HCH: conditions and the state of the art

Elaborated and reviewed by LINDANET project

From the end of World War II to the 2010s, lindane has been one of the most extensively used pesticides due to its insecticidal properties. Lindane is the gamma isomer of hexachlorocyclohexane (HCH). At its manufacturing, a high amount of other isomers with no use is produced (around 85%), which become waste in the production process. An estimate of 600,000 tons of lindane have been used in the world –most of them in the EU-, therefore, the amount of waste generated is considered between 4.8 and 7.2 million tons. As at the time of its production waste was considered inert, it was usually dumped without any control. The advantages of the use of lindane and the lack of isolation of the waste generated have been revealed a problem of enormous dimensions. The manufacture and use of HCH (including lindane) was banned in the EU at the end of 2007. Lindane, α-HCH and β-HCH are listed as POP in the Stockholm Convention since August 2010.

Numerous works have been developed related to the problems caused by the production of lindane, recently highlighting at the European level the LINDANET project (an ambitious project that aims to join efforts among European regions to work together towards the improvement of the HCH contaminated sites), the "HCH in the EU" project (a project to identify sites where HCH was handled in the 27 EU Member States and to provide a full roadmap for sustainable management of seven selected HCH contaminated sites), the LIFE SURFING project (the project aims to demonstrate the feasibility in the field of a decontamination technique for soils containing Dense Non-aqueous Liquid Phase (DNAPL), composed of a multicomponent mixture of organic pollutants and persistent organic pollutants (POPs)) and the LIFEPOPWAT project (a European project focusing on innovative technology based on constructed wetlands for treatment of pesticide contaminated waters). The objective of this article is, based on the overview of the HCH pollution problem and the existing remediation alternatives, to present a methodology that considers the characteristics of each site contaminated by HCH and allows the classification of both these characteristics and the site as a whole, to prioritize both the locations and the actions to be taken, which is one more step towards solving the problem. In addition, this methodology can also be applied to the case of sites affected by other pollutants.

1 HCH Manufacturing, characteristics, uses and legislation

1.1 HCH and lindane manufacture

HCH was first synthesized by Michael Faraday in 1852, by reacting benzene with chlorine in bright sunlight (TAUW, CDM Smith and Sarga, 2021). Raw HCH contains a total of eight stereoisomers which are termed α- to θ-HCH depending on the spatial arrangements of the chlorine atoms. Among these, only the α, β, γ, δ, and ε isomers (Figure 1) are stable and are formed in the following percentages in reaction mixtures: α, 55–80%; β, 5–14%; γ, 8–15%; δ, 2–16%, and ε, 3–5%. The remaining three isomers are formed in trace amounts (Vijgen, Lal, Li, & Forter, 2011). The Dutch chemist Teunis van der Linden isolated pure γ-HCH in 1912.

In the late 1940s and early 1950s, the production of technical HCH -containing mixtures of several isomers- began. Failed batches of chlorination resulted in the production of a non-aqueous dense phase liquid (DNAPL), composed of mostly chlorobenzenes, chlorinated cyclohexanes, extraction liquids and HCH. Its composition, density (1.5 kg/L) and uncontrolled discharge make it a by-product with a big capacity for contamination.

Technical HCH was used as insecticide. It was soon discovered, however, due to its strong odour and flavour resulted in inedible crops. Of all HCH isomers, only the γ-isomer (lindane) has specific insecticidal properties, with the added benefit that it is nearly odourless and does not influence crop quality. Hence, some companies began in the 1950s to isolate it through methanol distillation.

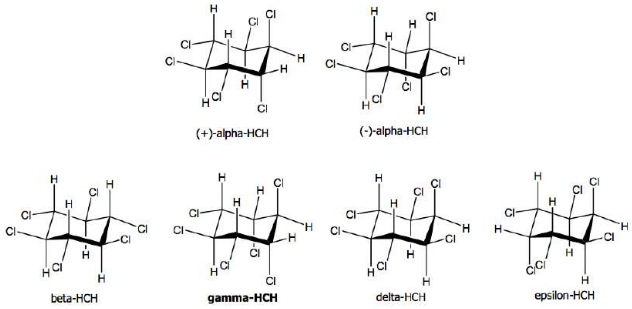

Figure 1 Molecular structure of α, β, γ (lindane), delta and epsilon HCH isomers (Vega, Romano, & Uotila, 2016)

1.2 Characteristics and uses

Due to the differences in the molecular structure and physical properties of HCH isomers, the bioactivity of HCHs differs significantly (Chen, Gao, & Wang, 2015). The greatest are between β-HCH and γ-HCH. β-HCH has a relatively plane shape with weak physiological activity as an inert or weak depressant, and γ-HCH has a relatively spherical shape with strong insecticidal action. β-HCH and γ-HCH act differently within the cellular membrane. A membrane is mainly composed of phospholipid macromolecules arranged in a regular hexagonal packing. The interspaces of these macromolecules can act as transport pathways of the membrane, by which the HCHs can be introduced. Based on plane orientation, the cyclohexane ring γ-HCH (8.5 Å) is smaller than that of β-HCH (9.6 Å). It can be easier for γ-HCH to penetrate the membranes. Thus, bioactivity difference between these two isomers can be expected.

