green remediation
	Soil remediation	
Technologies	Excavation, thermal neutralization, chemical treatment	Phytoremediation (use of plants), bioremediation (microorganisms)
Environmental impact	High (disruption of the ecosystem, greenhouse gas emissions)	Low (minimal intervention in the ecosystem)
Cost	Usually high due to costs of equipment and materials	Usually lower, but depends on duration and methods
Execution time	Fast, but temporary solutions often require subsequent measures	Long-term (from months to several years), requires monitoring
Energy consumption	High due to the use of heavy machinery and equipment	Low, based on natural processes
	Water remediation	
Technologies	Chemical precipitation, filtration, sorption	Biofiltration, bioremediation (use of microbes and plants)
Environmental impact	Medium (may include the use of chemical reagents)	Low (use of natural cleaning methods)
Cost	High due to the application of complex technologies and chemicals	Usually lower, except in cases of long-term monitoring
Execution time	Fast, but requires constant control and replacement of filters	Depends on natural processes, may take more time
Energy consumption	High, requires energy for operation of equipment	Low, natural processes work on solar and biomass energy
	Air remediation	
Technologies	Adsorption, thermal oxidation, chemical restoration	Biofiltration, use of vegetation for absorption of pollutants
Environmental impact	Medium, may include emissions from cleaning installations	Low, based on natural processes
Cost	High, requires complex technologies and constant maintenance	May be lower, especially when using vegetation
Execution time	Fast, but requires regular maintenance	Long-term processes, but more sustainable
Energy consumption	High, equipment requires constant operation	Low, based on natural processes

In the conditions of a post-conflict landscape, especially in the presence of: threats to the life and health of the population (explosive ordnance, chemical contamination); critically damaged infrastructure (water supply systems, sewerage, transport); acute necessity for sanitary isolation (for example, in case of flooding or spread of pathogens); the application of traditional methods of remediation (TR) may be not only justified, but also inevitable. However, such methods are accompanied by a significant ecological footprint, as was already mentioned above.

Invasiveness, in the author's view, is always associated with an increase of the ecological footprint, but in the scenario management model this is perceived as a controlled risk, compensated by: rapid localization of the threat; reduction of secondary risks (for example, delayed migration of pollutants); the possibility of the fastest transition to restorative, GR-oriented measures.

Thus, it appears fully logical and expedient to substantiate the concept of the I-S-R cycle (invasion–stabilization–restoration) as a phase model of digital management of remediation, where each stage corresponds to certain strategic tasks, the choice of which is based on scenario analysis of threats and opportunities.

This cycle allows the formation of an adaptive logic of management, in which both traditional (TR) and green (GR) methods of remediation are used in a complementary model. The ambivalence and complementarity of TR and GR are conditioned by:

– the difference of goals by phases of the I-S-R cycle: TR – elimination of critical threats (invasion), GR – creation of conditions for sustainable recovery (regeneration);

– the difference of methods and approaches: TR is aggressive and radical, GR is gentle and nature-oriented;

– the difference of consequences: TR can worsen the state of the ecosystem in the long-term perspective, GR – restore and improve.

At the same time, the complementary combination of TR and GR in an integrated model allows the implementation of optimal scenarios, where TR ensures rapid elimination of acute risks, and GR ensures long-term sustainability and ecological safety.

In the context of this study, the focus of the author's attention was concentrated on the in-depth study of the book "Natural resources and post-conflict assessment, remediation, restoration, and reconstruction: Lessons and emerging issues" [12]. The authors of the study emphasized the assessment of remediation of post-conflict territory, which demonstrates obtaining tangible benefits, in particular, the restoration of resource stability, including the improvement of the population's standard of living, state revenues, creation of new jobs, as well as the expansion of opportunities for business development.

The author's position consists in that the multiplicative effect of remediation of territory lies in the comprehensive impact of recovery activities aimed at improving the ecological balance, which as a result allows launching a cascade of chain reactions and positive changes affecting various aspects of socio-economic, ecological, and even political life of the region (both domestic political and foreign political).

