

Review

Environmental Site-Specific Risk Assessments—A Review of Methodological Frameworks, Contaminated Land Assessment, and Ecological Risk Characterization Approaches

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Abstract

Environmental site-specific risk assessment (SSRA) has developed into a complex, multi-tiered discipline that integrates contaminated land characterization, ecological endpoint selection, exposure pathway analysis, and uncertainty quantification to facilitate remediation decision-making. This literature review integrates findings from 33 highly relevant peer-reviewed publications over three decades (1994–2024). Overall, our narrative synthesis indicated that while SSRA methodologies share a common conceptual foundation, the implementation varies notably across regions, contaminants, and ecological contexts. This review reveals a gradual move away from deterministic screening-level assessments and toward probabilistic, spatially explicit frameworks that incorporate multiple lines of evidence, advanced uncertainty analysis, and decision support systems. The key findings show that tiered assessment methods that combine screening and definitive evaluations are still the most common and that Bayesian networks, Monte Carlo simulations, and weight-of-evidence methods are being used more to deal with uncertainty in parameters and models.

Keywords: environmental assessment; risk classification; soil and ground pollution; groundwater contamination; environmental data; decision support; sustainable remediation



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1. Introduction

Environmental site-specific risk assessment (SSRA) is an important link between environmental science, toxicology, and regulatory decision-making [1–3]. It gives the analytical basis for evaluating ecological risks at contaminated sites and setting science-based remediation goals. Site-specific risk assessments use detailed site characterization data, local ecological conditions, and contaminant-specific fate and transport processes to make risk estimates that are specific to each contaminated site [4]. Generic risk assessments, on the other hand, use standardized exposure scenarios and conservative assumptions [5].

The evolution of ecological risk assessment for contaminated sites has been driven by multiple factors. These include advances in analytical chemistry that make it possible to find trace contaminants, improved knowledge of bioavailability and bioaccumulation

processes, development of complex exposure models, and policy regulations that require proof of ecological protection [5,6]. The U.S. Environmental Protection Agency (EPA) set up a basic framework that was later adopted internationally. This framework stresses a systematic, science-based process that includes problem formulation, exposure assessment, effects assessment, and risk characterization [5,7,8].

Contemporary SSRA faces several interconnected challenges. First, contaminated sites typically involve complex mixtures of chemicals with varying toxicological properties, bioavailability characteristics, and environmental persistence [5]. Second, ecological receptors include a wide range of taxonomic groups and trophic levels, each with its own exposure pathways, sensitivities, and ecological importance [5,7,8]. Third, spatial and temporal heterogeneity in contaminant distribution, environmental conditions, and receptor populations introduces substantial variability that must be characterized and incorporated into risk estimates [9]. Lastly, there are many sources of uncertainty, such as parameter uncertainty, model uncertainty, and natural variability, that make it hard to understand risk estimates and share the results with decision-makers [10–12].

This study reviews current knowledge on methodological frameworks, contaminated land assessment approaches, and ecological risk characterization approaches for site-specific risk assessment, revealing 33 highly relevant publications identified through a systematic literature search and relevance ranking. It focuses on three main topics: (1) methodological frameworks and assessment approaches, (2) contaminated land characterization and exposure pathway analysis, and (3) ecological risk characterization and uncertainty quantification. The objectives are to identify established best practices that have already been proven to work, evaluate emerging methodologies, characterize existing critical knowledge gaps, and provide recommendations for improvement of science and practice of site-specific ecological risk assessment.

This manuscript presents a narrative review of methodological approaches used in contaminated land and groundwater site-specific risk assessment (SSRA), with an emphasis on recent methodological frameworks, contaminated land assessment approaches, ecological risk characterization approaches, uncertainty analysis, and regulatory systems.

2. Materials and Methods

2.1. Review Design

Our study employed a narrative literature review methodology [13,14] to synthesize and critically interpret existing research on SSRA. This approach to literature review was selected because the field contains a multitude of study designs, theoretical perspectives, and conceptual frameworks that are not readily usable for meta-analysis or strict systematic review procedures. Unlike in a systematic review, our objective here is not to identify or quantitatively synthesize all available studies through a pre-defined search protocol but rather to critically examine SSRA methodologies, compare current assessment frameworks, and identify future research needs. This approach enabled us to examine broad or complex research questions, integrate findings from diverse methodologies, and identify conceptual patterns, theoretical developments, and knowledge gaps across the literature.

2.2. Search Strategy

Relevant literature sources were identified from two databases—Scopus and Web of Science Core Collection (WoSCC). These are the most prominent global citation databases used to track, analyze, and evaluate peer-reviewed research. Scopus (owned by Elsevier) is the world's largest (>27,000 journals) abstract and citation database of peer-reviewed publications. WoSCC (owned by Clarivate) is more selective, indexing >20,000 top-tier, high-impact journals.

The literature search included four stages: Search, Appraisal, Synthesis, and Analysis (the SALSA framework). It is an analytical framework used to describe and organize the review process [14]. In the first stage—Search—only peer-reviewed, published papers describing empirical, original research were included. Search was carried out using online scientific databases, SCOPUS and Web of Science Core Collection (WoSCC), applying the same search logic but adapting it to respective databases. The search was conducted only in the English language. We did not use pilot searches, but our search strategy was developed iteratively through several rounds of testing and refinement. These refinements entailed running search queries to optimize the adequacy of results: for example, searching for “uncertainty analysis” yielded too many publications outside the field of SSRA, and consequently, the query was updated to “uncertainty analysis in risk assessment”. At the second stage—Appraisal—all results from the search were reviewed at the title and abstract level to ensure that they met a set of defined criteria (Table 1)—defined type of publication, language, and clearly described study design and outcomes.

Table 1. Inclusion and exclusion criteria for literature review.

Variable	Inclusion Criteria	Exclusion Criteria
Publication type	Peer-reviewed articles, book chapters	Gray literature, data papers
Language	Articles in English	Articles in other languages
Study design	Clearly described	Lacking clearly described methodology
Outcomes	Articles reporting measurable outcomes	Articles lacking clear outcome measures

The keywords were selected for exploratory analysis of the available literature, and in order to minimize subjectivity, the literature search was conducted by strictly following the identified keywords:

- “site-specific risk assessment”, “methodological frameworks”, “tiered”, “probabilistic and deterministic”, “decision support systems and tools”, “integrated assessment”;
- “contaminated land assessment”, “site characterization”, “contamination”, “types, environment”, “spatial and temporal considerations”, “exposure pathways”;
- “ecological/environmental risk characterization”, “assessment”, “toxicity evaluation”, “bioaccumulation”, “modelling”, “weight-of-evidence”;
- “uncertainty analysis in risk assessment”, “types and sources of uncertainty”, “quantitative methods”, “sensitivity analysis”;
- “case studies and applications”, “regulatory and international context”, “critical gaps and limitations”.

At the third stage—Synthesis—publications that have met the inclusion criteria were collected in a database. These publications were read in full to extract information for carrying out the narrative synthesis. The fourth stage—Analysis—includes a comparison of results and conclusions: Relevant studies were collected, and their findings were summarized based on key topics according to previously mentioned themes. The results were compared across the selected sources by identifying similarities, discrepancies, and patterns regarding SSRA. The collected information was further synthesized to provide cross-cutting analysis of the topic. Additionally, practical, methodological implications of future trends were discussed, leading to conclusions. A concise summary of the literature review findings is presented at the end of the Discussion.

Several thousand publications were retrieved from the first stage of the literature search (Figure 1), both from Scopus and Web of Science. At the screening stage, the majority of identified articles were excluded from the search results based on accessibility, title,

abstract, and full-text screening. After the critical appraisal stage, 33 papers were selected for the literature review.

ROSES flow diagram for literature review

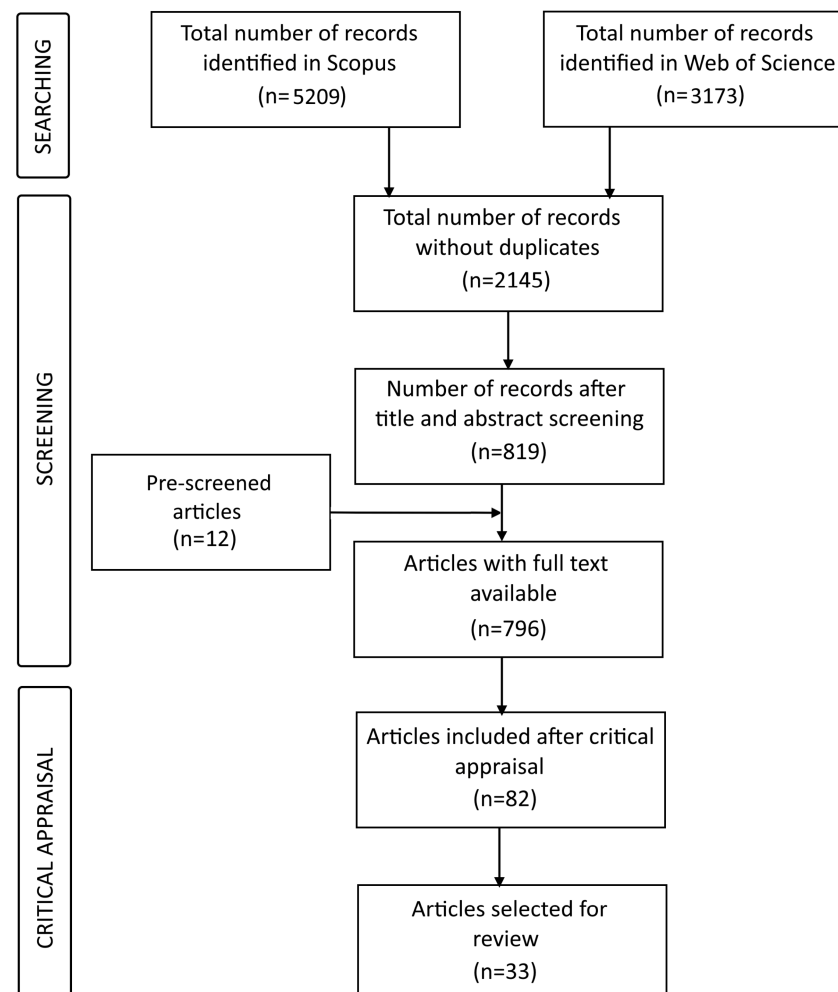


Figure 1. ROSES flow diagram for literature review in Scopus and Web of Science Core Collection (WoSCC) databases [15].

