A SYSTEMATIC REVIEW OF RISK ASSESSMENT TOOLS FOR CONTAMINATED SITES – Current Perspectives and Future Prospects

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Abstract

Health hazards associated with the redevelopment of contaminated sites can be complex and pose considerable risks. A systematic literature review was conducted on risk assessment tools for contaminated sites. These tools have been identified from searching through leading academic databases and other professional sources. For each of the identified tools the relevant risk assessment stages, harm type, hazard category, receptor type and pathways are reported. Findings reveal that despite growing interest in the development of risk assessment tools, there are persistent knowledge gaps identified in this study, which serve as a basis for future research direction to where more advanced practical tools could be invented. For instance, it is evidenced there is a shortfall in practical tools available to contaminated site assessors conducting investigations at the preliminary risk assessment stage. Addressing this opening can benefit the planning process, coordinated between relevant stakeholders and, moreover, reduce uncertainty in the decision-making of contaminated site developers.

Keywords: *Risk Assessment Tools; Health hazards; Contaminated Sites; Decision Making*

1 Introduction

1.1 Background

Redevelopment of contaminated sites can raise concerns for the health and safety of building site workers and subsequent building users (Environmental Agency, 2008). Injuries, loss of life, civil penalties, financial losses and collateral damage can be issues. For instance, the documentary Toxic Town: The Corby Poisonings (Kennedy, 2020) narrates the story of a landmark legal battle by a group of women aiming to uncover the truth about birth defects in the Northamptonshire town being caused by toxic waste from the steelworks that had not been disposed of safely. They alleged that they ingested or inhaled the toxic substances that affected the development of their embryos limbs while they were still in the womb. In addition, the concentration of cadmium in the livestock organs exceeding the acceptable limits has been observed due to the presence of lead and cadmium from a previous mining site in Morocco (Nouri and Haddioui, 2015). Likewise, in China, cadmium from a zinc smelter contaminated leaf and root vegetables particularly (Li *et al.*, 2016). Furthermore, in 2009, a gas explosion during redevelopment of contaminated land on the site of a former hospital in south Manchester destroyed dozens of homes. Ultimately, leading to a fine of £100,000 (plus £21,404 costs) served on a property developer (BBC, 2012). Similarly, in 1986, a house built over a former landfill site in Derbyshire was completely destroyed by a methane gas explosion, badly injuring three occupants (Williams and Aitkenhead, 1991).

The UK Government introduced new legislation in April 2000 (Part 2A of the Environmental Protection Act 1990) to identify the potential pathways and unacceptable risk that could reasonably exist to receptors including human health, or ecological system (Environmental Agency, 2008; Swartjes, 2015; Locatelli *et al.*, 2019; Burger *et al.*, 2019). For example, soil contaminated by heavy metals has a major effect on human health. This is evidenced by several studies, which illustrated the hazards of the soil contamination to human health (Duruibe, Ogwuegbu and Egwurugwu, 2007; Ljung *et al.*, 2007; Augustsson *et al.*, 2015). In addition, Charles *et al.* (2002) discussed that all buildings and constructed facilities come into contact with the unforeseen ground related problems often lead to increase in cost and delays. Moreover, issues related to ground may appear after many years of completion of construction. This aforesaid problem has increased significantly in many parts of the country where most new housing developments take place on land where previous usage have left a wide range of hazards which categorised into physical, chemical and biological hazards (Charles and Skinner, 2004; Skinner, Charles and Tedd, 2005). The potential harms that could come from the hazards would have already been identified in contaminated sites are classified by Butt *et al.* (2016) into toxic (i.e. carcinogenic) and non-toxic (i.e. fire, injuries explosion).

1.2 Problem statement

Risk assessment can progress with the level of complexity as required from preliminary risk assessment (PRA) to generic quantitative risk assessment (GQRS) then detailed quantitative risk assessment (DQRS) (Environmental Agency, 2008). The preliminary risk assessment (PRA) is to develop an initial conceptual model of the site and establish whether or not there are potentially unacceptable risks in relation to the previous history of the site or adjacent areas. If the unacceptable risk(s) is not eliminated, a generic detailed risk assessment (GQRA) is then considered to gather more information about the site and may include a staged intrusive site investigation. If more investigations are needed to assess the risk, a detailed quantitative risk assessment (DQRA) is considered, typically, involves the use of modelling software to estimate the movement of contaminants in the media (e.g. groundwater and plants) and detailed exposure features of the receptor (e.g. human health) (Locatelli *et al.*, 2019). For these three levels, several tools have been developed in order to establish conceptual site model covering sources, pathways and receptors. The absence of state-of-the-art of the existing risk assessment tools rises concerns to where further investigation is required for future research. Therefore, there is a need for an inclusive analysis of the approaches adopted for each level of risk assessment of contaminated sites, which will help to identify and highlight the areas that require further investigation.