This happens due to the fact that the improvement of the ecological condition of the territory makes it more attractive for the life of the population, development of economic activity, infrastructure, tourism, and inflow of investments. Thus, a healthy ecosystem ultimately stimulates the revitalization of territories affected by military activity. This leads to the creation of new jobs, an increase of tax revenues, growth of budget income at all levels, and as a result, an increase of national competitiveness.

Visually, the multiplication effect can be presented in the form of circles on water: one change (in our case, this is remediation of the ecosystem) creates waves spreading far beyond the epicenter of impact. Similar to circles on water, the multiplicative effect of remediation spreads to various spheres (social, economic), creating cascading positive changes that gradually cover ever wider areas, improving the condition and well-being of the entire territory as a whole. For example, the scientists K. Williams and J. Hoffman in their study describe a similar effect in the form of feedback chains [13].

Thus, various approaches to remediation can generate a cascading reaction of positive changes in each of the spheres (ecological, social, economic) and influence the sustainable development of the territory, namely:

– green methods of remediation produce a more pronounced multiplicative effect, especially in the long-term perspective, impacting all three spheres of influence in the mode of permanent transformation;

– traditional methods are recommended and effective for rapid elimination of problems – "*express sanitation*" but their influence on the long-term multiplicative effect is limited, especially in the social and economic spheres.

In the view of the author of this scientific work, the main goal of "*express sanitation*" is the rapid elimination of environmental risks and prevention of their scaling. This makes it possible in a short time to stabilize the situation and prevent further damage, which is critical in conditions affected by military activity or technogenic disasters. "Express sanitation" using radical tools of traditional remediation is recommended in situations where immediate intervention is required; however, it does not provide for a strategic goal in the form of deep restoration of ecosystems or permanent transformation of the socio-economic situation. In the long-term perspective, such territories often need additional remediation using green methods for the purpose of sustainable recovery.

In the author's conviction, a complementary combination of traditional methods (TR) and green methods of remediation (GR) can become an effective strategy for achieving both short-term and long-term recovery goals of Ukraine after the end of active military actions. The possibility of applying a combined approach will allow the rapid elimination of the most critical threats, and then ensure the sustainable recovery of ecosystems and the territory as a whole. The unconditional advantage will be that such an approach, in addition, strengthens the multiplicative effect: express sanitation allows the elimination of the most significant and negatively influencing contamination, protecting the population and creating conditions for economic activity, and at the subsequent stage green remediation generates long-term benefits, contributing to the creation of sustainable economic opportunities, such as, for example, ecotourism or agriculture [14] (**Fig. 4.1**).

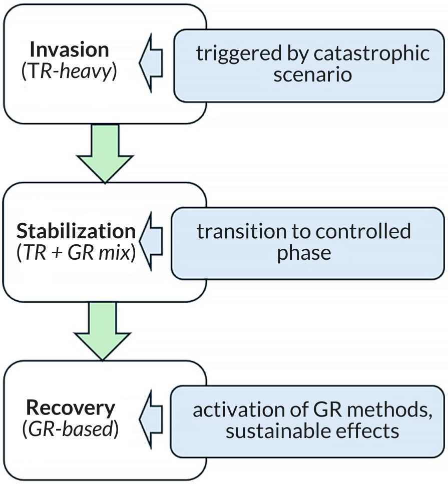

Fig. 4.1 Analytical scheme of the Invasion-Stabilization-Recovery (I-S-R) cycle

The multiplication effect is repeatedly described by the author of this study in a number of scientific works [15, 16]. The multiplicative effect arising as a result of the implementation of remediation activities with the involvement of TR and GR methods in the context of the issues of this study represents a reflexive (impulse) dynamics of positive cascading changes covering the ecological, economic, and social spheres of life of post-conflict territories, which in the long term leads to their complete revitalization. The hypothesis of the author of this scientific work consists in that the developed and then implemented digital model of remediation will possess the same property. Namely: the ability of the digital integrated model to generate a chain reaction of positive changes into a single end-to-end digital amplification through the transformation of local results into a systemic sustainable effect, creating a basis for sustainable socio-economic post-war development of the territory.