The large reduction in the number of identified publications and the final set of 33 sources are primarily a consequence of the broad search strategy we employed to maximize sensitivity. We followed up by applying highly specific eligibility criteria designed to identify studies directly addressing SSRA. For instance, many initially retrieved literature sources were excluded because they focused on generic risk assessment, contaminated site management without SSRA methodology, or laboratory or modelling studies without a site-specific assessment component. Other examples of excluded sources were conference abstracts, non-peer-reviewed publications, duplicate records, etc. Consequently, only 33 publications met all inclusion criteria and were considered sufficiently relevant to address the objectives of this narrative review.

We have included elements of a systematic literature review, like the S.A.L.S.A. framework and ROSES flow diagram, to strengthen the scientific rigor of this type of study.

3. Results

3.1. Literature Search

The literature search yielded a large number of publications (8382 in total) from both databases. Overall, the SCOPUS database contained more relevant results over the longer timespan compared to the WoSCC (Table 2).

Table 2. Identified numbers of publications from SCOPUS and Web of Science Core Collection (WoSCC).

Variables	Inclusion Criteria	Number of Publications in SCOPUS	Number of Publications in WoSCC	Last 10 Years (2016–2026)
site-specific risk assessment	site-specific risk assessment	5185	3119	4750
	methodological frameworks	30	131	118
	tiered	55	178	69
	probabilistic and deterministic	63	136	75
	decision support systems and tools	71	133	61
	integrated assessment	433	613	454
contaminated land assessment	contaminated land assessment	3835	1965	3456
	site characterization	168	162	71
	contamination	2266	1059	1880
	types	528	385	523
	environment	995	584	574
	spatial and temporal considerations	74	68	58
environmental risk characterization	exposure pathways	194	198	161
	environmental risk characterization	12,994	8863	10,844
	assessment	6637	3637	5434
	toxicity evaluation	470	385	362
	bioaccumulation	432	301	399
	modelling	1313	2490	1842
uncertainty analysis in risk assessment	weight of evidence	128	98	74
	uncertainty analysis in risk assessment	482	102	366
	types and sources of uncertainty	181	121	92
	quantitative methods	596	283	457
case studies and applications	sensitivity analysis	1299	716	994
	case studies and applications	3549	1819	2463
	regulatory and international context	327	272	213
	critical gaps and limitations	220	114	164

The literature search also showed a gradual increase in the number of publications in both databases, with a particularly rapid rise after 2020. Domain keywords like “site-specific risk assessment” and “environmental risk characterization” became more prevalent during recent decades (Figure 2).

Analyzing the countries where reviewed studies originate (Figure 3), we found that the United States dominates the field, with 15.8–24% of publications identified by keyword search. The only exception was “contaminated land assessment”, where China had the largest share (18%). The other top 10 countries were the United Kingdom, Italy, Canada, Germany, the Netherlands, Spain, Australia, and France.

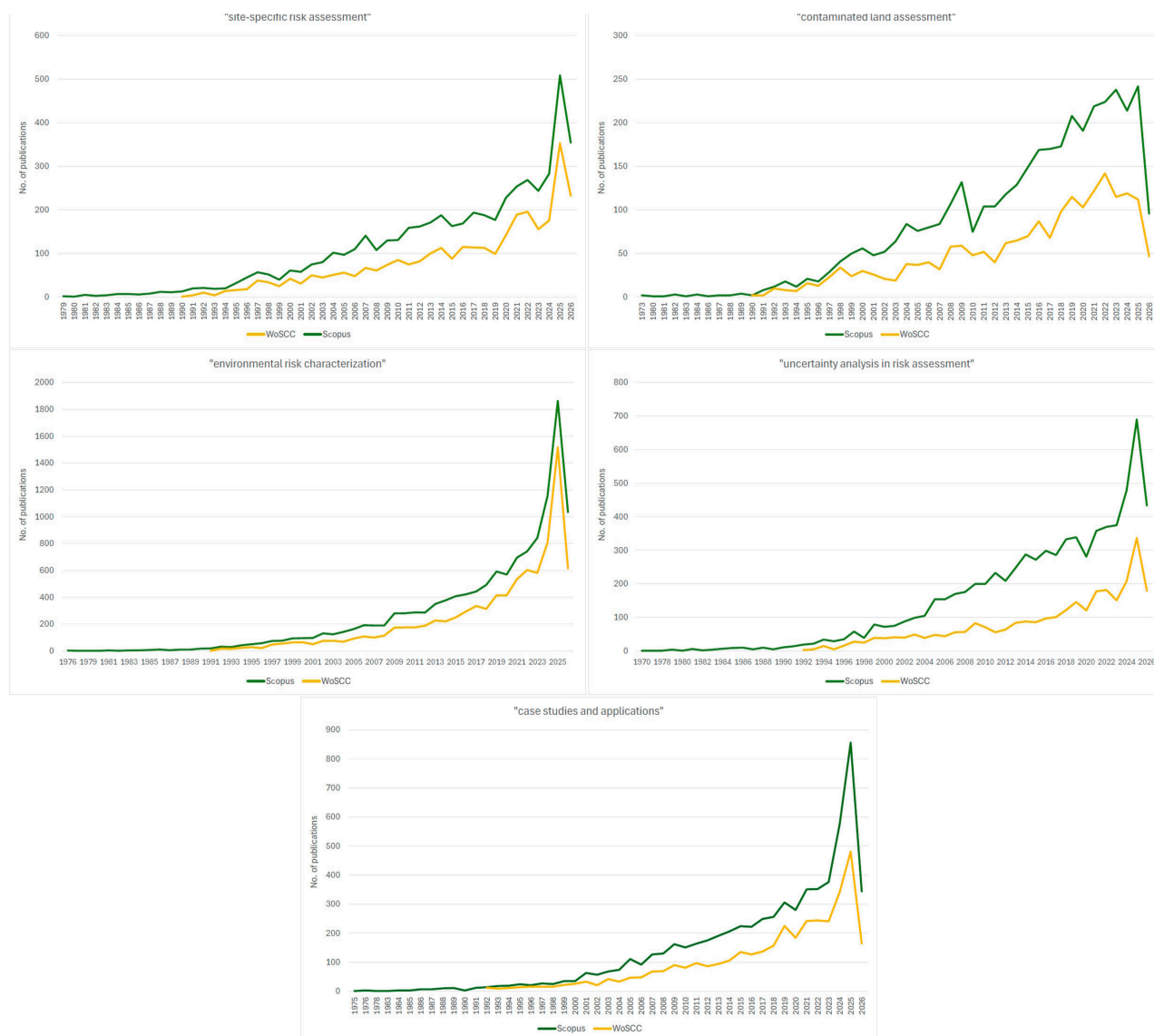


Figure 2. Number of publications according to keyword search in Scopus and Web of Science Core Collection (WoSCC) databases.

Other countries comprised a notable portion of the identified articles—from 35.8% ("site-specific risk assessment") to 40.1% ("environmental risk characterization").

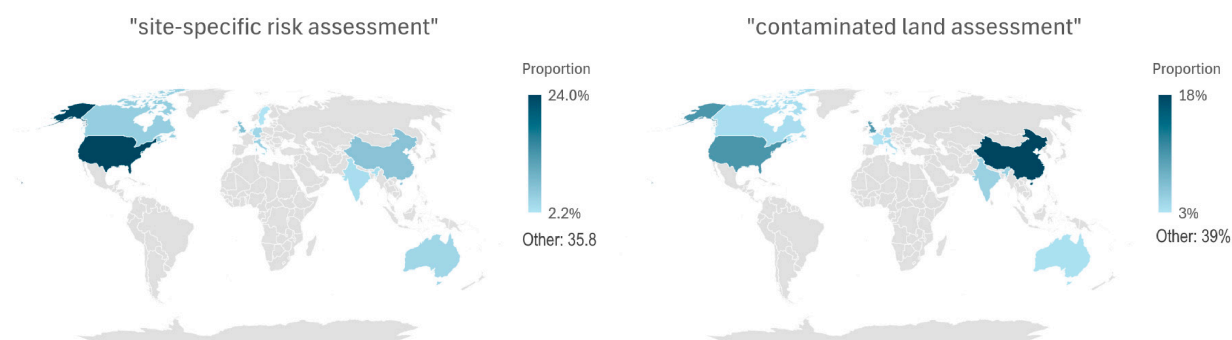


Figure 3. Cont.

