Challenges and Countermeasures for Large-Scale Complex Contaminated Site Remediation in China (Postprint)

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Abstract

Remediation of large complex contaminated sites constitutes a major challenge confronting the environmental field both domestically and internationally. Such sites are characterized by extensive impact ranges, diverse pollutant types, and substantial threats to ecological environments. Both understanding the environmental behaviors of pollutants at these sites and achieving efficient remediation face enormous challenges, with key scientific and technological issues—including formation mechanisms of soil and groundwater contamination, precise identification of pollution sources, and intelligent decision-making optimization—urgently requiring resolution. In China, large complex contaminated sites exhibit clustered distribution in economically developed regions such as the Beijing-Tianjin-Hebei region, the Yangtze River Economic Belt, and the Pearl River Delta, encompassing industries like chemical manufacturing, petroleum and other fuel processing, and ferrous metal smelting. Based on China's national conditions, this article proposes a key "three-step approach" (TSRTCM) for remediating large complex contaminated sites, addressing remediation challenges through three aspects: investigation and assessment with scientific understanding, scheme decision-making and technology selection, and engineering implementation and monitoring evaluation. Environmental remediation of large complex contaminated sites can effectively support the battle against pollution prevention and control, and facilitate green development of regional economies and societies.

Full Text

Challenges and Countermeasures for Treatment and Remediation of Contaminated Mega-Sites in China

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Abstract

The treatment and remediation of contaminated mega-sites represents a major challenge in environmental science both domestically and internationally. Contaminated mega-sites are characterized by their extensive impact areas, diverse pollutant types, and significant threats to ecological environments. Both understanding the environmental behavior of pollutants and implementing efficient remediation at these sites face enormous challenges, with critical scientific issues such as the formation mechanisms of soil and groundwater pollution, precise identification of pollution sources, and intelligent decision-making optimization urgently requiring solutions. In China, contaminated mega-sites are clustered in economically developed regions such as the Beijing-Tianjin-Hebei area, the Yangtze River Economic Belt, and the Pearl River Delta, involving industries including chemical manufacturing, petroleum and other fuel processing, and ferrous metal smelting. Based on China' s national context, this article proposes a key "Three-Step Remediation and Treatment Model for Contaminated Mega-sites" (TSRTCM), focusing on addressing remediation challenges through three aspects: investigation and scientific cognition, decision-making and technology screening, and engineering implementation and monitoring evaluation. Environmental remediation of contaminated mega-sites can effectively support the battle against pollution prevention and control, and contribute to the green development of regional economies and societies.

Keywords: contaminated mega-site, soil pollution, environmental remediation, formation mechanism, decision-making

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1. Basic Concepts of Contaminated Mega-Sites

1.1 Historical Evolution International attention to contaminated mega-sites can be traced back to the late 19th century, when rapid industrial development and neglect of environmental protection caused numerous environmental pollution incidents and left behind a large number of industrial contaminated sites, such as the Ruhr region in Germany, the Port of Rotterdam in the Netherlands, and Donora in the United States [?]. In the 1970s, the Love Canal toxic site incident in the United States prompted the passage of the Comprehensive Environmental Response, Compensation, and Liability Act in 1980. This act, known for its Environmental Protection Superfund, is commonly referred to as the Superfund Act, which provided the U.S. government with special funds for emergency response and remediation of environmental pollution incidents, becoming the first legislation in the world specifically targeting contaminated site remediation. In the 21st century, international understanding of contaminated mega-sites has continuously improved, with governments and international organizations gradually attaching importance to their remediation. Currently, while some countries and regions have issued relevant documents to define contaminated mega-sites, there is still no unified definition. The U.S. Environmental Protection Agency began formulating policies on contaminated mega-sites in the early 21st century, defining them as "any hazardous waste site where the total cost of investigation and cleanup (excluding long-term care) equals or exceeds $50 million." The European Contaminated Land Network (NICOLE) proposed the concept of "mega-sites" in 2003 but did not provide a clear definition [?]. In 2004, the EU proposed the WELCOME (water, environment and landscape management at contaminated mega-sites) integrated management strategy for contaminated mega-sites to prevent and reduce risks. China' s Ministry of Ecology and Environment has defined the concept of contaminated sites in the standard "Terms of Contaminated Sites" (HJ 682-2014), but has not further defined contaminated mega-sites.