The benchmarks described below demonstrate the successful application of combinations of TR and GR, emphasizing their complementarity in achieving short-term (express sanitation) and long-term (sustainable recovery) goals:

1. *Kosovo.* Thus, after the military conflict in Kosovo, combinations of soil excavation (extraction) and subsequent biorecultivation were applied for the cleanup of contaminated sites, which as a result made it possible to restore land for agricultural use [17, 18].

2. *Vietnam.* Phytoremediation was used after chemical treatment for the cleanup of land contaminated with dioxin from "Agent Orange". As is known, this is a herbicide that was used by the US army during the Vietnam War to destroy foliage and forests. It contained dioxin, which is poisonous and has a long-term negative impact on human health and the environment [19].

3. *Kuwait.* After the end of the Gulf War, projects for the remediation of oil-contaminated soils in Kuwait included traditional methods, such as skimmers for oil removal, and biorecultivation using compost and microorganisms, which contributed to the restoration of desert ecosystems and the reduction of hydrocarbon content [20, 21].

4. *Nigeria.* After oil spills in the Niger Delta, combinations of contaminated soil excavation and bioremediation using microorganisms were applied for the cleanup of oil-contaminated soils, which made it possible to partially restore land for agricultural use and improve the ecological condition of the region [22, 23].

Unlike Kosovo and Vietnam, the contamination in Nigeria and Kuwait is mainly associated with oil production, and not with military actions, however, with certain reservations, they can also be considered benchmarks. It should be noted that their environmental consequences (oil spills, soil and water contamination) are similar to those observed in post-conflict zones such as Ukraine, where military actions caused oil contamination and other environmental problems.

The integrated remediation model combining TR and GR makes it possible to achieve a balance between efficiency (cleanup speed, percentage of pollutant removal) and rationality (minimization of costs and ecological footprint). Successful benchmarks, such as combined remediation in Kosovo (extraction + bioremediation), in Kuwait (skimmers + bioremediation) and in Vietnam (chemical treatment + phytoremediation), demonstrate the possibility of integration [24]. Computer modeling, including GIS and ML, can optimize the choice of methods by predicting their impact on ecosystems and socio-economic indicators [25].

Thus, the integrated remediation model precisely due to the properties of optimal complementarity, synergistic and multiplicative effect of TR and GR methods, as well as the variable possibility of choice, represents a powerful tool for solving complex environmental problems, especially in post-conflict zones such as Ukraine. By combining the rapid action of traditional methods with the sustainability of green methods, it will be able to ensure the environmental safety of territories in the short term and their subsequent recovery for long-term use.

4.3 Development of an integrated remediation model (TR and GR) using computer modeling for the purposes of sustainable recovery of post-conflict territories

This section reveals the structure and logic of building the integrated model and is the next logical step in the study, focusing attention on its functional elements and synergistic effect. The development of the integrated remediation model using computer modeling is aimed at the formation of a scientifically substantiated approach to the sustainable recovery of post-conflict territories. Such an approach, as was described earlier, makes it possible to optimally combine traditional and green remediation technologies (TR and GR) into a single complementary system taking into account the complex spatial-temporal dynamics of contamination. At the basis of the model lies the formalization of key components and the use of digital technologies (ML, IoT, GIS), which ensures adaptability and optimization of managerial decisions in conditions of high uncertainty (**Table 4.2**).

Thus, the developed integrated complementary model takes into account the synergy of traditional and green remediation methods with optimal use of digital components. Each component of the model is reasonably substantiated and plays its necessary role in achieving the goals of the study:

– input parameters provide a comprehensive description of contaminants of the contaminated territory and specific conditions;

– remediation methods support the combined unity of TR and GR methods;

– the objective function optimizes the balance between criteria;

– the ML model predicts effectiveness taking uncertainty into account;

– monitoring allows adaptation to dynamic conditions of the external and internal environment.

It is necessary to emphasize the strengths of the developed formalization, namely:

1. Complexity – the model takes into account all key aspects (ecological, technical, social), which makes it relevant for different phases of the I-S-R cycle.

2. Multicriteriality – the use of the objective function allows adapting priorities to different scenarios (express sanitation, sustainable recovery).