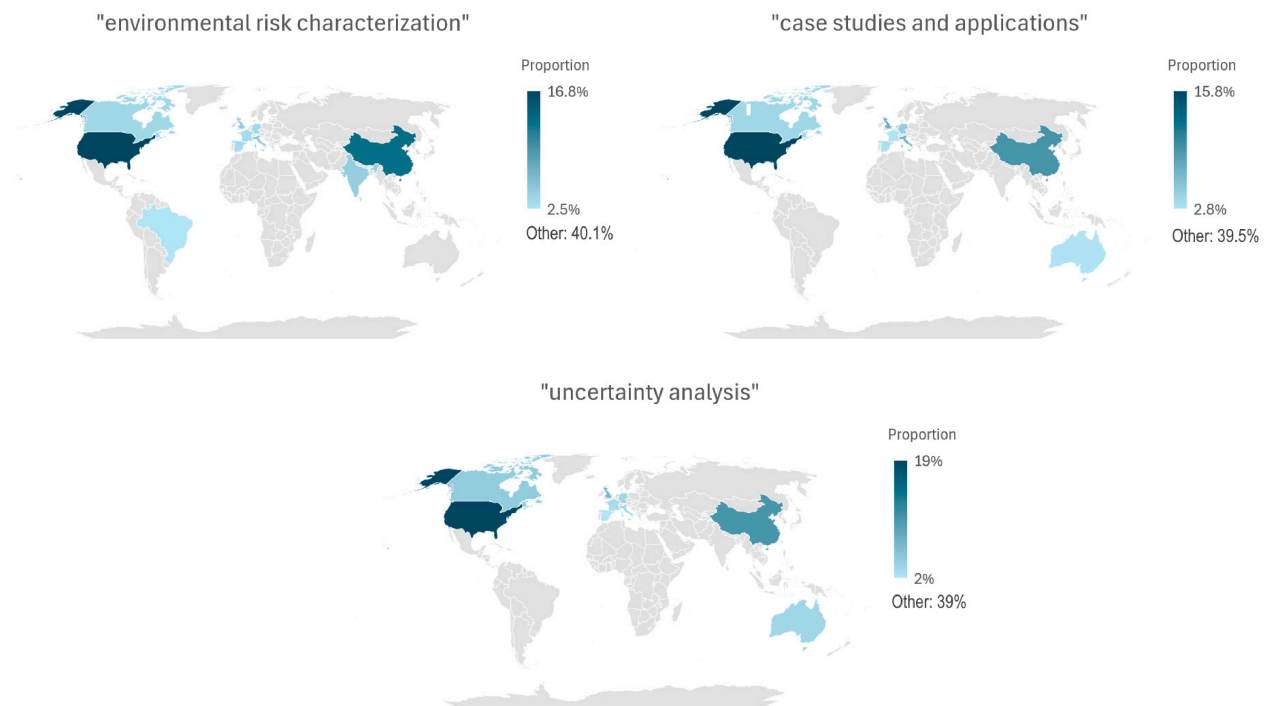


Figure 3. Top 10 countries by their share of publications according to keyword search in the Scopus database.

3.2. Methodological Frameworks

Tiered Assessment Approaches

Modern site-specific environmental risk assessment methodologies generally follow a tiered, iterative paradigm designed to balance scientific rigor with resource efficiency [16]. Tiered assessment frameworks provide a structured way to go from conservative screening-level evaluations to more detailed, data-intensive definitive assessments [1,16]. The basic ECOSRISK framework that Suter et al. [5] established has three levels: scoping, screening, and definitive assessments. This helps identify contaminants and site areas that need more study. Definitive assessments use site-specific toxicity data, improved exposure models, probabilistic methods, and multiple lines of evidence to characterize risks with reduced uncertainty [5].

The tiered framework incorporates several key decision points that determine whether progression to more detailed assessment tiers is warranted. If a site passes a screening-level evaluation (i.e., all exposure levels are below conservative benchmarks), it usually does not need any more ecological assessment. If a site exceeds screening benchmarks, it moves on to definitive assessment or interim remedial actions [5,17]. This decision-making structure enables efficient allocation of assessment resources while maintaining protective standards for ecological receptors.

Jensen et al. [1] expanded the tiered concept by integrating decision support for site-specific investigations. They stressed that ecological risk assessment is a process that happens over and over again and that assessment strategies need to be flexible enough to change when new data comes in.

International applications of tiered frameworks demonstrate both consistency in core principles and variations in implementation details. For instance, the Italian environmental risk assessment guideline developed by Bizzotto et al. [7] adapts the tiered approach to the European regulatory context, incorporating EU directives on environmental quality standards while maintaining flexibility for site-specific conditions.

Probabilistic and Deterministic Methods

The choice between probabilistic and deterministic assessment methods represents a fundamental methodological decision with significant implications for risk characterization, uncertainty representation, and regulatory acceptance [10]. Deterministic methods use point estimates for exposure parameters and toxicity benchmarks, resulting in single-value risk estimates that are easy to compare to regulatory criteria [5]. Probabilistic methods, on the other hand, treat input parameters as distributions instead of point values—they spread uncertainty through exposure and effects models to come up with risk estimates that are shown as probability distributions [10,18].

Thongsri's comprehensive analysis of uncertainty in ecological risk assessment modelling [10] demonstrates the application of Monte Carlo simulations to characterize both parameter uncertainty and natural variability in exposure estimates. The study used probabilistic methods and treated all model parameters as uncertain and ran sensitivity analyses to find the parameters that had the biggest effect on output variance. This approach enables quantification of confidence intervals around risk estimates and identification of data gaps where additional site characterization would most effectively reduce uncertainty. MacIntosh et al. [18] were the first to use stochastic food web models to assess contaminated sites. They made a distinction between knowledge uncertainty (which shows that parameter knowledge is not perfect) and stochastic uncertainty (which shows that organisms naturally vary from one another). Their models for the bioaccumulation of PCBs and mercury in the food webs of mink and great blue herons showed that using probabilities gives more accurate estimates of exposure distributions and lets you figure out how likely it is that individual organisms will exceed toxicity thresholds. Validation using field monitoring data demonstrated that probabilistic models produce accurate estimates of both central tendency and variance in receptor body burdens [18].

The advantages of probabilistic methods include explicit representation of uncertainty, ability to estimate the probability of exceeding effect thresholds, identification of sensitive parameters, and improved communication of risk to decision makers [10,18]. However, regulatory frameworks in numerous jurisdictions continue to focus on deterministic risk estimates, which may hinder the acceptance of probabilistic results [11].

A practical middle ground is to use both deterministic screening and probabilistic definitive assessment. A tiered probabilistic method that uses conservative deterministic screening methods, while definitive assessments use probabilistic methods, makes the best use of resources [5,10].

Decision Support Systems and Software Tools

The complexity of SSRA has led to the creation of specialized decision support systems (DSS) and software tools that combine exposure modelling, effects assessment, uncertainty analysis, and risk characterization into one computational framework. These tools enhance assessment consistency, facilitate sensitivity analysis, and enable the evaluation of alternative remediation scenarios [19,20].

The DSS-ERAMANIA system created by Semenzin et al. [19] is a complete platform for assessing the ecological risk of contaminated sites on a site-by-site basis. This system supports both screening and definitive assessments, takes into account multiple exposure routes, and generates outputs that are ready for regulatory reporting. RESRAD-ECORISK [21] is a widely used software program that was developed to determine the ecological risks at places that are polluted with chemical and radionuclide contaminants. The code implements standardized exposure models for land and water receptors, incorporates the decay of radionuclides and the growth of their progeny, and allows for probabilistic analysis through Monte Carlo simulation. Linkov et al. [20] improved spatially

explicit exposure assessment with the Risk-Trace software, which incorporates habitat characterization and spatial variability in contaminant distribution, receptor home ranges, and patterns of habitat use. This method takes into account that ecological receptors gather in preferred habitats, where they may be exposed to levels of contamination that are very different from the average levels across the site. The FRAMES-3MRA platform developed by Babendreier and Castleton [22] provides integrated tools for uncertainty and sensitivity analyses in multimedia environmental models. The system supports multiple uncertainty analysis methods, including Monte Carlo simulations, Latin hypercube sampling, and differential sensitivity analyses, making it possible to fully evaluate both parameter and model uncertainty.

These tools improve the efficiency, transparency, and reproducibility of SSRA by facilitating scenario analysis, uncertainty evaluation, spatial visualization, and the integration of multiple lines of evidence into a singular assessment framework. However, their utility and reliability depend on the quality of input data, model assumptions, and appropriate user expertise, highlighting the need for rigorous validation and transparent documentation of their application [23,24].

Despite advances in DSS tools, several limitations persist. Many tools necessitate considerable technical proficiency for parameterization and interpretation, which may restrict accessibility [19]. Validation of model predictions against independent field data is still not possible for many tools [22], and most tools focus on chemical exposure pathways and may inadequately address habitat alteration, physical disturbance, or other non-chemical stressors relevant to contaminated sites [5].