1.2 Definition and Characteristics of Contaminated Mega-Sites Based on a comprehensive review of domestic and international literature and scientific research, this study proposes the following definition for contaminated mega-sites: industrial contaminated sites with large areas (over 500,000 square meters), multiple pollution sources, and various types of pollutants. These site contaminations are caused by industrial activities, accidents, or waste disposal, including large factories, industrial clusters, military sites, ports, and other types.

The main characteristics of contaminated mega-sites are as follows [?]: (1) Large site scale. The area exceeds 500,000 square meters with clear boundaries from the surrounding environment. Since there is no explicit definition of the area threshold for contaminated mega-sites domestically or internationally, this study comprehensively considers factors such as pollution scale, environmental risk, complexity of response, and remediation costs, categorizing sites over 500,000 square meters as contaminated mega-sites. (2) Independent pollution sources. The site contains multiple independent pollution sources with diverse pollutant types, complex distribution patterns, and strong spatial variability. (3) High environmental risk. Contaminated mega-sites represent long-term potential sources of regional groundwater, surface water, and sediments, posing significant ecological and human health risks to surrounding areas, though the vast land area can be transformed into multiple land use types with substantial conversion and potential utilization value. (4) Difficult remediation. Remediation requires enormous investment and long timeframes, necessitating consideration of multiple media, larger areas, and more stakeholders.

2. Spatial Distribution Characteristics of Contaminated Mega-Sites in China

Contaminated mega-sites in China are widely distributed, clustering in economically developed regions such as the Beijing-Tianjin-Hebei area, the Yangtze River Economic Belt, and the Pearl River Delta [Figure 1: see original paper]. The overall trend shows more sites in the east than in the west, with roughly equal numbers in the north and south. The proportion of contaminated mega-sites in China' s typical geographical regions is as follows: East China (28.15%), North China (12.13%), Central China (11.66%), Southwest China (10.42%), Northwest China (7.15%), Northeast China (6.38%), and South China (5.44%). Shandong Province has the largest number of contaminated mega-sites (95), followed by Hebei Province (45) and Guangdong Province (42). Hainan Province and Qinghai Province have very few contaminated mega-sites, while the Tibet Autonomous Region has none.

Contaminated mega-sites are dominated by manufacturing industries. The main industry types are: chemical raw materials and chemical products manufacturing (23.14%), petroleum, coal and other fuel processing (14.34%), ferrous metal smelting and rolling processing (10.33%), and automobile manufacturing (4.21%) [Figure 1: see original paper]. These are mainly distributed in East China, North China, and Central China. Heavy industries such as chemical, petroleum, and steel have high resource consumption and large pollutant emissions, and their complex production processes require multiple large-scale production facilities, resulting in large land occupation and more severe contamination.

Economic development and natural resources are the main drivers of the spatial distribution of contaminated mega-sites. Economically developed regions typically have the foundation for large factory layout and construction, including complete industrial layouts, large population density, and advanced process technology [?]. Meanwhile, natural resources are important factors for site selection of resource-based enterprises such as chemical, mining, and smelting industries. For example, petroleum and coal processing industries are mainly distributed in Shandong, Hebei, Inner Mongolia, Shaanxi, and other regions rich in petroleum and coal resources.

3. Key Scientific and Technological Challenges in the Management and Remediation of Contaminated Mega-Sites in China

3.1 Precise Identification of Pollution Sources in Contaminated Mega-Sites As a complex geographical system, contaminated mega-sites comprise multiple elements including soil, groundwater, and industrial activities, exhibiting comprehensive, coupled, nonlinear, and non-stationary characteristics. The behavior of pollutants among various environmental elements is interconnected and inseparable, posing challenges for precise identification and detailed characterization of pollution sources [?]. In research on source apportionment and characterization of composite pollution at sites, domestic and international scholars have mainly used receptor models, diffusion models, and isotope tracing. However, such point-to-surface source identification results have large uncertainties and can no longer meet the growing demand for refined environmental management, with a significant gap remaining between current capabilities and future needs for precision, real-time monitoring, and intelligent management [?].