3. Hybridization of TR and GR – the architecture of complementarity of methods is embedded, which ensures compliance with the phases of the I-S-R cycle: TR $\to$ invasion; TR + GR $\to$ stabilization; GR $\to$ recovery.

4. Online adaptation – real-time monitoring, which allows correcting the model depending on the dynamics of contamination and the course of implementation of remediation activities.

Table 4.2 Formalization of the integrated remediation model

Components	Model formalization
Input parameters	$Z = \{z_1, z_2, ..., z_n\}, z_i = (t_i, c_i(t), A_i, L_i, r_i, \tau_i, e_i, s_i)$, $t_i \in T$ – type of contamination (including unexploded ordnance, heavy metals, petroleum products, radionuclides and others); $c_i(t) \in R^+$ – concentration taking into account temporal dynamics; $A_i \in R^+$ – remediation area; $L_i \in R^2$ – contamination coordinates; $r_i \in [0,1]$ – risk range; $\tau_i \in R^+$ – time period since contamination; e_i – ecological characteristics of resources (soil type, pH, hydrology and others); s_i – socio-economic characteristics (proximity to population, land value and others)
Remediation methods	$M = M_{TR} \cup M_{GR}$. For each remediation method $m_j \in M$: effectiveness $E_{ij} = f(t_i, c_i(t), \tau_i, e_i, m_j, S_i)$; cost C_{ij}, including expenses of method m_j; ecological footprint LCA_{ij}; application time of method $m_j T_{ij}$; risk of secondary contamination r_{ij}^{sec}
Objective function	$\max_{S_i \subset M} \lambda_1(\phi) \cdot \frac{Eff(S_i)}{E_{\max}} + \lambda_2(\phi) \cdot \left(1 - \frac{\sum_{j \in S_i} LCA_{ij} + r_{ij}^{sec}}{LCA_{\max}}\right) + $ $+ \lambda_3(\phi) \cdot \frac{M_{eff}(S_i)}{M_{\max}} - \lambda_4(\phi) \cdot \frac{C_{ost}(S_i)}{C_{\max}}$. Constraints: $\sum_{j \in S_i} C_{ij} \le B_i, \sum_{j \in S_i} T_{ij} \le T_{\max}, E_{ff}(S_i) = g\left(\sum_{j \in S_i} E_{ij} w_j, S_i\right)$ – nonlinear function that allows accounting for synergy of TR and GR methods; $M_{eff}(S_i)$ – obtained multiplicative effect; $\lambda_i(\phi)$ – weights determined using ML
ML model	$X = \{(t_i, c_i(t), \tau_i, A_i, r_i, v_i, e_i, s_i, S_i)\}, y = E_{ij}^{fact}, \hat{E}_{ij} = Gradient\ Boosting\ (X; \theta)$, sources of data – IoT, GIS, satellite images, data of similar territory recovery projects; accounting for uncertainty – Bayesian methods or ensembles. Gradient boosting is chosen for its ability to handle complex nonlinear dependencies and heterogeneous data, which corresponds to the tasks of ecological modeling
Monitoring and adaptation	Observed contamination $\theta_{i,t} = (c_{i,t}, r_{i,t}, M_{eff,t})$, Forecast error $\in_{i,t} = \lvert \hat{\theta}_{i,t} - \theta_{i,t} \rvert$. ML Model$_{t+1}$ = Online Gradient Boosting (ML Model$_t$, $\in_{i,t}$, Data$_{IoT, GIS}$) – online learning is suitable for real time, model updating using new IoT and GIS data, which as a result ensures adaptability

4.4 Simulation scenario modeling

Simulation scenario modeling of contaminated territories makes it possible to predict the dynamics of contamination, assess the forecasted effectiveness of the methods of remediation planned for application, and optimize resources for the ecological recovery of the territory. In the context of the current situation in the regions of Ukraine, reflected in **Fig. 4.2**, the predominant part of the country's regions is contaminated with unexploded mines, explosives, petroleum products, heavy metals, and other toxins. In this situation, modeling becomes a critically important and significant tool for crisis management, elimination of environmental risks, and negative consequences associated with ongoing military activity.