Integrated Assessment Frameworks

Recent improvements highlight the need to combine different assessment methods, data sources, and endpoints in order to get a complete and more reliable picture of risk. Integrated frameworks try to get around problems with single assessment methods by putting together different types of evidence and looking at how human health and ecological endpoints affect each other [25]. Carriger et al. [26] developed conceptual Bayesian networks for assessing the ecological risk of contaminated sites. This approach provides a probabilistic framework that combines data from different sources, expert judgment, and the ability to make decisions that can change based on new information, making it easier to combine different types of data, such as chemical measurements, toxicity data, biological surveys, and habitat assessments, into one probabilistic framework [26]. The Aggregate Exposure Pathway (AEP) and Adverse Outcome Pathway (AOP) frameworks [27] are developed on a new concept of source-to-outcome relationships in environmental risk assessment. The integrated AEP-AOP approach provides mechanistic linkages between external exposure and adverse effects, enhances transparency regarding assumptions and uncertainties, and facilitates integration of human health and ecological endpoints. The TRIAD method, which combines chemical analysis, bioassays, and ecological surveys, is another integrated framework that is becoming popular around the world [28]. An et al. [29] conducted a comprehensive analysis and validation of the modified TRIAD approach in soil ecological risk assessment, demonstrating that integration of multiple lines of evidence provides more robust risk characterization than reliance on chemical analysis alone.

A general overview of methodological approaches (Table 3) summarizes the main assessment frameworks in representative studies and highlights advantages and limitations.

Table 3. The overview of methodological approaches.

Methodological Framework	Core Approach	Advantages	Limitations
Tiered risk assessment	Progresses from conservative screening to increasingly site-specific quantitative assessment.	Efficient; Avoids detailed modeling for low-risk sites; Widely accepted by regulators.	Early tiers may be overly conservative; Higher tiers require extensive data and expert judgement.
Deterministic quantitative risk assessment	Uses point estimates for exposure, toxicity, and risk.	Clear, reproducible, regulator-friendly; Suitable for screening and compliance comparison.	Poor representation of variability and uncertainty; Can create misleading precision.
Probabilistic risk assessment	Uses distributions and simulations to characterize uncertainty and variability.	Good for complex sites with heterogeneous contamination and variable exposure; Supports sensitivity analysis.	Data-intensive; Outputs are harder to communicate to regulators and stakeholders.
Ecological risk assessment framework	Evaluates exposure and effects for ecological receptors using endpoints, toxicity data, field evidence, and risk characterization.	Captures non-human receptors and ecosystem protection goals; Compatible with Superfund ecological risk assessment.	Endpoint selection, extrapolation from lab toxicity data, mixture effects, and ecological interactions are major uncertainties.
Weight-of-Evidence framework	Integrates chemistry, toxicity, ecological surveys, modelling, and field observations.	Particularly useful where individual lines of evidence conflict or are incomplete; Supports transparent expert judgement.	Weighting can be subjective; Reproducibility depends on explicit scoring and documentation.
Integrated framework/ TRIAD approach	Combines site chemistry, toxicity testing, and ecological or biological field data.	Good for complex ecological assessments and contaminated soils; Reduces reliance on chemistry alone.	More costly and time-consuming; Interpretation can be difficult where stressors are multiple or confounded.

For complex contaminated sites, the most suitable approach is not a single framework but an integrated methodology built around a robust CSM, a tiered SSRA structure, and multiple lines of evidence. For heterogeneous sites with mixed contaminants, uncertain groundwater pathways, ecological receptors, or emerging contaminants, a CSM-based tiered SSRA should be combined with fate-and-transport modelling, probabilistic or sensitivity analysis, and WoE evaluation.

3.3. Contaminated Land Assessment Approaches

Site Characterization and Problem Formulation

Effective site-specific risk assessment depends fundamentally on comprehensive site characterization and rigorous problem formulation that establish the spatial scope, temporal frame, contaminants of concern, and ecological values at risk. Problem formulation is the most important first step in SSRA—it sets the endpoints for the assessment, develops conceptual site models, and comes up with risk hypotheses that will help with data collection and analysis later on [5]. It begins with preliminary site characterization to identify contaminant sources, release mechanisms, affected environmental media, and potentially exposed ecological receptors. Suter et al. [5] emphasize the importance of

defining appropriate spatial units for assessment, including source units, watershed units, groundwater units, and terrestrial integrator units. This spatial framework ensures that the assessment boundaries include all the relevant exposure pathways and receptor populations while keeping the assessment scope manageable.

Conceptual site models (CSMs) provide graphical or narrative representations of contaminant sources, release mechanisms, transport pathways, exposure media, and ecological receptors, establishing causal linkages between contamination and potential ecological effects [5,30]. Well-formed CSMs identify complete exposure pathways (source-pathway-receptor links) requiring quantitative evaluation, as well as incomplete pathways that can be disregarded [5]. Carriger et al. [26] demonstrated that Bayesian network representations of CSMs enable probabilistic evaluation of pathway completeness and facilitate adaptive refinement as new data become available.

Endpoint selection in SSRA represents a critical problem formulation decision that determines which ecological entities and their properties will be evaluated in the risk assessment. Suter et al. [5] provide detailed guidance on endpoint selection, underscoring that endpoints must be ecologically pertinent (reflecting valued ecosystem components), vulnerable to contaminant exposure, and suitable for measurement or modelling.

Contaminant Types and Environmental Media

SSRAs address diverse contaminant types, and each type presents its own set of challenges for exposure assessment and effect evaluation. The literature reviewed includes studies on heavy metals including chromium, cadmium, and mercury [9,10]; organic pollutants such as PCBs, DDT, and petroleum hydrocarbons; and radionuclides, including depleted uranium and tritium [10]. Metal contamination presents particular challenges due to complex speciation, variable bioavailability, and strong dependence of toxicity on environmental conditions such as pH, organic matter content, and competing cations [5]. Kooistra et al. [9] investigated spatial variability and uncertainty in cadmium risk assessment in a Dutch river floodplain, illustrating that metal bioavailability significantly differs among soil types, and neglecting this variability may result in considerable over- or underestimation of risks. Their research showed how important it is to look at bioavailability at specific sites instead of just looking at total metal concentrations.

Organic contaminants exhibit diverse environmental behaviors ranging from highly persistent, bioaccumulative compounds (e.g., PCBs, DDT) to readily degradable substances, for instance, petroleum hydrocarbons [5,18,20]. Rundegren's probabilistic assessment of secondary poisoning from DDT [31] demonstrated the importance of food web bioaccumulation modelling for persistent organic pollutants, showing that predatory wildlife may be exposed to levels of these pollutants that are much higher than predicted from environmental concentrations alone.

Environmental media evaluated in site-specific assessments typically include soil, sediment, surface water, groundwater, and air, with media selection driven by contaminant properties, site characteristics, and receptor exposure pathways [5,32]. Soil represents the primary exposure medium for terrestrial receptors, with exposure occurring through direct ingestion, dermal contact, consumption of soil invertebrates, and uptake by plants [5,10]. Surface water and groundwater represent exposure media for aquatic organisms and terrestrial wildlife consuming contaminated water [5].

Spatial and Temporal Considerations

Spatial heterogeneity in contaminant distribution, habitat quality, and receptor populations is a widespread feature of contaminated sites that significantly impacts exposure assessment and risk characterization. Failure to adequately characterize and incorporate

spatial variability can lead to substantial bias in risk estimates and suboptimal remediation decisions [9,33].

Kooistra et al. [9] conducted an in-depth analysis of spatial variability in cadmium contamination and the related ecological risks in a river floodplain, finding that risk estimates fluctuated by over an order of magnitude across the site, influenced by soil characteristics, vegetation type, and prey availability. Their research utilized geostatistical techniques to delineate spatial patterns and assess uncertainty due to insufficient sampling density [5]. Linkov et al. [20] improved spatially explicit exposure assessment by adding habitat characterization and receptor movement patterns to the Risk-Trace software. This spatially explicit modelling approach allows for the assessment of remediation scenarios that focus on high-exposure areas instead of achieving uniform cleanup throughout entire sites.

Temporal considerations in site-specific risk assessment encompass both short-term dynamics (seasonal variation in receptor activity, contaminant mobility, and bioavailability) and long-term trends (contaminant degradation, natural attenuation, and ecological succession) [5]. Powers & Barnes [34] added temporal dynamics into the Amchitka assessment by modelling the decay of radionuclides and their movement over long periods of time. However, most reviewed assessments employ steady-state assumptions that may inadequately represent temporal variability in exposure and effects [5].

Exposure Pathway Analysis

Comprehensive exposure pathway analysis represents the cornerstone of SSRA, quantifying the linkages between contaminant sources and ecological receptor exposure through multiple environmental media and uptake routes. The reviewed literature demonstrates progressive refinement of exposure pathway modelling from simple screening calculations to sophisticated, multi-pathway, probabilistic models [5,10,18].

Suter et al. [5] demonstrated exhaustive treatment of exposure pathways for diverse receptor groups, including aquatic organisms, terrestrial plants, soil invertebrates, and wildlife. For aquatic organisms, exposure pathways include directly taking in water through their gills, eating contaminated food and water, and, for benthic species, being exposed to contaminated sediments. Plants on land mostly get their exposure through their roots taking up nutrients from the soil. Other ways include volatile compounds getting into the leaves and particles settling on the leaves. Wildlife exposure pathways are generally more intricate, encompassing various routes such as incidental soil ingestion, consumption of contaminated food sources (plants, invertebrates, and prey species), ingestion of contaminated water, and inhalation of volatile compounds or contaminated dust [5,10].