HCHs primarily affect the central nervous system. In insects, γ-HCH stimulates the central nervous system and causes rapid, violent convulsions that are generally followed by either death or recovery within 24 h. Other physiological systems affected by HCH isomers include renal and liver function, haematology and biochemical homeostasis.

Alpha, beta and gamma-HCH (lindane) were included in the fourth meeting of the Conference of Plenipotentiaries of the Stockholm Convention held in Geneva in May 2009, as they fulfil the criteria set out in its Annex D for being persistent, bioaccumulative, harmful for human health or the environment and with potential for long range transport. Lindane can produce chronic and systemic diseases, having effects on the central nervous an endocrine systems and being classified carcinogenic to humans. It is additionally highly toxic to aquatic organisms, birds, mammals and bees. HCH isomers, including lindane, are subject to "global distillation" in which warm climates at lower latitudes favour evaporation into the atmosphere where the chemicals can be carried to higher latitudes. At high latitudes, cold temperatures favour atmospheric deposition. The other principal HCH isomers have similar properties (Vega, Romano, & Uotila, 2016).

The life cycle of HCH and lindane (Bensaïah & Fokke, 2021) outlines the different uses that these products have been given over time, among them:

- Crop husbandry: field, vegetable and fruit crops, viticulture, ornamentals, pasture and forage crops.
- Animal husbandry: veterinarian and domestic animals.
- Health care: indoor pest, outdoor, clothes fabric and body treatment.
- Forestry: pest control.
- Protection and preservation of wood, plastic and stored material.
- Military purposes: smoke generating devices.

1.3 Applicable legislation

Regarding the use and manufacture of HCH within the European Union, Directive 79/117/EEC established the prohibition of placing on the market and using HCH containing less than 99.0 % of the gamma isomer. Subsequently, Regulation 850/2004, repealed by Regulation 2019/1021 established restrictions to lindane uses until 2007. After 2007 the production and all uses of lindane were totally prohibited in the European Union.

In relation to water, the Water Framework Directive 2000/60/CE establishes limits for HCH sum of isomers and the individual ones and Directive 2008/105/EC establishes the admissible concentrations in terms of Annual Average (AA) and Maximum Allowable Concentration (MAC) of HCH for surface waters.

As for soil, it is not currently subject to a comprehensive and coherent set of rules in the European Union. The Commission in May 2014 decided to withdraw the proposal for a Soil Framework Directive, included in the Seventh Environment Action Programme. Reporting on progress in managing soil contamination is currently voluntary, irregular and based on a changing methodology, different national definitions, screening values and risk assessment methodologies. In light of this lack of level playing field, the Commission approved in November 2021 the EU Strategy for Soil Protection 2030. In the framework of which the European Commission will explore the need for legal provisions to make such reporting mandatory and uniform across the EU in the context of a Soil Health Law.

2 HCH remediation

In "HCH in EU project", 299 sites were identified in the EU (Van de Cortelet, 2021), where lindane and/or HCH was handled in the past. Given the magnitude of the pollution problem caused by HCH and lindane production, many techniques have been developed to achieve the sites remediation. Some solutions are commercially available, others are in a demonstration phase and the most recent ones are in a laboratory testing phase.

2.1 Remediation technologies

The following list includes commercially available remediation technologies, grouped into containment, thermal, physical chemical, and biological. A final group is included for a different approach solution (Vega, Romano, & Uotila, 2016) (Federal Remediation Technologies Roundtable, n.d.). It is to be noted that, at this time, no remediation technology is available on a commercial scale that allows the recycling of the different isomers of HCH. In fact, the attempt of recycling the waste isomers to trichlorobenzene resulted in highly polychlorinated dibenzodioxins and polychlorinated dibenzofurans contaminated residues (Vijgen, Li, Forter, & Lal, 2006).