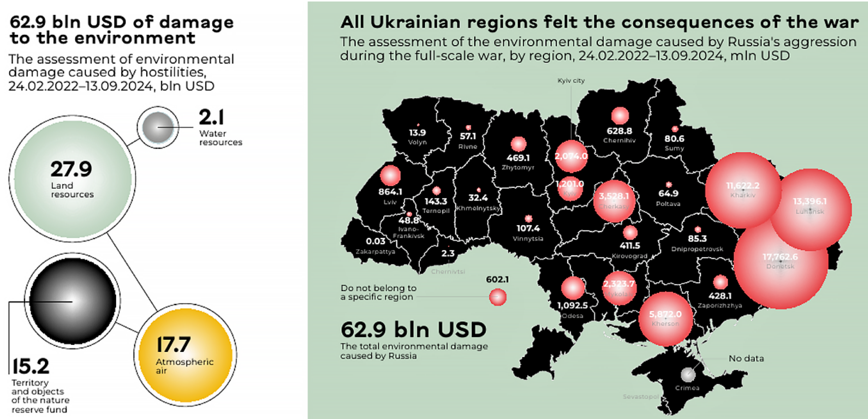

Fig. 4.2 General and regional assessment of the consequences of the war from 24.02.2022 to 13.09.2024
Source: [26]

For conducting simulation modeling the author selected three regions of Ukraine: Kherson region (eco-catastrophe due to the blowing up of the Kakhovka HPP), Zaporizhzhia region, city of Enerhodar (ecological danger of the nearby Zaporizhzhia NPP), and Kharkiv region (destruction of industrial facilities, contamination of soil and water resources). These regions reflect diverse types of environmental threats caused by military actions, but all of them have strategic significance for Ukraine. Below is presented a detailed analysis of the justification of the selection of the regions, as well as an assessment of the risks and significance of the modeling (**Table 4.3**).

The validity of the integrated model developed by the author was determined by the method of multi-criteria analysis (MCDA), using aggregated data on the accuracy of ML model forecasts, expert assessments, and data coverage coefficients by regions (**Table 4.4**). The average validity ≈ 64.8%, which is scientifically justified for the stage of pilot testing. It should be noted that in international practice (such international projects as UNEP, EPA, CEOBS, INSIDE Model) for systemic models in post-conflict ecology, validity of 65–80% is considered adequate for the pilot level, provided that the model is adapted in the process of operation.

Table 4.3 Scientific justification of the selection of regions for scenario modeling

Fundamental characteristics	Description
1	2
Kherson region	
Types of contamination	Petroleum products, heavy metals, chemicals (pesticides, fertilizers) washed away from flooded warehouses correspond to the parameter t_i of the model. The dynamics of concentration $c_i(t)$ require accounting for the migration of contaminants into groundwater and the Black Sea
Ecological characteristics	Chernozems, high fertility, proximity to the Dnipro and the Black Sea make the region critically important for agriculture. Loss of irrigation threatens desertification of 584 thousand ha of land
Risks	High risk to health (contaminated water), food security, and ecosystems (disruption of food chains)
Significance of modeling	The selection of Kherson region is justified by the scale of the environmental disaster, the diversity of contamination, and the strategic importance for agriculture. The environmental consequences of the blowing up of the Kakhovka HPP dam include contamination of soil and water with petroleum products, chemicals, death of biological resources (11 tons of fish), desalination of the Black Sea, and the loss of 94% of irrigation systems in the region. Modeling will make it possible to optimize remediation, minimize the ecological footprint, and restore food security [15]
Zaporizhzhia region	
Types of contamination	Probability of contamination with radionuclides (cesium-137, strontium-90), heavy metals from ammunition, chemicals from damaged infrastructure. A potential accident at the ZNPP could lead to radioactive contamination over an area up to 30 thousand km²
Ecological characteristics	Lowering of the level of the Kakhovka reservoir threatens the cooling system, and sandy soils of the region contribute to the migration of radionuclides
Risks	Catastrophic risk of a nuclear accident (comparable to Chernobyl), threat to the health of millions of people and long-term contamination not only of Ukraine but also of EU countries