Bioaccumulation is a major way that persistent pollutants get into organisms and build up in their tissues and through food webs [35]. MacIntosh et al. [18] used stochastic food web models for PCBs and mercury that show how these chemicals build up in living things at different trophic levels: from primary producers to invertebrates and fish to birds and mammals that eat fish. Their models included bioaccumulation factors, trophic transfer efficiencies, and metabolic elimination rates, which made it possible to guess the tissue concentrations in endpoint species based on the concentrations in the environment [16].

Emerging contaminants

Emerging contaminants are increasingly considered in contaminated land assessment because many were not historically included in site investigations, regulatory monitoring programs, or CSM [36,37]. This group includes per- and polyfluoroalkyl substances (PFASs), microplastics, pharmaceuticals, and other substances, which have received particular attention due to their environmental persistence, mobility, slow degradation, and potential for bioaccumulation, as well as adverse human and ecological health effects [38,39]. Unlike many conventional contaminants, PFASs comprise a diverse group of compounds with

widely varying physicochemical properties, making their environmental behavior difficult to predict using traditional contaminant fate and transport models.

Conventional contaminated land assessment frameworks, which were developed for metals, petroleum hydrocarbons, and chlorinated solvents, are increasingly being adapted to incorporate these contaminants into site conceptual models, monitoring strategies, and risk characterization [38,40]. However, the inclusion of emerging contaminants in SSRA is accompanied by substantial scientific and regulatory uncertainty. Analytical methods continue to evolve, and many contaminants, including numerous PFAS precursors and products, remain difficult to identify and quantify, resulting in incomplete characterization of site contamination [41]. As regulatory frameworks continue to evolve internationally, practitioners are increasingly using adaptive, multiple-lines-of-evidence approaches that integrate high-resolution site characterization, advanced analytical techniques, fate and transport modelling, and uncertainty analysis to support defensible risk management decisions [38,42].

3.4. Ecological Risk Characterization Approaches

Ecological Endpoint Selection

Selection of appropriate ecological endpoints represents a critical decision that determines the scope, focus, and ultimate utility of site-specific risk assessments. Assessment endpoints must balance ecological relevance, policy relevance, and operational feasibility while also covering all ecological values that could be harmed by site contamination [1,5].

Suter et al. set out detailed criteria for choosing endpoints, stressing that they should represent important ecosystem components (species, communities, or ecosystem functions that are important to society or the environment), be vulnerable to exposure to contaminants, and be easy to measure or model [1]. The framework makes a difference between assessment endpoints, which are clear statements of the environmental values that need to be protected, and measurement endpoints, which are measurable responses that are used to judge how well assessment endpoints are protected [1].

Common assessment endpoints for contaminated sites encompass population-level attributes of wildlife species (abundance, productivity, and persistence), community-level characteristics (species richness, diversity, and composition), and ecosystem-level metrics (primary productivity, decomposition rates, and nutrient cycling) [1,14]. The choice of these endpoint types depends on the site's ecological values, the characteristics of the contaminant, and the rules that must be followed [1].

Kooistra et al. chose the little owl as a way to measure cadmium contamination in a Dutch floodplain because the species is a predator, needs floodplain habitats, and there is toxicity data available [5]. Thongsri et al.'s assessments at Army sites [10] looked at a variety of wildlife endpoints, such as black-tailed jackrabbits, mule deer, cactus mice, white-footed mice, white-tailed deer, and cottontail rabbits. These animals belong to different feeding guilds and live in different types of habitats. Soil microbial communities and invertebrate communities are important for the environment but are often not given enough attention when it comes to assessments [29]. These communities play a key role in ecosystem functions, like breaking down dead plants and animals, recycling nutrients, and keeping the soil's structure stable [5]. An et al.'s modified TRIAD approach used soil ecological surveys to look at effects at the community level [29].

Effects Assessment and Toxicity Evaluation

Effects assessment determines the correlation between contaminant exposure and negative impacts on assessment endpoints, thereby establishing the toxicological basis for risk characterization. The reviewed literature demonstrates diverse approaches to effects

assessment, ranging from comparisons against generic toxicity benchmarks to site-specific toxicity testing and biological surveys [5,29,30].

Screening-level effects assessment generally utilizes toxicity reference values (TRVs) obtained from the published literature, regulatory databases, or species sensitivity distributions. Suter et al. [5] offer comprehensive guidance on the selection and application of TRVs, underscoring the necessity of aligning test species, exposure pathways, and effect magnitudes with assessment endpoints. Some common TRVs are no-observed-adverse-effect levels (NOAELs), lowest-observed-adverse-effect levels (LOAELs), and median lethal concentrations (LC50s).

Hlohowskyj et al. [32] did a full ecological risk assessment at J-Field, Aberdeen Proving Ground, using both TRVs from the literature and site-specific toxicity testing. The assessment included tests on the toxicity of water and sediment samples from the site, tests on the toxicity of plants on land using soils from the site, and models of how wildlife would be affected by the contaminants based on their concentrations and the characteristics of the receptors. This multi-tiered approach made it possible to find the most dangerous contaminants and ways people are exposed to them.

Biological surveys evaluate in situ ecological conditions by quantifying community composition, abundance, diversity, and functional metrics [29], with survey data amending direct evidence of ecological impacts under authentic site conditions, encompassing all exposure pathways and stressors [5]. However, analyzing survey data necessitates meticulous evaluation of confounding variables such as natural variability, habitat quality, and non-chemical stressors [5,29].

Bioaccumulation and Food Web Modeling

Bioaccumulation and biomagnification of persistent contaminants via food webs constitute significant exposure routes for predatory wildlife and piscivorous (feeding on fish) species, frequently leading to tissue concentrations several orders of magnitude greater than environmental concentrations. The literature examined illustrates advanced methodologies in food web modelling that incorporate bioaccumulation kinetics, trophic transfer, and population-level exposure distributions [18,31].

MacIntosh et al. [18] created stochastic food web models for PCBs and mercury in the food webs of mink and great blue herons, considering bioaccumulation as a dynamic process affected by uptake rates, assimilation efficiencies, metabolic transformation, and elimination rates. All model parameters were regarded as uncertain, utilizing distributions obtained from literature and site-specific measurements. The models differentiated between knowledge uncertainty and stochastic uncertainty, facilitating the distinct quantification of these sources of uncertainty [18]. Monte Carlo simulation disseminated both types of uncertainty throughout the models, producing probability distributions of tissue concentrations in endpoint species. Validation with field monitoring data showed that the models gave good estimates of both the average and the range of heron egg and nestling tissue concentrations. Rundegren [31] conducted a probabilistic ecological risk assessment of secondary poisoning from DDT, focusing on how it builds up in food webs on land. The evaluation utilized species-specific bioaccumulation factors, dietary compositions, and toxicity thresholds to assess risks to predatory avian and mammalian species. Probabilistic methods allowed for the quantification of the likelihood that specific predators would surpass toxicity thresholds, taking into account variations in prey consumption rates, prey tissue concentrations, and predator body weights.

Bioaccumulation modelling requires careful consideration of factors influencing uptake and retention, including lipid content, metabolic capacity, trophic position, and feeding behavior [18]. Suter et al. [5] offer comprehensive guidance on the selection of bioaccumulation factors, highlighting the necessity of aligning test species with assessment

endpoints and considering the variations in exposure pathways between laboratory and field conditions.

Weight-of-Evidence Approaches

The integration of multiple lines of evidence when chemical, toxicological, and ecological datasets yield conflicting results has been a persistent challenge in SSRA. Weight-of-evidence (WoE) methods combine data from chemical analysis, toxicity testing, and biological surveys to give a more complete and reliable picture of risk than using just one source of data. The TRIAD approach is the most common WoE framework. It combines chemical, toxicological, and ecological data in a systematic way [28,29].

An et al. [29] carried out extensive analysis and validation of the modified TRIAD approach in soil ecological risk assessment at an electroplating site in China. The evaluation incorporated three strands of evidence: (1) chemical analysis of soil contaminants; (2) ecotoxicological testing; and (3) ecological surveys of soil invertebrate communities. Each piece of evidence was looked at and scored on its own, and then they were all put together in a structured decision framework to sort site areas by risk level [29]. The modified TRIAD approach had a number of benefits over assessments that only used one line of evidence. Chemical data alone may overstate risks when contaminants are in forms that are not bioavailable, or they may understate risks when interactions between different chemicals or contaminants that are not measured add to toxicity [28]. Toxicity tests provide direct evidence of biological effects but may not reflect long-term population or community responses [29]. Ecological surveys assess actual in situ conditions but may be confounded by natural variability or non-chemical stressors. The integration of all three lines of evidence provides more reliable risk characterization and greater confidence in decision-making [28,29].

Suter et al. delineate a thorough weight-of-evidence framework for risk characterization that surpasses the TRIAD approach by integrating supplementary data sources such as biomarkers, tissue residues, and mechanistic toxicity data [5]. The framework stresses the need for a systematic assessment of the quality, relevance, and consistency of data across different lines of evidence, with a clear focus on the agreement and disagreement between data sources.