1.3 Aims and objectives

This study aims to systematically appraise existing risk assessment tools for contaminated sites, with regard to the degree of comprehensiveness from low to high (preliminary risk assessment, generic quantitative risk assessment and detailed quantitative risk assessment). Furthermore, the review also encapsulates these curcial factors of risk assessment: harm types, hazards category, receptors nature and varying pathways. Thereby, pave a path for further research, based on the identified knowledge gaps. This aim is achieved by the following key objectives:

- To establish the state-of-the-art of existing risk assessment tools of contaminated sites.
- To define knowledge gaps in the current approaches particulary regarding preliminary risk assessemment

- To formulate recommmendations on how the knowledge gaps could be bridged to develop more appropriate prelimianry risk assessment tools

1.4 Scope of the Study

- In this review, risk assessment tools can be any software, methods or numerical analysis models used to qualify or quantify the risk posed from contaminated sites.
- This paper covers human heath, groundwater and buildings as receptors. Wherease the other components of the environment such as air/ atmosphere, contaminated vegetables or animals/ biotecs are excluded.

The scope of this paper is presented in Figure 1.

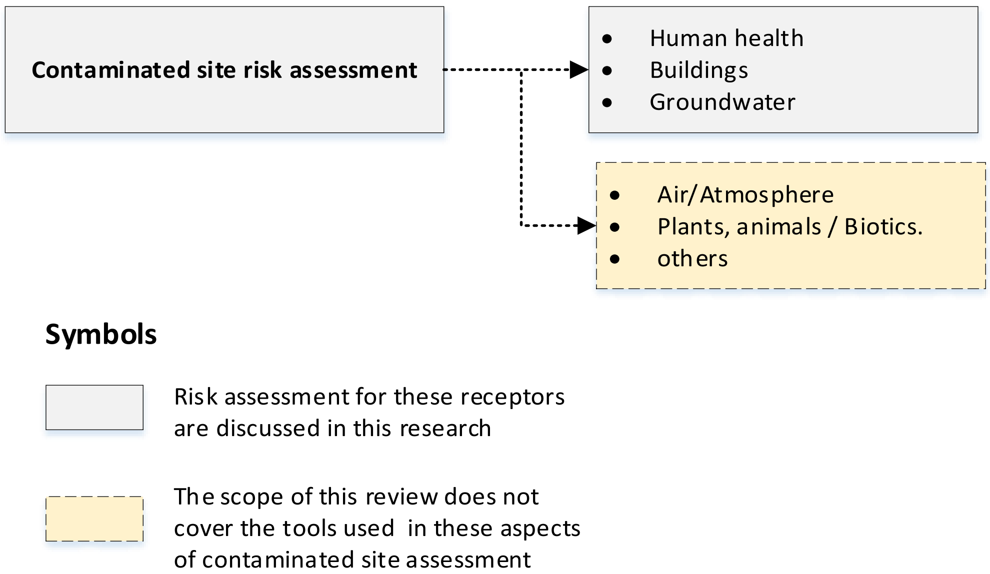

Figure 1 Scope of the study

2 Research Methodology

The investigative procedures adopted for this study (Figure 2), which was inspired by Gao and Pishdad-Bozorgi (2019), consists of five main steps: (i) define the research strategy and selection criteria; (ii) identify tools relevant to the review; (iii) analysis and discussion of selected tools based on risk assessment stages, type of harm, hazard type, receptor type and pathways; (iv) identify research gaps and future reconmendations; and (v) provide conclusions.