Contaminated mega-sites feature "multiple pollution sources, multi-media coexistence, and multi-temporal evolution," placing extremely high demands on accurate source apportionment technologies for composite pollution. Future research should focus on three key scientific questions: How to establish a quantitative "source-sink" relationship between pollution sources and soil pollutants, decouple multiple pollution source superposition, and achieve precise tracing of composite pollution? How to clarify the relationship between site multi-elements and pollution distribution, analyze the interactive coupling effects of multiple elements, and reveal the formation mechanisms of pollution distribution in contaminated mega-sites? How to address the current limitations of site pollution tracing technology where speed and accuracy cannot meet mobile supervision needs, couple multiple tracing technologies, construct a high-precision composite pollution tracing system, and improve tracing accuracy and intelligent diagnosis levels?

3.2 Spatiotemporal Variation Patterns of Pollutants in Contaminated Mega-Sites Compared with small-scale contaminated sites, contaminated mega-sites exhibit stronger spatial heterogeneity of pollution, making precise prevention and control of pollutant transport and diffusion more difficult. The accuracy of pollution pattern analysis will affect subsequent risk diagnosis, remediation decision-making, and engineering implementation [?]. Therefore, it is necessary to account for the "strong heterogeneity" and "non-stationarity" characteristics of soil pollutant spatial distribution, improve pollution characterization accuracy under "sparse and biased" soil drilling sample conditions, and scientifically understand the spatiotemporal variation and evolution patterns of pollution.

Specifically, four key technological issues require attention. First, how to overcome the "sparse and biased" nature of soil drilling data, balance the high cost of soil drilling investigations with characterization accuracy, and scientifically layout sampling points to achieve cost-effectiveness optimization. Second, how to overcome the stationary assumption limitations and excessive smoothing limitations of traditional geostatistical methods based on limited drilling data, and accurately characterize the spatial distribution of soil-groundwater multi-media pollutants at sites. Third, how to utilize migration numerical models, spatial statistical models, and artificial intelligence models to simulate the spatiotemporal evolution patterns of pollutants and achieve predictive warning of pollution spatial changes. Fourth, how to combine the production functional characteristics and hydrogeological features of contaminated mega-sites to quantitatively assess pollutant diffusion, migration pathways, and distribution characteristics, and predict potential environmental impacts to provide scientific basis for subsequent control and remediation decisions.

3.3 Regional Ecological and Environmental Risk Assessment for Contaminated Mega-Sites The accuracy of site pollution risk assessment determines remediation scope, treatment costs, and potential risks. Before remediation, human health risk assessment must be conducted to quantify site pollution risks and determine remediation target values and scope [?]. Compared with ordinary-scale contaminated sites, risk assessment for contaminated mega-sites is more critical. First, contaminated mega-sites typically involve broader areas and more affected parties. Second, they may involve more types of pollutants, higher concentrations, and longer exposure durations [?]. Therefore, comprehensive and accurate assessment of ecological and environmental risks is necessary to implement appropriate risk control measures.

Various countries have established site environmental risk assessment methods and systems suitable for their own contexts and applied risk management concepts to site remediation [?]. China' s "Technical Guidelines for Risk Assessment of Soil Contamination of Construction Land" (HJ 25.3-2019) and related research have mostly drawn on mature foreign methods and models [?, ?]. In recent years, some studies have recognized the impact of directly applying existing models and parameters on the credibility of risk assessment results, and have explored conceptual model analysis, assessment model comparison, and parameter correction [?, ?]. Due to the strong heterogeneity and non-stationarity of soil pollution distribution in contaminated mega-sites, pollution spatial characterization based on discrete drilling samples and statistical inference models has large uncertainties [?]. Therefore, three scientific questions should be considered: How to assess the cumulative pollution risks among different functional areas and depths within and around contaminated mega-sites, and construct scientific assessment models and methods? How to consider the spatiotemporal variability and non-stationarity of risk assessment parameters for contaminated mega-sites, and obtain refined risk assessment parameters? How to consider pollutant migration and transformation patterns, exposure pathways, and influencing factors in different media, accurately assess the extent and scope of environmental risk impacts, and achieve scientific risk assessment?