Although WoE frameworks provide a structured approach for integrating various types of evidence, their application often relies on expert judgement, and there remains no universally accepted methodology for resolving conflicting evidence [29]. Thus, improving objectivity, transparency, and standardization of evidence integration remains an important priority for future SSRA research.

Limitations of Ecological Risk Characterization Approaches

Naturally, the reviewed approaches, however well-established, have certain limitations for their applicability. We see these limitations as useful contributions to the consideration of uncertainty in ecological risk characterization rather than as methodological flaws of these approaches.

One fundamental limitation is the selection of appropriate assessment endpoints, which are often chosen based on data availability or regulatory requirements rather than ecological relevance. This may result in inadequate representation of ecosystem structure and function. The emphasis is frequently placed on a limited number of surrogate species or taxonomic groups, while indirect effects, ecological interactions, and ecosystem services receive less attention. This often leads to either too conservative or underestimated ecological risk scores [28,43].

Effects assessment approach is constrained by the limited availability and applicability of ecotoxicological data—it utilizes toxicity reference values, commonly derived from

standardized laboratory studies, which may not adequately reflect field conditions or the sensitivity levels of local communities [27]. Contaminated sites frequently contain complex mixtures of chemicals, whereas toxicity assessments typically rely on single-compound data, thus excluding additive, synergistic, or antagonistic interactions and increasing uncertainty in ecological risk estimates [3,44].

Substantial data requirements and simplifying assumptions are also limiting for bioaccumulation and food web models. Accurate estimates of contaminant bioavailability, species-specific uptake and elimination rates, and trophic interactions are highly site-dependent. In soil and groundwater assessments, spatial heterogeneity, seasonal variation, and multiple exposure pathways further complicate model parameterization and validation, thus potentially reducing confidence in modeled risk scores for higher trophic levels [44,45].

Last but not least, the implementation of Weight-of-Evidence (WoE) approaches is limited by the lack of standardized frameworks for selecting, weighting, and integrating diverse data sources. Thus, expert judgment often plays a prominent role in assigning relative importance to different evidence sources, introducing subjectivity and limiting assessment reproducibility [28,46].

3.5. Case Studies and Applications

The literature reviewed contains numerous case studies that show how SSRA frameworks can be used on different contaminated sites, providing useful information about the problems that come up in practice, the data that is needed, and the decisions that are made. These case studies encompass military installations, industrial sites, mining regions, and Superfund sites [9,32,47,48].

Hlohowskyj et al. [32] conducted a comprehensive ecological risk assessment at J-Field, Aberdeen Proving Ground, Maryland, a former military testing ground that is now polluted with explosives, metals, and organic compounds. The assessment used a tiered approach that started with a screening-level evaluation against ecological benchmarks and ended with a definitive assessment that included site-specific toxicity testing, modelling of wildlife exposure, and biological surveys. The study found that white phosphorus in surface soil was the main cause of ecological risk. Kooistra et al. [9] evaluated spatial variability and uncertainty in cadmium risk assessment for little owls in a Dutch river floodplain contaminated by historical metal smelting operations. The evaluation included geostatistical analyses of soil cadmium levels, bioavailability modelling that took into account soil properties, and spatially explicit exposure modelling that included owl home ranges and prey distributions. The results demonstrated that risk estimates varied by more than an order of magnitude across the site, with highest risks in areas combining elevated cadmium concentrations with high prey availability. Powers et al. [47] developed a detailed science plan for carrying out an independent ecological risk assessment at Amchitka Island, Alaska, where three underground nuclear tests were conducted in the 1960s and 1970s. The assessment addressed potential exposure of marine and terrestrial receptors to radionuclides, including tritium, cesium-137, and plutonium isotopes. The assessment used a phased approach, starting with screening calculations and then going into more detail about the site and modelling for pathways that went beyond the screening criteria. Niemeyer [48] evaluated ecological risks at Santo Amaro, Bahia, Brazil, a tropical metal-contaminated area with lead smelting contamination. The evaluation confronted distinctive challenges of tropical ecosystems, such as elevated biodiversity, insufficient toxicity data for tropical species, and intricate exposure pathways in humid conditions. The study demonstrated the need for region-specific assessment approaches that account

for climatic, ecological, and socioeconomic differences from temperate regions where most assessment methods were developed.

3.6. Regulatory Context and International Perspectives

Ecological risk assessment for contaminated sites operates within diverse regulatory frameworks that vary substantially across jurisdictions in their legal requirements, technical guidance, and implementation approaches. The reviewed literature provides insights into regulatory contexts in the United States, Europe, and other regions. It shows that there are some similarities in the main ideas but also some major differences in how they are put into practice [1,5,7].

In the United States, ecological risk assessment for contaminated sites is required by several regulatory bodies, such as the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA/Superfund), the Resource Conservation and Recovery Act (RCRA), and state-level programs [5]. The U.S. EPA's ecological risk assessment framework, which is spelled out in basic guidance documents, sets the standard for how to do things: problem formulation, exposure assessment, effects assessment, and risk characterization. Suter et al.'s thorough analysis mirrors and expands upon this regulatory framework, offering extensive technical guidance for execution [5].

European regulatory approaches to contaminated site assessment differ in several respects from U.S. frameworks, reflecting different legal structures, environmental priorities, and stakeholder engagement processes. Bizzotto et al. [7] note that Europe lacks a common framework for ecological risk assessment at contaminated sites, with substantial variation among member states in legal requirements and technical approaches. The Italian ERA guideline they developed seeks to address this gap by providing a flexible but robust framework aligned with EU environmental directives while adapted to the Italian regulatory context [7]. Rutgers and Jensen [49] describe SSRA methods used in the Netherlands, focusing on how they can be combined with frameworks for assessing soil quality and ecosystem services. The Dutch method puts more weight on assessing microbial communities and the ecological function of soil than most U.S. assessments do [49]. Jensen et al.'s [1] framework for assessing the ecological risks of contaminated land in Denmark focuses on helping people make decisions about site-specific investigations and combining these with land use planning. The method makes it clear how assessment levels are connected to regulatory decision points and cleanup needs.

Ongoing international harmonization efforts seek to promote consistency in ecological risk assessment approaches while respecting regional differences in ecological conditions, regulatory structures, and societal values [7].

3.7. Uncertainty Analysis in Ecological Risk Assessment

Uncertainty is an inherent component of SSRA, arising from limitations in site characterization, variability in environmental conditions, conceptual model assumptions, exposure parameters, and toxicity data. Across various SSRA approaches, uncertainty is typically quantified using either deterministic approaches, which apply conservative assumptions and assessment factors, or probabilistic methods, such as Monte Carlo simulation, Bayesian inference, and sensitivity analysis, which explicitly characterize variability and parameter uncertainty [26,50]. For risk-based decision-making that can be defended and for correctly interpreting assessment results [9–11,22], it is important to carefully define and communicate uncertainty. The reviewed literature identified various types and sources of uncertainty in ecological risk assessment. Parameter uncertainty happens when we do not know the exact values of input parameters like contaminant concentrations, exposure factors, and toxicity thresholds [9,10,18]. Model uncertainty signifies constraints in the

mathematical representations of exposure processes, bioaccumulation kinetics, and dose–response relationships [5]. Model uncertainty is more difficult to quantify than parameter uncertainty and typically requires comparisons of alternative models or expert elicitation. Measurement uncertainty is caused by problems with analysis, sampling errors, and quality control and assurance. While typically smaller than other uncertainty sources, it can be significant for contaminants near detection limits or in complex matrices [5]. However, few studies evaluate how uncertainties accumulate across multiple tiers of the assessment, from source characterization to exposure modelling and risk characterization.

Spatial variability is a significant source of uncertainty in contaminated site assessments, stemming from heterogeneous contaminant distribution, variable soil characteristics, and uneven habitat distribution [9,33]. Kooistra et al. [9] showed that differences in the availability of cadmium and prey in different parts of a floodplain site have led to risk estimates that were more than an order of magnitude different from each other.

Temporal variability adds more uncertainty because receptor activity, contaminant mobility, and environmental conditions change with the seasons [5]. Most assessments use steady-state assumptions that might not accurately show how things change over time.

Quantitative methods for uncertainty analysis facilitate the precise delineation of uncertainty in risk assessments and the identification of parameters that significantly influence output variability. Monte Carlo simulation is the most commonly used quantitative method for estimating ecological risk [9,10,18,22].

Thongsri [10] used Monte Carlo simulation with 10,000 iterations to carry out a full uncertainty analysis in ecological risk assessment modelling at army-contaminated sites. The analysis generated probability distributions of hazard quotients for multiple receptor species, enabling the estimation of the probability that risks exceed regulatory thresholds.