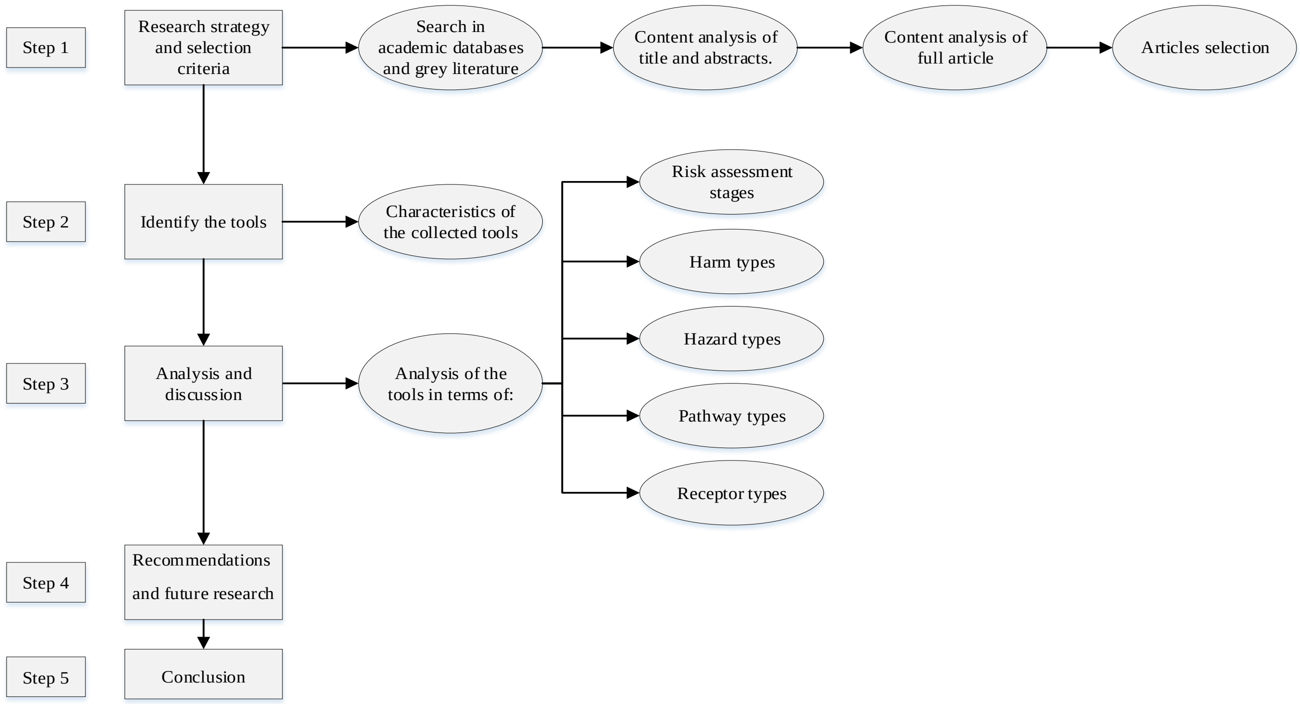

Figure 2 Flow chart diagram of the research project

2.1 Research strategy and selection criteria

A systematic review (guided by the PRISMA process) was conducted on academic databases, including Scopus, American Society of Civil Engineers (ASCE) and other leading search facilities. The keyword selection was divided into two blocks: (1) the "tool" section which included 2 elements: "risk assessment" and "assessment tool"; and (2) the "contaminated sites" section that included 4 elements: "contaminated site", "human health", "groundwater" and "buildings". "OR" operator was used between the terms in each section and then an "AND" operator between the two sections. Selected articles should include at least one element of each section.

After excluding the duplicates there were following exclusion rounds by reading the titles, then the abstract and finally the full articles. Subsequent steps involved the removal of irrelevant articles, they were identified and screened based on the following eligibility criteria:

- Select just tools that have been cited by peer viewed papers.
- This review considers the latest version of the tools and earlier versions are not included.
- The availability of support, ask if there is extensive documentation or help files available to assist users with issues they encounter.

Once the tools were identified, a more comprehensive analysis was undertaken to examine each tool based on six main categories presented in Table 1. The first category presents general information about characteristics of the collected tools. Second category selects the appropriate tool for each stage of risk assessment of contaminated sites. Third category identifies the harms considered by each tool. Fourth category determines the type of hazards considered by each tool. Fifth category selects the receptor considered by each tool. Sixth category determines the pathway considered by each tool.

Table 1. The main categories used to analyses the tools

Characteristics of the tools	General information about the tool **Author** **Year** **Tool name** **Year of publication**
Risk assessment stage	What tools used in preliminary risk assessment stage? What tools used in generic quantitative risk assessment? What tools used in detailed quantitative risk assessment? What approach relevant to each tool?
Harm types	What is the harm considered by the tool? **Toxic:** inclusion any substance that may cause toxic **Non-Toxic**: inclusion any harms from explosion, fires or injuries etc.
Hazard types	What is the type of hazard considered by the tool? **Chemical hazards**: hazards related to chemical substances example: metals and organics **Physical hazards**: hazards related to buried services (underground services and storage tanks etc.) **Biological hazards**: hazards such as virus, bacteria etc.
Receptor types	What is the receptor considered by the tool? **Human health:** this may include site workers, residents **Buildings**: the foundations may be affected by the contaminated sites **Groundwater**: contaminants could migrate into aquifer
Pathway types	How receptors can be affected or exposed by contaminants (Ingestion, inhalation, dermal contact for human health and leaching for environmental health for example groundwater)

3 Identified tools

The results of the preliminary search through databases identified 222 articles, with 151 articles identified through grey literature. Based on the process discussed in the methodology section, this screening process has reduced the tools to 31, which were included for the final review, Figure 3 presents a synthesis of the literature selection steps, as well as a combined quantitative and qualitative approach was taken to further classification and analysis.