2.1.1 Containment technologies

- Impermeable walls, achieved by the construction of a low-permeability or impermeable cut-off walls, with the objective to contain contaminated groundwaters or soil within a site, or to divert ground or surface waters away from a contaminated site.
- Landfill, soil and sediment capping are containment technologies that form a barrier between a waste body or contamination source area and the ground surface using clean layers of geologic materials and/or synthetic liners.

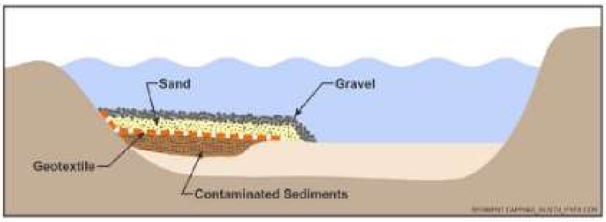

Figure 2 In-situ capping of contaminated sediments cross section **(Federal Remediation Technologies Roundtable, n.d.)**

It should be considered that the different containment technologies are mostly transferring the waste and the problem to future generations with associated long term cost (Vijgen, de Borst, Weber, Stobiecki, & Forter, 2019) (Fernández, Arjol, & Cacho, 2011) (Vijgen, Li, Forter, & Lal, 2006) (State Official Newsletter (consolidated legislation), 2005).

2.1.2 Thermal technologies

- Cement kilns are primarily designed to burn limestone at temperatures between 1400- 2000ºC and are generally fuelled by fossil fuel. Their use to destroy toxic chemicals entails co-fuelling the kiln with fossil fuels and an appropriate mix of waste chemicals, depending on their properties.
- Thermal desorption is a physical process designed to remove contaminants at relatively low temperatures, ranging from 90 to 560°C. The contaminated media is heated to volatilize water and organic contaminants, followed by treatment in a gas treatment system.
- Incineration operates at higher temperatures, ranging from 870 to 1,200°C. Systems are designed to volatilize and combust (in the presence of oxygen) halogenated and other recalcitrant organic compounds in soil and sediment that are difficult to remove at lower temperatures.

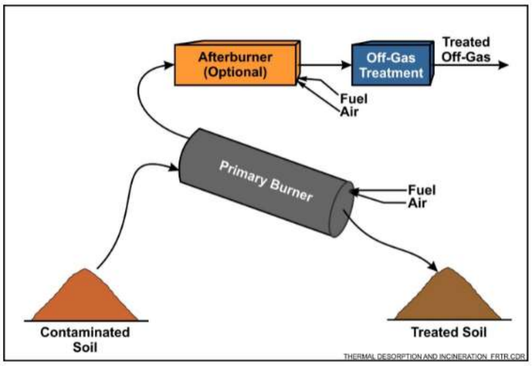

Figure 3 Thermal desorption and incineration **(Federal Remediation Technologies Roundtable, n.d.)**

- Plasma arc operates on principles similar to an arc-welding machine, where an electrical arc is struck between two electrodes. The high-energy arc creates high temperatures ranging from 3,000 degrees to 7,000 degrees Celsius. The plasma, being highly ionized gas, is enclosed in a chamber. Waste material is fed into the chamber and the intense heat of the plasma breaks down organic molecules into their elemental atoms.

2.1.3 Physical – chemical technologies

IN-SITU

- Air sparging is used to strip volatile compounds from groundwater and to elevate dissolved oxygen (DO) levels throughout the contaminated zone and stimulate aerobic biodegradation of the contaminants in the aquifer.
- In situ chemical oxidation (ISCO) is a remediation technology that involves the injection of oxidants into the ground. ISCO is applicable to treat a wide range of contaminants of concern.
- In situ chemical reduction (ISCR) is the in-place abiotic transformation of contaminants by chemical reductants. Contaminants treated by ISCR typically include chlorinated compounds, metals in a high oxidation state, explosives, and oxidized inorganics.
- Free product recovery consists of several technologies to remove light nonaqueous phase liquids, ranging from simple hand bailers and passive skimmer systems to more complex active skimming systems and large-scale total fluids recovery systems.
- Large diameter auger mixing is a treatment technology that involves aggressive mixing of amendments into soil to treat or sequester a variety of contaminants.
- Monitored natural recovery is a remediation approach for contaminated sediments that relies on naturally occurring physical, chemical, and biological processes to contain, destroy, or reduce the bioavailability and/or toxicity of contaminants. Recovery over time is monitored to verify that it progresses at the expected rate. Combined with engineering measures, it is referred to as Enhanced monitored natural recovery.

- Multi-phase extraction is a technology designed to simultaneously remove any combination of light non-aqueous phase liquid, groundwater, and vapour, targeting remediation of the vadose zone, capillary zone and shallow saturated zone.