3.4 Decision-Making for Environmental Control and Remediation of Contaminated Mega-Sites The remediation of contaminated mega-sites is a complex, costly, and time-consuming endeavor. Scientifically formulated risk control and remediation strategies can maximize resource cost savings. Site remediation decision-making has evolved through three stages: early focus on cost, feasibility, and risk, to gradually considering more factors such as technical performance, environmental impact, land planning, and economic benefits, creating significant uncertainty in the decision-making process [?]. Therefore, it is necessary to introduce decision support tools into the site remediation process to help decision-makers clarify objectives and balance interests, improve problem-solving capabilities and scope, and optimize resource allocation and management.

In 1971, foreign scholars first proposed the concept of "decision support systems" [?]. Currently, widely used remediation decision systems internationally include the U.S. SMARTe, EU' s REC and WELCOME, and Italy' s DESYRE. These systems can be categorized by framework construction method into: those built according to site investigation and management steps; those built according to mathematical modeling ideas and methods; and those built for specific site problems [?]. Compared with ordinary-scale sites, remediation decision optimization research for contaminated mega-sites must also consider big data processing, multi-decision objectives, uncertainty management, long-term sustainability, and scale effects. Specifically, four scientific questions need to be addressed: How to mine multi-source big data in contaminated mega-sites and present it in a visual and interactive manner to support site remediation decisions? How to solve the trade-offs and optimization problems among multiple decision objectives and stakeholders in contaminated mega-sites to find optimal solutions? How to meet the remediation needs and constraints of different zones within contaminated mega-sites and develop adaptive strategies? How to account for scale effects in the management and remediation process of contaminated mega-sites to achieve optimal resource allocation?

4. Approaches and Countermeasures for Treatment and Remediation of Contaminated Mega-Sites in China

Globally, the remediation of contaminated mega-sites has always been an extremely challenging task. Developed countries in Europe and America have accumulated rich experience and advanced technologies through long-term practice, providing valuable insights for China's contaminated mega-site remediation. By drawing on these experiences and combining them with China' s national context, the following targeted countermeasures and suggestions are proposed.

4.1 Three-Step Model for Remediation and Treatment of Contaminated Mega-Sites Contaminated mega-sites should focus on detailed pollution characterization and boundary delineation, risk-based integrated management strategies, engineering implementation, and post-remediation supervision. This study proposes a key "Three-Step Remediation and Treatment Model for Contaminated Mega-sites" (TSRTCM) applicable to China. The first step is investigation and scientific cognition based on the principles of big data, multi-elements, and multi-models. This involves comprehensively utilizing multi-source big data, multi-element information, and various methods to deeply explore data from contaminated mega-sites, scientifically understand pollution sources, migration pathways, distribution characteristics, environmental risks, and diffusion trends to support subsequent remediation strategies and engineering implementation. The second step is decision-making and technology screening based on the principles of zoning, timing, and classification. Based on scientific cognition of contaminated mega-sites, this step couples spatial, temporal, and pollutant type dimensions to implement zone-specific, time-specific, and type-specific remediation, using artificial intelligence, big data analysis, and simulation prediction to construct an intelligent decision support system for formulating multi-dimensional comprehensive remediation strategies that are qualitative, timed, located, and quantitative. The third step is engineering implementation and monitoring evaluation based on the principles of comprehensiveness, whole-process, and whole-cycle. This involves establishing comprehensive, three-dimensional monitoring methods for multiple media including soil, groundwater, and atmosphere to dynamically monitor and track the entire remediation process, ensuring the effectiveness and green sustainability of the remediation over the full cycle [Figure 2: see original paper].

4.2 Investigation and Scientific Cognition–Big Data, Multi-Elements, Multi-Models Following the principles of big data, multi-elements, and multi-models, investigation and scientific cognition of pollution characteristics and risks at contaminated mega-sites should be conducted. Given the numerous elements and large data volumes at contaminated mega-sites, a unified data management and visualization platform should be established by integrating multi-source data including remote sensing, sampling surveys, environmental monitoring, and historical records. This platform would promote data integration and standardization, enabling comprehensive management and convenient querying of contaminated mega-site data. Based on multi-element information both inside and outside the site, including production activities, hydrogeology, pollution concentrations, and sensitive receptors, the pollution distribution patterns, diffusion trends, and correlations should be explored to scientifically understand pollution sources, migration pathways, distribution characteristics, and risk warnings. Multiple model methods including artificial intelligence, spatial statistical models, pollutant migration numerical models, and multivariate statistical models should be comprehensively applied to quantitatively assess pollutant diffusion, migration pathways, and distribution characteristics, predict potential environmental impacts, and provide scientific basis for subsequent control and remediation decisions.