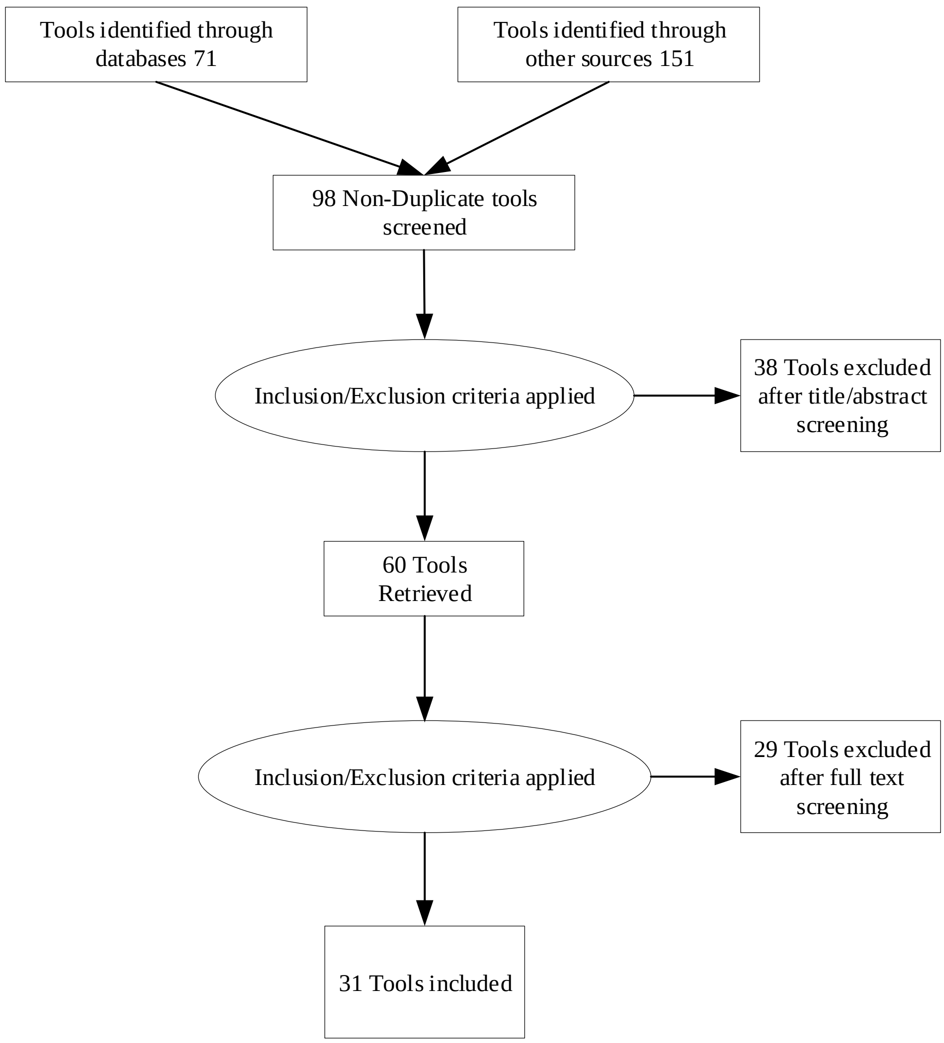

Figure 3 Selection process of tools

3.1 Characteristics of the selected tools

Details of the risk assessment tools (n=31) derived from the PRISMA search are summarised in Table 2. This shows the origins of the risk assessment tools are mostly derived from the USA (n=17) and UK (n=9), and accounts for more than 80%; whereas, Denmark (n=3), Spain (=1) and the Netherlands (n=1) account for the remainder. Since 1996 there has been between 1-3 risk assessment tools produced per year, with the exception of 2019, which saw a spike in the number of tools produced (n=8).

Table 2 Existing contaminated site risk assessment tools

#	Year	Country	Tool name	Author(s)
1.	2019	UK	ATRISK	Atkins
2.	2019	USA	IRIS	US National Library of Medicine
3.	2019	USA	ToxRefDB	(Watford *et al.*, 2019)
4.	2019	USA	HERO	US Environmental Agency
5.	2019	Denmark Spain	-	Locatelli *et al.*
6.	2019	USA	BMDS	Jeff *et al.*
7.	2019	USA	Toxicological Profiles	Agency for Toxic Substances and Disease Registry (ATSDR)
8.	2017	UK	Groundwater Vulnerability maps	Environment Agency
9.	2015b	UK	LQM Roadmaps	Land Quality Management
10.	2015	USA	RBCA	American Society for Testing and Materials (ASTM)
11.	2012	UK	GasSim	Environment Agency and Golder Associates
12.	2011	USA	RISC (v5)	Spence and Walden
13.	2011	Denmark	Discrete Dracture	Chambon *et al.*
14.	2009	UK	CLEA	Environment Agency
15.	2009	USA	FOOTPRINT	Noman, Wilson; and Mingyu
16.	2008	USA	ACToR	(Judson *et al.*, 2008)
17.	2008	USA	ARAMS	U.S. Army Engineer Research and Development Center (ERDC)
18.	2008	Denmark	CatchRisk model	Troldborg *et al.*
19.	2008	Spain	SRC-DSS	López *et al.*
20.	2007	Netherlands	CSOIL	Brand, Otte and Lijzen
21.	2006	USA	SADA	The Institute of Environmental Modelling (TIEM)
22.	2006	USA	BioBalance	Savannnah River National Laboratory and U.S. Departement of Energy
23.	2006	UK	-	Martin and Toll
24.	2005	USA	AALM	U.S. Environmental Protection Agency
25.	2005	UK	-	Bonniface *et al.*
26.	2003	USA	3MRA	U.S. Environmental Protection Agency
27.	2003	UK	LandSim	(Environment Agency and Golder Associates, 2003)
28.	2003	UK	ConSim	Environment Agency
29.	2002	USA	EMSOFT	US Environmental Protection Agency
30.	1997b	USA	3DFATMIC	Gour-Tshy *et al.*
31.	1997a	USA	2DFATMIC	(Gour-Tshy, Cheng; and Short, 1997a)

4 Analysis and discussion

As discussed in the methodology section of this paper, more comprehensive analysis of the reviewed tools is conducted and illustrated in Table 3.