Continuation of Table 4.3

1	2
Significance of modeling	The region is critical due to the nuclear threat and the dependence of southern Ukraine on water supply. Modeling will make it possible to develop preventive measures and remediation plans in case of an accident, which is relevant for international security
	Kharkiv region
Types of contamination	Heavy metals (including lead, cadmium), petroleum products, explosives (including TNT, RDX), as well as phosphorus from ammunition. The dynamics of $c_i(t)$ are complicated by the possibility of migration of contaminants into water bodies
Ecological characteristics	Predominantly chernozem and forest-steppe soils of the region are quite sensitive to the listed types of contamination, and the rivers of the region are part of the Don basin, which potentially can negatively affect the ecological situation of neighboring regions
Risks	High risk to health (contaminated water and soil), threat to food security (contamination of agricultural land) and ecosystems (disruption of aquatic ecosystems) [27]
Significance of modeling	Kharkiv region, as an industrial center, suffered from the destruction of factories, warehouses, and infrastructure, which led to contamination of soil with heavy metals, ammunition (including lead, TNT), petroleum products, and chemicals. Water resources, including the Siverskyi Donets and Oskil rivers, are contaminated with discharges and toxins. Kharkiv region represents a typical case of industrial and military contamination, which makes it suitable for testing the model on complex scenarios. Recovery of the region is critical for the economy and security of Ukraine

Table 4.4 Testing of the integrated remediation model by regions: Kherson, Zaporizhzhia, and Kharkiv regions

Regions	Validity (%)	Data sources	Data limitation	Correspondence to I-S-R scenario
Kherson	67.1	Satellites (Sentinel, Landsat), IoT (pointwise), laboratory analyses of water and soil	Limitation of real-time monitoring, lack of IoT networks	High at phases I (TR) and S (TR + GR), moderate at R (GR)
Zaporizhzhia	53.4	IAEA, satellites, partially drones (demining)	Low availability of monitoring data, shortage of ecological data on radiation levels	Good at phase I (TR), weak at S (TR + GR) and R (GR)
Kharkiv	73.8	Satellites, laboratory analyses of soil and water, GIS mapping	Lack of comprehensive information about the ecological situation in the region, no full IoT network	Excellent at phases I and S, good at R

In the opinion of the author, digital management of remediation of post-conflict territories requires the application of tools that allow systemic assessment and selection of IT solutions. Within the framework of this study, two types of validity matrices of digital components in the form of heat maps were developed and tested:

1. A universal matrix, which is built in the context of key criteria, such as adaptability, feasibility, strategic priority, cost-effectiveness, environmental impact.

2. Regional I-S-R matrices, oriented towards the implementation of remediation scenarios taking into account the specifics of territories (Kherson, Zaporizhzhia, Kharkiv regions).

For these purposes, a list of key digital components (IoT, ML libraries, GIS, server solutions and others) relevant for remediation scenarios was compiled and grouping of components by functional blocks was carried out (**Fig. 4.3**). Further, evaluation criteria were identified (in particular: adaptability, feasibility, ease of implementation, strategic priority, cost-effectiveness, environmental sustainability), as well as weighting coefficients of the criteria, which were selected taking into account the scenarios (express sanitation, long-term recovery, hybrid approaches). Then, based on data of expert evaluation of digital components from open sources and normalization, information was collected and aggregated (on a scale from 1 to 5). Then the scores were normalized according to regional and scenario features.