MacIntosh et al. enhanced probabilistic methodologies by distinctly addressing knowledge uncertainty and stochastic uncertainty within food web models. Knowledge uncertainty was illustrated through probability distributions that indicate imperfect parameter knowledge, whereas stochastic uncertainty was depicted by distributions that represent natural variability among individual organisms [18]. Babendreier & Castleton [22] created a full set of tools for uncertainty and sensitivity analysis in the FRAMES-3MRA platform. These tools support a number of methods, such as Monte Carlo simulation, Latin hypercube sampling, and differential sensitivity analysis. Bayesian methods offer a distinct probabilistic framework that systematically integrates prior knowledge, adjusts probability distributions with the emergence of new data, and facilitates the amalgamation of varied data sources [25,26]. Carriger et al. [26] illustrated the utilization of Bayesian networks in contaminated site risk assessment, demonstrating that this methodology enables adaptive decision-making amidst uncertainty and the explicit integration of expert opinion. However, despite their considerable flexibility and ability to integrate heterogeneous data sources, Bayesian model performance depends strongly on the availability, quality, and representativeness of input data [51]. For instance, sparse datasets often require parameterization through expert judgement, potentially introducing subjective bias [52].

Sensitivity analysis identifies parameters that most strongly influence risk estimates, providing critical information for prioritizing data collection, evaluating model assumptions, and interpreting assessment results. The literature reviewed shows a wide range of sensitivity analysis methods, from simple ones that change one parameter at a time to more advanced global sensitivity methods [10,22].

Thongsri's uncertainty analysis utilized sensitivity analysis to determine the parameters that significantly influence the variability in hazard quotients for terrestrial wildlife [10]. The analysis showed that the concentrations of contaminants in soil, bioaccumulation factors, and food ingestion rates were the main sources of output variance. These findings led

to suggestions for more site characterization and toxicity testing to make high-influence parameters less uncertain. Babendreier & Castleton [22] implemented multiple sensitivity analysis methods in FRAMES-3MRA, including differential sensitivity analysis (evaluating the rate of change in outputs with respect to inputs), correlation analysis (quantifying associations between input and output distributions), and contribution to variance analysis (partitioning output variance among input parameters). A comparison of methods revealed that different approaches may identify different parameters as most influential, emphasizing the importance of employing multiple sensitivity analysis techniques. Methods for global sensitivity analysis, like Sobol indices and extended FAST (Fourier Amplitude Sensitivity Test), take a lot of computer power, but they give a better picture of how important each parameter is than local sensitivity methods [22].

Generally, deterministic assessments propagate uncertainty implicitly through conservative input assumptions, whereas probabilistic approaches quantify how uncertainties in multiple input parameters influence model outputs and risk estimates [9,53].

Effective **communication of uncertainty to risk managers** and stakeholders represents a critical but often inadequately addressed aspect of SSRA. The reviewed literature emphasizes that uncertainty communication must balance technical rigor with accessibility, providing decision-makers with sufficient information to make informed choices while avoiding overwhelming complexity [5,10]. Although many guidelines recommend transparent reporting of assumptions, data limitations, and confidence in risk estimates, uncertainty is often presented qualitatively or embedded within conservative assessment factors, which makes it difficult for decision-makers to distinguish between uncertainty arising from data limitations and natural environmental variability [10,11].

Suter et al. underscore the necessity of distinctly differentiating between point estimates, confidence intervals, and probability distributions. For deterministic evaluations, uncertainty must be conveyed via sensitivity analysis that illustrates the variation in risk estimates with different parameter values. For probabilistic evaluations, outcomes must be displayed as probability distributions, accompanied by a lucid explanation of the significance of the distributions [5]. Norrman's review on decision analysis in the context of risk and uncertainty at contaminated sites underscores the necessity of integrating uncertainty characterization with decision-making processes [11]. The review identifies decision-analytic methods that explicitly incorporate uncertainty into remediation decisions, enabling evaluation of alternative actions under uncertainty and identification of decisions that are robust across plausible parameter ranges. Graphical presentations of uncertainty through probability distributions, confidence intervals, and sensitivity plots enhance the comprehension of non-technical audiences [10]. Kooistra et al. employed spatial maps showing the probability of risk exceedance across the study area, enabling visual identification of high-risk zones and communication of spatial uncertainty [9]. The Italian ERA guideline developed by Bizzotto et al. [7] emphasizes the need for templates, checklists, and standard reporting formats to make it easier for everyone to communicate uncertainty across assessments.

4. Narrative Synthesis and Discussion

4.1. Narrative Synthesis

The studies included in this review were synthesized by taking into account the methodological heterogeneity of domains of environmental site-specific risk assessment (SSRA) frameworks, contaminated land assessment tools, and ecological risk characterization approaches. This synthesis is focused on identifying recurring conceptual structures, methodological approaches, and divergences across the regulatory, scientific, and applied case-study literature.

Overall, our narrative synthesis indicated that, while SSRA methodologies share a **common conceptual foundation** [2,16], the **implementation varies** widely across regions, contaminants, and ecological contexts. Historically, risk assessments relied on soil quality standards and generic guidelines, often failing to account for local variability and complex exposure scenarios [54]. The field is moving toward more holistic, data-rich, and model-supported approaches [55,56]; however, practical constraints, regulatory traditions, and data availability continue to shape the degree of site specificity achieved in real-world applications [57,58].

Across the reviewed studies, three overarching themes can be identified. First, most frameworks adopt a **tiered assessment** structure, beginning with conservative screening-level evaluations and progressing toward increasingly site-specific analyses. This structure is evident in classical ecological risk assessment frameworks [2,16], in contaminated land management systems—RBCA and CLEA—and in more recent guideline harmonization efforts [59]. The tiered approach consistently strives to balance resource efficiency with the necessity for detailed characterization where risks are uncertain. Second, the synthesis revealed a strong emphasis on **integrating multiple indicators** to address uncertainty and boost ecological relevance. TRIAD-based approaches [60,61] and weight-of-evidence frameworks [20,25] are widely applied in both soil and sediment contexts. These methods combine multiple indicators—chemical, toxicological, and ecological—to support more robust site-specific conclusions. Third, the reviewed literature highlights the increasing use of **bioavailability, spatial heterogeneity, and mechanistic modelling** aspects in SSRA. Advances in soil ecotoxicology [62,63], spatial modelling [9], and Bayesian network models [26,64] indicate a shift toward more ecologically realistic assessments. A case study in the Netherlands [65] demonstrates that the inclusion of site-specific exposure pathways, habitat conditions, and organism traits can substantially alter risk scores compared to generic guideline-based assessments.

By integrating these perspectives, this review provides a comprehensive overview of the current state of SSRA methodology, identifies areas where consensus has not yet been achieved, and outlines opportunities for future methodological development. The synthesis from the reviewed studies highlights several novel insights that transcend the sum of individual methodological contributions:

1. **Methodological Convergence:** Reviewed studies increasingly recognize that probabilistic, spatially explicit, and multi-evidence tools are no longer discrete innovations but are converging into one methodological core. The main implication is that future frameworks should be built around this integration rather than being cobbled together by repurposing newer tools onto older deterministic foundations. A detectable convergence towards a hybrid methodological paradigm is evident: Probabilistic uncertainty quantification, spatially explicit modelling, and multi-evidence integration are no longer isolated innovations but are coalescing into an interconnected methodological core. This convergence indicates that future SSRA frameworks will have to be constructed from scratch around data heterogeneity, model transparency, and iterative decision support instead of adding probabilistic or spatial tools on top of deterministic foundations.

2. **Science–regulation tension** highlights the understudied mismatch between the increasing complexity of methodology and regulatory operability: Increased site specificity does not necessarily translate into better regulatory outcomes where jurisdictions lack harmonized criteria for interpreting probabilistic evidence. The cross-domain synthesis reveals an enduring and underappreciated tension between scientific sophistication and regulatory operability: frameworks that include more site-specificity and model complexity do not necessarily yield clearer or more defensible remediation outcomes, in part because

the criteria for translating probabilistic risk characterizations into binary decisions are harmonized only within—not across—jurisdictions.

3. **CSM primacy** provides an integrative lesson that is not explicitly expressed in any single study. For all types of frameworks and classes of contaminants, it is the quality of the Conceptual Site Model, not the downstream statistical approach, that is the dominant determinant of assessment quality and defensibility. The reviewed case studies collectively demonstrate that the primary determinant of assessment quality and defensibility is the Conceptual Site Model (CSM) and not the statistical or probabilistic method employed downstream. Poor CSM construction consistently propagated the largest errors in risk estimates across various framework types and contaminant classes. These integrative insights have brought the discipline to a critical juncture: technically able to provide high-resolution, defensible assessments but limited by regulatory fragmentation, limited model validation, and the lack of cross-jurisdictional harmonization on core methodological standards.

4.2. Limitations and Constraints

The applicability of assessment frameworks generally depends on the complexity of sites. Modern SSRAs often use tiered assessment approaches like TRIAD [29]. For complex situations, the strongest methodological combination combines CSM with tiered SSRA, bioavailability assessment, and WoE/multiple-lines-of-evidence. This is most appropriate in situations where data are sufficient, receptors are sensitive, and regulatory decisions require defensible remediation targets [59,66].

Critical analyses of literature revealed an interplay between methodological innovation and practical challenges. Probabilistic and spatially explicit SSRA frameworks are advancing the accuracy and transparency of modern risk assessments, but regulatory, technical, and data-related barriers persist [67,68]. Additionally, rapid field techniques and adaptive management strategies offer promising solutions for future improvement [69].