Table 3 Analysis of the risk assessment tools

	Risk assessment stages			Harms		Hazards categorization			Receptors			Pathways
	PR[A]	GQRA[B]	DQRA[C]	Toxic	Non-toxic	Chemical hazards	Biological hazards	Physical Hazards	Human health	Building materials	Ground-water	
1.		✓		✓		✓			✓			1,2,3,4,5,6
2.		✓		✓		✓			✓			1,4, 5
3.	✓			✓		✓			✓			1,2,4,5
4.		✓		✓		✓			✓		✓	1,2,3,4,5,7
5.			✓	✓		✓					✓	7
6.			✓	✓		✓			✓			1,2,4,6
7.		✓		✓		✓			✓			1,2,4,5,6
8.	✓			✓		✓					✓	7
9.			✓	✓		✓			✓			1,2,3,4,6
10.			✓	✓	✓	✓			✓		✓	1,2,3,4,5,6,7
11.			✓		✓	✓			✓			1,2,3,4,5,6
12.			✓	✓	✓	✓			✓		✓	1,2,3,4,5,6,7
13.			✓	✓		✓					✓	7
14.		✓	✓	✓		✓			✓			1,2,3,4,5,6
15.			✓	✓		✓					✓	7
16.	✓			✓		✓			✓			1,2,4,5
17.			✓	✓		✓			✓		✓	1,2,3,4,5,6,7
18.			✓	✓		✓					✓	7
19.	✓			✓		✓			✓			1,2,3,4,5,6,7
20.			✓	✓		✓			✓			1,2,3,4,5,6
21.			✓	✓		✓			✓		✓	1,2,3,4,5,6,7
22.			✓	✓		✓					✓	7
23.	✓			✓	✓	✓		✓	✓	✓		1,2,3,4,5,6,7
24.			✓	✓		✓			✓			1,2,4,5,6
25.	✓			✓		✓			✓	✓		1,2,3,4,5,6
26.			✓	✓		✓			✓		✓	7
27.			✓	✓		✓					✓	7
28.			✓		✓	✓					✓	7
29.			✓	✓		✓			✓			6
30.			✓	✓		✓	✓				✓	7
31.			✓	✓		✓	✓				✓	7

A= Preliminary risk assessment; B=Generic quantitative risk assessment; C= Detailed quantitative risk assessment; 1=Direct Soil ingestion; 2= Dust ingestion; 3= Consumption of home-grown produce; 4= Inhalation of dust; 5= Dermal contact with soils; 6= Inhalation of vapours;7=Leaching to pore water

4.1 Tools corresponding to risk assessment stages

As observed from column of risk assessment stages in Table 3, most of tools are developed for DQRK by twenty tools, followed by five tools for GQRA. Only three tools for PRA. Further analysis is presented in Table 4, which indicates methods used for the development of risk assessment tools are diverse and are classified in this study into five types including: databases, fate and transport, exposure assessment, maps and dose-response.

Table 4: Distribution of tools by risk assessment process and adopted approach

	Fate and transport models	Exposure assessment models	Databases	Dose response	Maps
Applies to these degrees of risk assessment. ➡	DGRA	PRA, GQRA and DGRA	PRA and GQRA	DGRA	PRA
1.		✓			
2.			✓	✓	
3.			✓		
4.			✓		
5.	✓				
6.				✓	
7.			✓		
8.					✓
9.				✓	
10.	✓	✓			
11.	✓				
12.	✓	✓			
13.	✓				
14.		✓			
15.	✓				
16.			✓		
17.		✓			
18.	✓				
19.	✓	✓			
20.		✓			
21.		✓			
22.	✓				
23.			✓		
24.		✓			
25.			✓		
26.		✓			
27.	✓				
28.	✓				
29.	✓				
30.	✓				
31.	✓				

Figure 4 shows that three approaches are used for preliminary risk assessment of contaminated sites, including: databases (four tools), exposure (one tool) and maps (one tool). While, the approaches used in generic quantitative risk assessment are exposure assessment models (two tools) and databases (three tools). Finally, detailed quantitative risk assessment used diverse approaches including fate and transport models (13 tools), followed by exposure assessment models and dose-response by 6 tools and 2 tools, respectively.