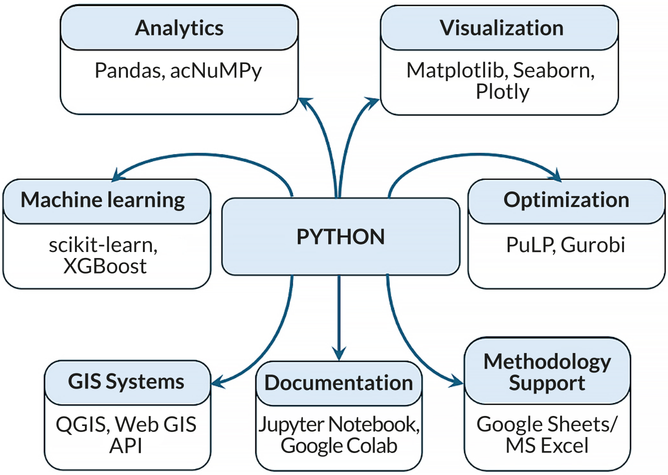

Fig. 4.3 Compositional ensemble of software and digital tools for remediation modeling

Thus, the validity matrix can act as a universal visual analytical tool that displays the comparative applicability of digital components according to a multitude of criteria (including in terms of adaptability, feasibility, ease of implementation, strategic priority, cost-effectiveness, as well as level of impact).

In the conviction of the author, the combination of two types of matrices forms the basis of adaptive digital management of remediation, allowing consideration of goals of different scale (sustainable recovery at micro- and meso-levels, national security), as well as micro-level tasks (elimination of local threats, stabilization of zones of ecological disaster) (**Fig. 4.4**, **4.5**). This will make it possible: to reasonably select digital solutions; to foresee in advance risks and complexities of implementation (for example, high cost or low adaptability of certain digital components); to form strategies for phased implementation from the basic level (QGIS + Python + River) to advanced (Gurobi + DGX Clusters); to substantiate funding requests by highlighting the most priority and effective components.