4.3 Decision-Making and Technology Screening–Zoning, Timing, Classification Following the principles of zoning, timing, and classification, remediation decision-making and technology screening for contaminated mega-sites should be conducted. Given the strong spatial heterogeneity of pollution distribution in contaminated mega-sites, a "zoned remediation" strategy should be adopted spatially to formulate differentiated remediation plans. This approach can quickly release clean and low-risk zones for redevelopment, directing more remediation funds to high-risk zones and promoting optimal allocation of remediation resources. The remediation of contaminated mega-sites is characterized by long-term duration, requiring a "timed remediation" strategy temporally. When formulating remediation plans, mechanisms such as pollutant migration, diffusion, and natural attenuation in media should be comprehensively considered to prevent deviations between delineated remediation scopes and actual pollution conditions. Under the premise of controllable pollution risks, low-cost measures such as natural attenuation should be reasonably utilized to maximize environmental and economic benefits. Contaminated mega-sites feature diverse pollutant types, and remediation technologies should be selected according to pollutant physicochemical characteristics and pollution levels, combined with physical, biological, and chemical remediation technologies to formulate reasonable technology combinations that maximize remediation effectiveness and achieve green, low-carbon remediation. By coupling spatial, temporal, and pollutant type dimensions and using artificial intelligence, big data analysis, and simulation prediction, an intelligent decision support system should be constructed to formulate multi-dimensional comprehensive remediation strategies.

4.4 Engineering Implementation and Monitoring Evaluation—Comprehensiveness, Whole-Process, Whole-Cycle Following the principles of comprehensiveness, whole-process, and whole-cycle, engineering implementation and monitoring evaluation for contaminated mega-sites should be conducted. Given the large area and deep contaminated soil at contaminated mega-sites, a comprehensive, three-dimensional monitoring system should be established. For multiple environmental media including soil, groundwater, surface water, and atmosphere, online monitoring, fixed-point sampling analysis, and on-site monitoring should be employed to strengthen standardized and refined construction process management, ensuring controllability of the remediation process and reliability of effectiveness evaluation. Whole-process monitoring of remediation projects should be conducted to track the sustainability of remediation effects and changes in environmental risks, with timely identification of problems and risks. Based on on-site engineering progress, a "dynamic remediation" approach should be adopted to adjust and improve remediation plans. For sustainable management of remediated land, long-term monitoring programs and review mechanisms should be established to prevent secondary pollution and rebound, restore the production and ecological functions of remediated soil, and achieve perpetual land use. Green, low-carbon, and sustainability throughout the entire remediation lifecycle should be prioritized, with high-energy-efficiency equipment and low-carbon remediation materials applied, emphasizing soil protection, green recycling, reusability, and construction safety during engineering implementation to reduce secondary damage to the soil environment, lower environmental loads, and improve resource recycling.

5. Conclusion

The management and remediation of contaminated mega-sites is one of the major environmental challenges facing China's economic and social development, affecting economic construction, urban development, and environmental safety.

Currently, China attaches great importance to soil pollution prevention, ecological civilization construction, and the building of a Beautiful China. These represent not only China' s own development needs but also a positive response to global development initiatives, with contaminated mega-site management and remediation playing a key role in these domains. China should establish a remediation model specifically for contaminated mega-sites, focusing on investigation and scientific cognition, decision-making and technology screening, and engineering implementation and monitoring evaluation to promote precision, informatization, and intelligence in contaminated mega-site remediation. This will provide scientific support and practical foundations for solving major resource and environmental problems of soil and groundwater pollution, comprehensively building a Beautiful China, and promoting green development and ecological civilization.

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Note: Figure translations are in progress. See original paper for figures.