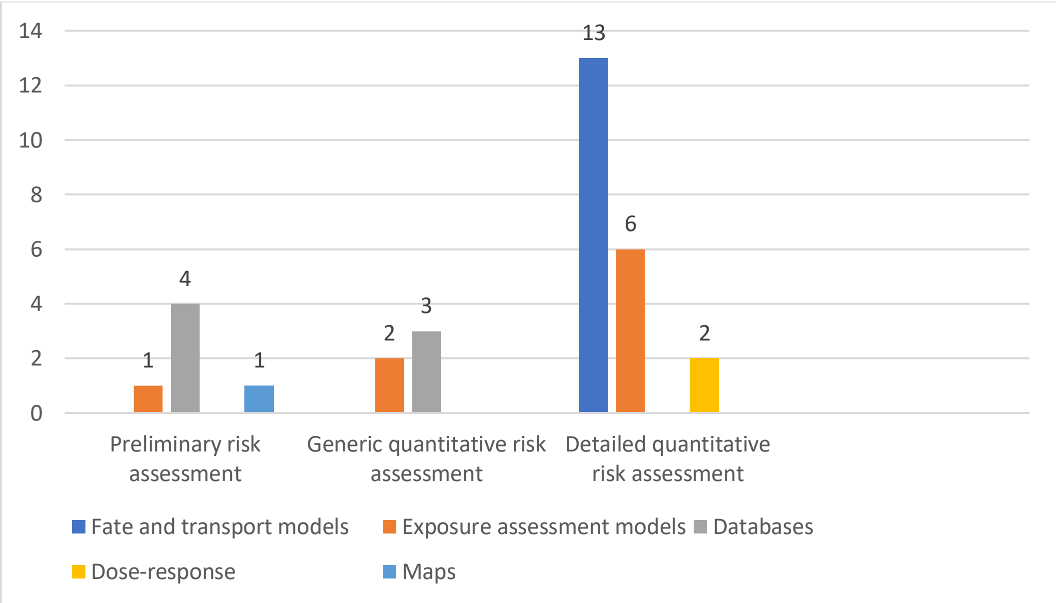

Figure 4 Classification of tools based on the approach adopted

Despite much development of tools based on the fate and transport approach, there is still a disappointing success and lack of well-established tools that encourage preliminary risk assessment. However, fate and transport approaches need considerable volumes of data and a large amount of work to set up, which is time consuming with high cost of investigation in case of management of thousands of contaminated sites (Smith, 2005; Locatelli *et al.*, 2019). Otherwise, one of the key limitations to adopt exposure assessment models, databases, dose-response models in the preliminary risk assessment is the uncertainties associated with the interpretation of toxicological information are likely to continue unless the development of comprehensive and easy to use tools enable assessors to reduce their uncertainty and boost their confidence in making decisions. For example, a developer may decide to use a remediation option that will bring a site up to standard higher than is strictly necessary to protect human health. This implies that "over remediation" leading to excessive cost for developers (Environmental Agency, 2008; Nathanail *et al.*, 2015; Swartjes, 2015; Locatelli *et al.*, 2019).

4.2 Risk assessment tools by harm types

Figure 5 shows twenty-nine of the tools addressed toxic harms, which can generally be divided into those that result from short-term (i.e. acute) exposure to a substance and those due to doses administered over a longer period (i.e. chronic exposure) (Barry, 1991). Acute hazards (from materials such as free cyanides, arsenic, phenols and sulphates) are of prime concern to the safety of site workers who may expose to risk for short periods to relatively high concentration. While, the term "chronic exposure" generally refers to exposures to "low" concentrations of a contaminant over a long period. Chronic hazards (from such contaminants as arsenic, phenols, some hydrocarbons and polychlorinated biphenyls (PCBs), organic materials and heavy metals) mostly affect the later residents and long term occupants of land (Leach and Goodger, 1991). It is noticeable that the existing tools do not explain how the human body will response when exposed to the toxic dose. In addition, the tools are based on animals' studies and human volunteers. So the benchmarks in the tools are not based on dose intake directly by children but extrapolation of the data in the epidemiological studies of humans and animals (Environment Agency, 2009), which raises the level of safety to higher standards than is strictly necessary to protect children health (Hong, 2015). Otherwise, only five tools addressed non-toxic harms, such as fire and suffocation hazards.

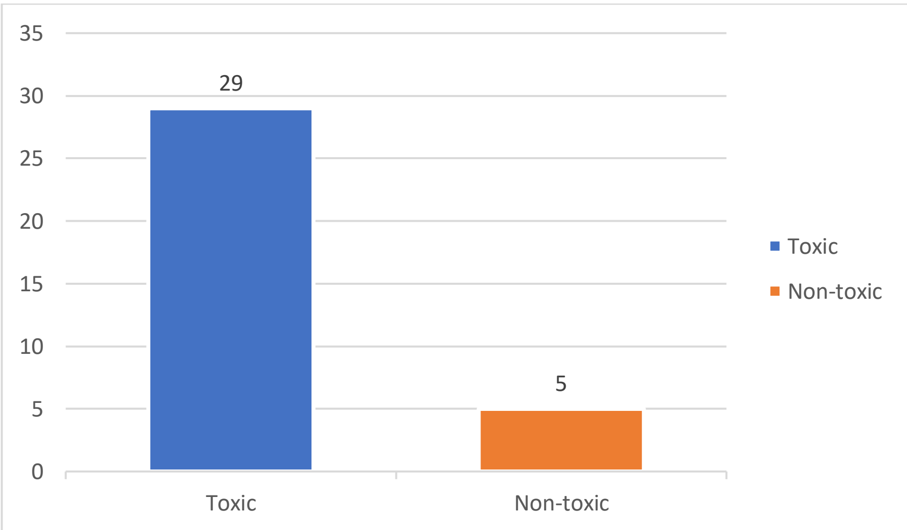

Figure 5 The Distribution number of tools by harm type

4.3 Risk assessment tool by hazard types

Figure 6 illustrates the distribution of tools by hazard category. However, development on contaminated sites present a huge hazard considering the difficulties to develop because of their constraints including physical, chemical and biological hazards (Charles *et al.*, 2002). As reported by (Skinner, Charles and Tedd, 2005), physical hazards are regarded as geotechnical, and chemical and biological hazards are regarded as geoenvironmental. The review shows an absence of tools that address physical problems, which may include buried foundations and settlement of filled ground (Watts and Charles, 2015). Otherwise, most tools are designed to assess chemical contamination that may cause long-term threat to human health through ground, groundwater or plants. In addition, a number of studies (Sarsby, 2000; HSE, 2018) conclude that contaminated sites could be a source of biological hazards, which may lead to serious disease, only a few risk assessment tools address biological hazards.