Despite the evolution of SSRA methodologies, relatively little attention has been devoted to unresolved scientific controversies regarding methodological reliability, best practices, and applicability under varying environmental conditions. One such debate relates to the balance between conservative screening-level assumptions and the use of increasingly site-specific data. While greater detail in site description can reduce uncertainty and lead to more realistic exposure estimates, it may also introduce new uncertainties associated with limited datasets, spatial heterogeneity, and the representativeness of local measurements [27,70]. This has led to ongoing disagreement over the extent to which additional site characterization data truly improves the reliability of risk estimates [71].

Another controversy involves the management and communication of uncertainty. Although probabilistic methods, sensitivity analyses, and weight-of-evidence approaches are increasingly advocated [26,54], there is no consensus regarding when these methods should supplement or replace traditional deterministic assessments. Questions also remain on the transferability of conceptual models across sites, the selection of assessment endpoints, and the degree to which standard regulatory frameworks adequately capture cumulative, long-term, and climate-driven environmental changes. These unresolved issues suggest that future SSRA research should focus on developing harmonized guidance that balances scientific rigor with practical considerations [4,72].

4.3. Critical Gaps

Despite substantial advances in methodological frameworks, exposure modelling, and uncertainty analysis, the reviewed literature revealed several critical methodological, scientific, and regulatory gaps and limitations that constrain the effectiveness and defensibility of SSRA.

Most assessment frameworks **concentrate on chemical stressors**, neglecting non-chemical stressors such as habitat modification, physical disruption, invasive species, and climate change [5,73]. Tannenbaum's different way of carrying out an ecological risk assessment stresses how important it is to look at different types of stressors and how they interact. However, methods for quantitatively integrating chemical and non-chemical stressors remain underdeveloped [73]. **Temporal dynamics** including seasonal variability, long-term trends, and ecological succession receive limited attention in most assessments. Steady-state assumptions may inadequately represent sites undergoing natural attenuation, ecological recovery, or changing land use [5]. **Population-level effects assessment** remains challenging due to the limited understanding of relationships between individual-level toxicity and population dynamics [5]. Most evaluations depend on individual-level endpoints (survival, growth, and reproduction) as proxies for population effects; however, extrapolation to the population level necessitates the consideration of density dependence, immigration, and compensatory mechanisms. **Mixture toxicity assessment** methods remain limited, with most assessments assuming concentration addition or response addition without empirical validation. Synergistic or antagonistic interactions may substantially alter risks but are rarely quantified [5]. Also, cumulative effects are rarely examined in full. It is uncommon to **validate exposure models** and risk predictions against independent field data, which makes it hard to trust the accuracy of the models [18,22]. The validation of food web models against monitoring data by MacIntosh et al. [18] is an anomaly rather than a standard practice. The **integration of human health and ecological risk assessment** is still limited, even though it is known that contaminated sites can be dangerous to both. Hines et al.'s [27] application of integrated AEP-AOP frameworks represents an emerging approach, but practical implementation challenges remain. Lastly, it is hard to compare results because assessment **methods are not standardized** across jurisdictions, which could lead to inconsistent levels of protection [7].

Additionally, another key gap is the lack of harmonized criteria for deciding when SSRA evidence is sufficiently reliable to override conservative default assumptions [74]. Regulatory systems often allow SSRA but remain anchored in generic screening values, tiered procedures, and nation- or jurisdiction-specific thresholds [75]. Thus, it is often unclear what counts as "acceptable" site-specific evidence, when bioavailability data may be used, and how uncertainty should affect remediation decisions [76].

4.4. Future Directions and Recommendations

Based on the comprehensive synthesis of current knowledge and identified gaps, several priority directions emerge for advancing the science and practice of site-specific ecological risk assessment:

- **Methodological Advances:** Future research should focus on creating and testing integrated assessment frameworks that bring together chemical analysis, toxicity testing, biological surveys, and ecosystem function assessment into a single decision-making framework [30]. Bayesian network methods are very promising for bringing together different data sources and helping people make decisions that change over time [25,26].
- **The Development of Standardized and Transparent Methodologies** for Integrating Multiple Lines of Evidence Within SSRA: Objective frameworks that reduce assessor subjectivity and improve the reproducibility and comparability of risk assessments across different sites and regulatory jurisdictions are still needed [5].
- **Uncertainty Quantification:** It is important to keep improving probabilistic methods and tools for analyzing uncertainty. This includes being able to tell the difference between reducible and irreducible uncertainty, doing thorough sensitivity analyses,

and finding better ways to explain uncertainty to decision-makers [10,18,22]. Two-dimensional Monte Carlo methods that independently disseminate knowledge and stochastic uncertainty ought to be established as standard procedures for conclusive evaluations [18].

- **Spatial and Temporal Considerations:** The development of spatially explicit assessment frameworks that account for heterogeneous contamination, habitat distribution, and receptor movement patterns represents a priority area [9,20]. Adding temporal dynamics like seasonal changes, the breakdown of pollutants, and the natural progression of ecosystems would make things more realistic and help compare natural attenuation and monitored natural recovery options [5].
- **Emerging Contaminants and Stressors:** Assessment frameworks must evolve to address emerging contaminants including per- and polyfluoroalkyl substances (PFASs), microplastics, and pharmaceuticals, as well as non-chemical stressors including climate change, habitat fragmentation, and invasive species [37,73]. The creation of effect-based assessment methodologies and adverse outcome pathway frameworks could enhance the evaluation of contaminants with insufficient toxicity data [27].
- **Model Validation:** Systematic validation of exposure models, bioaccumulation models, and risk predictions against independent field data should become standard practice [27]. Long-term monitoring programs at assessed sites would provide valuable validation datasets and enable adaptive refinement of assessment methods [5].
- **International Harmonization:** It would be easier to share knowledge and make things more consistent if people worked together to make sure that assessment frameworks were the same in all places, while still taking into account the differences in ecological conditions and rules in each area. Creating international guidelines, databases of case studies, and technical training programs could help with efforts to make things more consistent [7].
- **Decision Support Tools:** To make site-specific assessments easier to access and more consistent, user-friendly decision support systems that combine exposure modelling, effects assessment, uncertainty analysis, and remediation evaluation should continue to be developed [19]. Tools should have clear documentation, the ability to do sensitivity analysis, and output formats that can be used by a wide range of stakeholders [22].
- **Stakeholder Engagement:** Better ways to involve stakeholders and talk about risks would make ecological risk assessments more socially acceptable and useful in real life. Creating visualization tools, interactive platforms, and summaries in plain language could make it easier for stakeholders to take part in assessment and decision-making processes in a meaningful way [7]. Future research should focus on strengthening the **interface between science and regulation**. Greater international harmonization of SSRA guidance would improve consistency in methodological expectations, particularly regarding the use of site-specific data, bioavailability corrections, and weight-of-evidence approaches [36].

5. Conclusions

Unlike previous reviews and guidance documents, which primarily describe established SSRA methodologies or provide practical recommendations, this review synthesizes recent methodological developments across multiple assessment approaches within a single narrative thread. In addition, it critically examines current methodological trends, identifies unresolved scientific and regulatory challenges, discusses limitations associated with analyzed approaches, and highlights emerging research priorities. By integrating these perspectives, our review provides readers with a comprehensive overview of the

current state of SSRA methodology; identifies methodological, scientific, and regulatory gaps; and outlines opportunities for future development.

The synthesis of these 33 studies yields overarching conclusions that go further than what any one study could establish.

First, SSRA is undergoing an **epistemological shift** by framing the move to probabilistic assessment not as a technical upgrade but as a deeper change in how the field conceptualizes uncertainty itself. The field is moving away from deterministic certainty-seeking toward probabilistic risk characterization that recognizes irreducible uncertainty as an inherent and explicitly communicable feature of ecological systems rather than a methodological deficiency to be minimized.

Second, the integrated evidence base suggests **an important practical lesson for risk assessment practitioners**: CSM quality and tiered assessment design are the dominant determinants of assessment robustness and regulatory defensibility, outweighing the marginal gains derived from the application of more sophisticated statistical tools at later stages of the assessment.

Third, the literature we review collectively suggests that **regulatory harmonization is the binding constraint** on field-wide progress: Scientific methods are converging across jurisdictions, but their translation into remediation decisions is still governed by jurisdiction-specific frameworks that were not designed to embed probabilistic, spatially explicit, or multi-stressor evidence. Internationally harmonized SSRA guidance, especially with respect to the acceptable use of site-specific data, bioavailability corrections, and weight-of-evidence approaches, would fill this gap and be the single highest-leverage advance for both the science and practice of contaminated land risk assessment. The incorporation of sophisticated tools such as Monte Carlo simulations, Bayesian networks, and AI-driven models is still underway to enhance the quantification of uncertainty and decision support. However, advancements in model validation, stakeholder communication, and regulatory acceptance are needed to realize their full potential.

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primary discussion. The AI tool QuillBot <https://quillbot.com/> (accessed on 19 March 2026) was used for proofreading the original texts written by the authors. Proofreading involved correcting grammar and syntax and improving fluency. AI was not used elsewhere or otherwise, as stated here. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

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Abbreviations

The following abbreviations are used in this manuscript:

EPA	U.S. Environmental Protection Agency
ERA	Environmental Risk Assessment
CSM	Conceptual Site Model
DSS	Decision Support System
PFAS	Per- and Polyfluoroalkyl Substance
SSRA	Site-Specific Risk Assessment
WOE	Weight of Evidence
WoSCC	Web of Science Core Collection

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