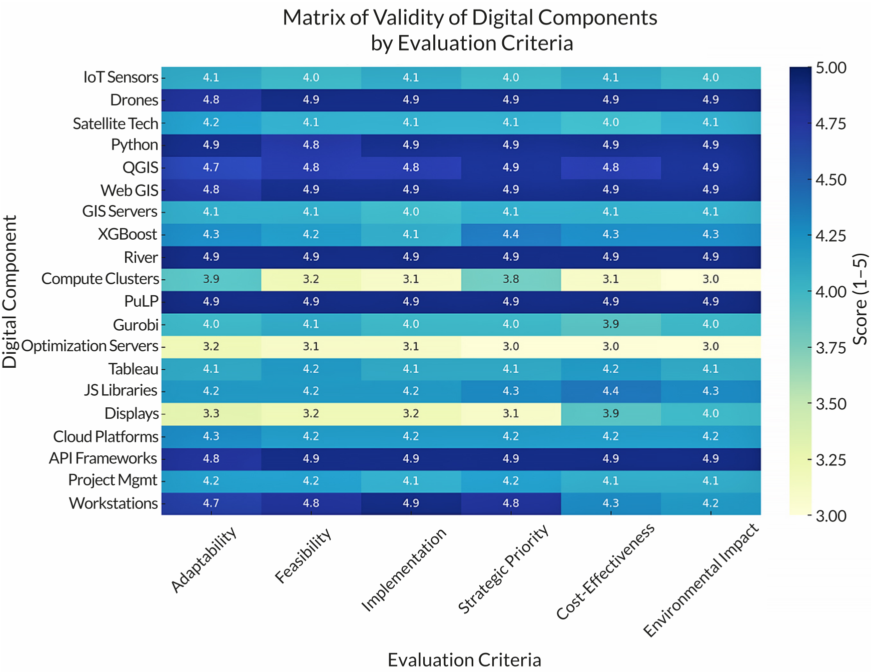

Fig. 4.4 Matrix of validity of digital components by evaluation criteria

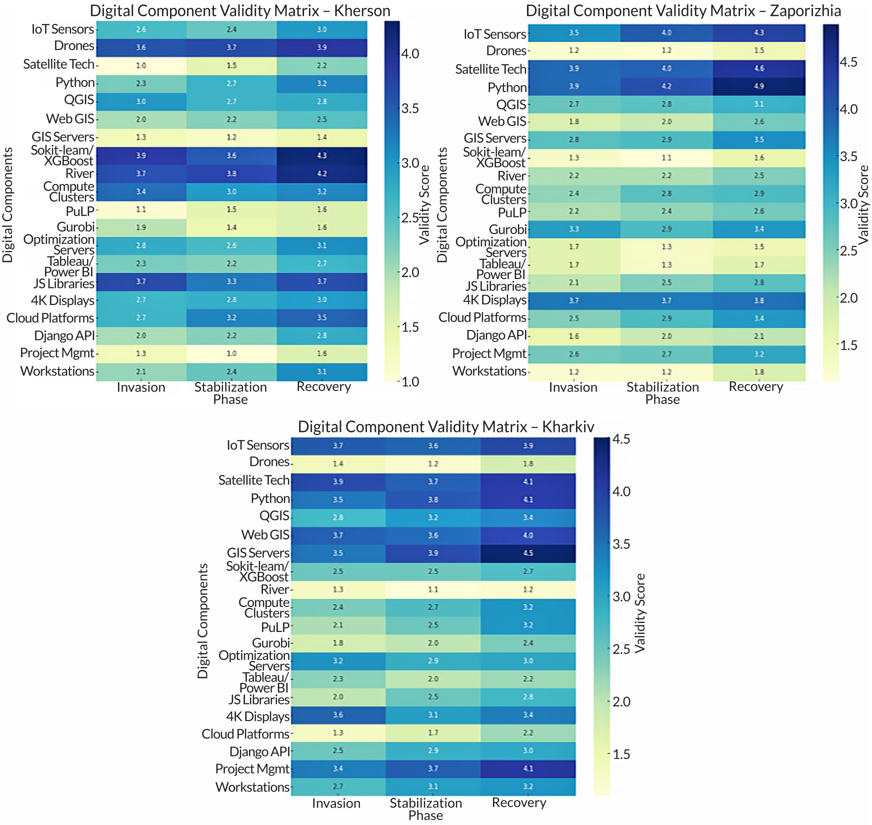

Fig. 4.5 Comparative heat maps for Kherson, Zaporizhzhia, and Kharkiv regions

The general conclusions reached by the author of the study are as follows: regarding the complementarity of the approach – at the invasion phase there is a priority for digital components providing speed (TR-focus), and at the recovery phase – for components that allow making sustainable decisions and optimally integrating them (GR-focus); regarding region-specificity – Zaporizhzhia region requires greater emphasis on radiation monitoring, Kherson – on hydro-ecological control, Kharkiv – on soil restoration and mine clearance; regarding the increase of adaptability of the integrated model proposed for implementation – digital components demonstrate flexibility in application by phases and make it possible to build scenario-justified remediation management.

4.5 Conclusion

The results obtained from the conducted study confirmed the achievement of the set goal – the development of a digital scenario model for the remediation of post-conflict territories, ensuring the transition from express sanitation to sustainable recovery based on modern IT solutions. The author developed an integrated architecture of digital management, adapting to the phases of Invasion-Stabilization-Recovery (I-S-R), where the key term becomes invasion – as a scientifically justified designation of the initial stage of acute anthropogenic intrusion, including military consequences for ecosystems. The proposed adaptive model of digital remediation for implementation combines methods of systems engineering, agent-based approach, and digital transformation through the application of: GIS for mapping environmental threats, IoT for real-time monitoring, ML/AI for scenario-based forecasting and multicriteria optimization. A pilot testing of the model was conducted in three strategically important regions of Ukraine (Kherson, Zaporizhzhia, and Kharkiv regions), with the identification of regional features and recommendations within the framework of selecting priority remediation measures: for Kherson region – priority is given to regular hydroecological monitoring, especially IoT networks for tracking the migration of contaminant pollutants in the region's water resources; for Zaporizhzhia region – emphasis on regular radiation monitoring and the development of preventive measures in case of an accident at the Zaporizhzhia Nuclear Power Plant; for Kharkiv region – the necessity of mapping contaminated areas using GIS and drones, followed by large-scale soil remediation, mine clearance, and elimination of pollutants in water bodies. For the purposes of operational remediation management, the author formed and proposes to use validity matrices (both universal and regional) in the form of heat maps. These will make it possible to assess the applicability of digital solutions across a number of criteria (adaptability, feasibility, environmental sustainability, etc.), as well as to visualize and select priority digital components in a regional context.

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