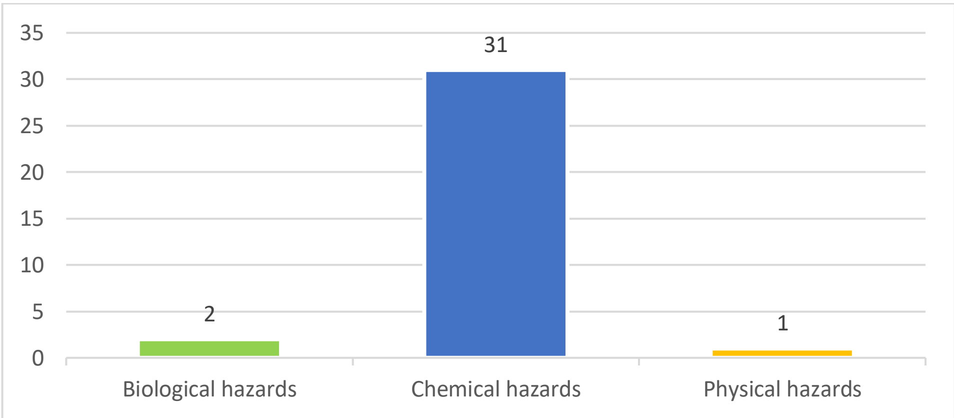

Figure 6 The distribution number of tools by hazard category

4.4 Risk assessment tools by receptor types

Figure 7 shows a considerable number of tools are developed to address the human health issues associated with contaminated sites, which is understandable as the human wellbeing is a stakeholder’s priority. In addition, the review shows an important number of tools could be applied to assess risks from contaminated site to the groundwater. It is important to bring the attention of the reader that groundwater, surface water and air are considered in some tools like receptors of the contaminants but may also act as pathways, via consumption of water, inhalation of air to human receptor (Syms, 2007; Nathanail and Bardos, 2005; Laidler, Bryce and Wilbourn, 2002; Leach and Goodger, 1991). For example, LanSim tool is used to assess risks of groundwater pollution from landfill by simulating the migration of contaminants from landfill site to groundwater over time and estimate pollutant concentration in groundwater

(Mishra *et al.*, 2017). Otherwise, risk assessment tools of buildings in contaminated sites are not covered.

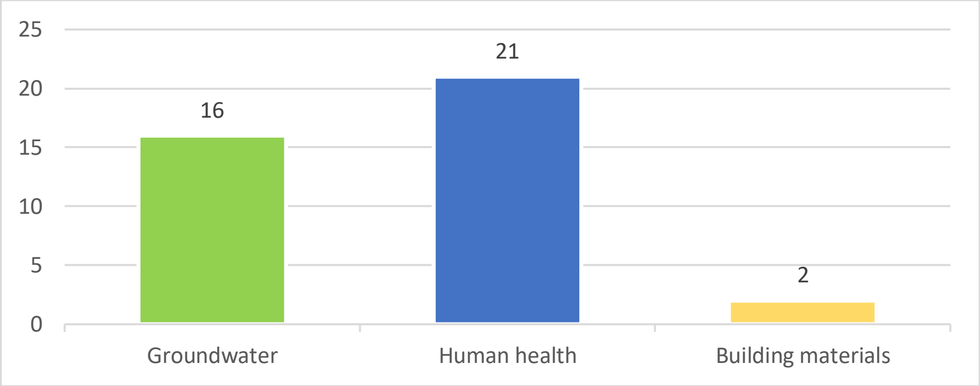

Figure 7 The distribution number of tools by receptors

4.5 Risk assessment tools by pathway types

Pathway in this study refers to a route or means by which a receptor can be exposed to, or affected by, a contaminant (UK Environment Agency, 2004). The same contaminant may be linked to two or more distinct types of receptor by different pathways, or different contaminants and/or pathways may affect the same receptor. It must first be noted that a tool can focus on more than one pathway. In terms of volume, Figure 8 shows that most tools (n=19) address direct ingestion and inhalation of dust (n=19), followed by dust ingestion, leaching to poor water and dermal contact with soils (18 tools, 18 tools and 17 tools, respectively). While, inhalation of vapours and consumption-grown produce were addressed by 16 tools and 13 tools successfully.

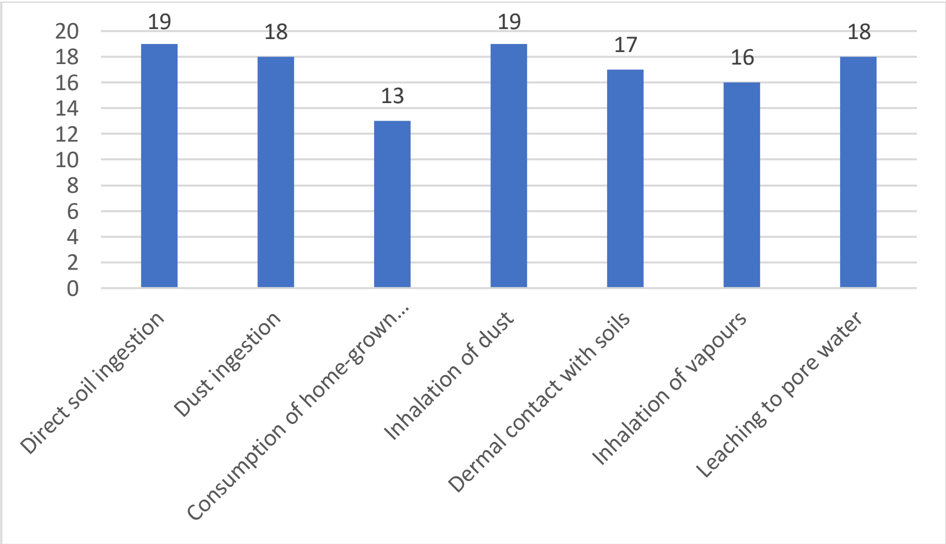

Figure 8 The Distribution number of tools by pathways

5 Recommendations and future research

Based on the findings of this study, it is recommended to focus on the following aspects while developing future tools for risk assessment of contaminated sites:

(1) Risk assessment tools by stages (PRA, GQRA and DQRA): future research may focus more on the development of a simple tools based on numerical solutions of contaminant fate transport models in particular at a preliminary risk assessment stage. Otherwise, tools based on exposure models, databases, and dose-response models should be comprehensive and user-friendly, enable people with limited knowledge who look deeper into data and who need to make decisions based on this.

(2) Risk assessment tools by harm types:

(a) The future tools should consider short-term exposure to contaminants, because the identified tools consider only toxic effects to a substance in long term exposure.

(b) Gases can be toxic or non-toxic or even both. For instance, most gases that are explosive (non-toxic hazard) are also toxic for example hydrogen sulphide, organic vapours such as benzene. There is a need for new tools which distinguish between such features.

(3) Risk assessment by hazard types:

The focus of this paper is not the number of biological hazards themselves but the fact that they are not accounted for as extensively in the existing tools as the chemical ones. Biological contaminants such as legionella, streptomyces, fleas, dust mites and fungal spores can be considered in site assessment. However, the tools that have been investigated in this study predominately consider chemical contaminants while the biological ones are not as much and as such. Hence, a recommendation is made that the new tools need to be developed which consider biological hazards as well.

(4) Risk assessment tools by receptor types:

The risk-based approach is applied in contaminated site assessment which is founded on the fundamental risk assessment principle – Source-pathway-receptor. In general, the tools consider humans, and the natural environment factors such as water as receptors. However, the buildings (the built environment) are not considered as receptors as much and as such. Therefore, there is a need for tools which more explicitly, also consider building materials as receptors, where hazards (such as aggressive chemicals, combustible materials, expansive slag) of a contaminated site can a pose a risk to building materials. A more specific example can be an acid (such as sulphuric acid coming from batteries) can adversely affect the concrete foundation in the form of corrosion.

(5) Risk assessment tools by pathway types:

In the tools the pathways which are considered, are generally direct and primary. The indirect and secondary pathways are not as distinctly and holistically included. For instance, there are tools which consider risks of dose intake via food such as vegetables and fruits grown on contaminated sites, however, according to Environment Agency (2009) other secondary poisoning pathways means such as meat, poultry and dairy produce are not. Thus, there is a need for new tools which can cater for all the secondary poisoning pathways scenarios.

6 Conclusions

The present research work is the systematic literature review conducted on risk assessment tools for contaminated sites. From a collection of 222 articles, 31 tools were identified for review and classification. The analysis was conducted in respect to the following aspects: risk assessment stages, type of harm, hazard category, receptor type and pathways. From these analyses and the underlying subject of the review, critical discussion was conducted to identify the knowledge gaps and propose recommendations to bridge these gaps for each aspect. For instance, in preliminary risk assessment stage, further work is needed to provide more options for contaminated site assessors to use tools based on different approaches including fate and transport models, exposure assessment models and, dose and response. In addition, more comprehensive tools are needed to reduce uncertainties regarding the interpretation of toxicological information and reference values, in particular, for stakeholders with limited knowledge for toxicological data.

Current approaches to risk assessment are limited for contaminated sites, as these do not cover the hazards which arise from biological contamination and poor land quality. Furthermore, the majority of tools address risks to human health and groundwater, while buildings are not considered. Finally, the pathways that are considered are also insufficient.

Researchers can make use of this review to define their future directions and efforts in developing better tools. Conversely, based on the existing list of tools reviewed, users can now select the most appropriate one to suit their objectives, needs, and contexts.

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