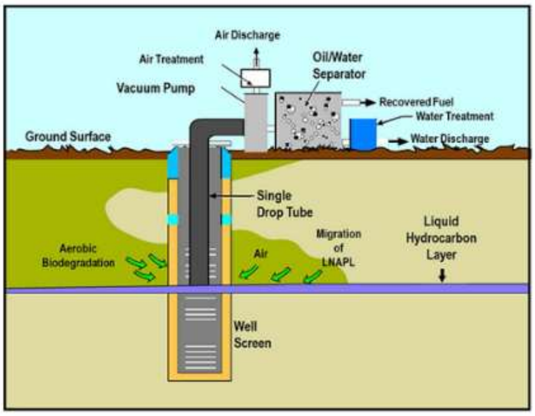

Figure 4 Multi-phase extraction **(Federal Remediation Technologies Roundtable, n.d.)**

- Permeable reactive barriers typically involve the installation of reactive media within a trench, a series of overlapping borings, or grouped injection points to create a permeable "wall" positioned perpendicular to the direction of groundwater flow.
- pH control is used to neutralize soil and groundwater having high or low pH. It can be used as a stand-alone technology or in conjunction with other remedies.
- Solidification and stabilization transform potentially hazardous liquid or solid contaminants of concern present in soil or sediment into environmentally innocuous materials of considerably reduced mobility.
- Soil flushing is a process that extracts contaminants from the formation using water, possibly combined with other suitable amendments. Contaminants in the soil partition move into the flushing solution by mechanisms such as solubilization, emulsification, or chemical reaction.
- Soil vapour extraction involves the application of a vacuum in the vadose zone to induce the controlled flow of air and removal of volatile and some semivolatile contaminants from the subsurface.

EX-SITU

- Air stripping is a technology that removes volatile organic compounds from pumped groundwater or wastewater by passing the water over a media having a large surface area while exposing the contaminated water to uncontaminated air flow.
- Base catalysed dechlorination/decomposition is a chemical reaction process used for dehalogenation or decomposition of a range of chlorinated and non-chlorinated persistent organic pollutants. It involves treatment of liquid and solid wastes in the presence of an alkaline reagent mixture which is heated at a temperature suitable for the decomposition reaction to take place.
- Environmental dredging is the process where contaminated sediment under water is removed, treated, and/or placed in a new location.
- Pump and treat. Contaminated groundwater and/or non-aqueous phase liquid can be pumped from the subsurface, treated above ground, and discharged.
- Soil washing systems utilize a wash solution to extract and concentrate contaminants of concern as well as assist in physical size separation of the finer particles from the larger particle bulk material.
- Super Critical Water Oxidation is a process that occurs in water at temperatures and pressures above a mixture's thermodynamic critical point. Then, behaviour of water as a solvent is "reversed" so that chlorinated hydrocarbons become soluble in the water, allowing single-phase reaction of aqueous waste with a dissolved oxidizer.

2.1.4 Biological technologies

IN-SITU

- Bioreactors rely on biological processes to remediate groundwater. The organic material is used as an energy source by naturally occurring or augmented microorganisms, creating a highly reducing and anaerobic environment in which contaminants can be degraded or immobilized.
- Biowalls are a type of permeable reactive barrier that relies on biological processes to treat groundwater in situ.

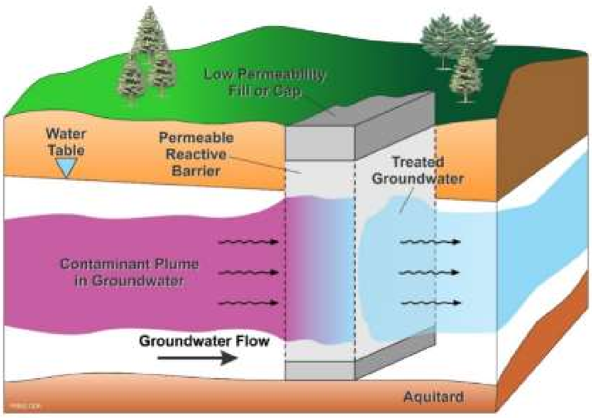

Figure 5 Biowall schematic **(Federal Remediation Technologies Roundtable, n.d.)**

- Enhanced aerobic biorremediation is the process of stimulating indigenous oxygen-dependent microorganisms in soil and groundwater to create the conditions necessary for the microorganisms to biotransform contaminants to innocuous by-products.
- Enhanced reductive dechlorination is the process of modifying chemical, physical, and biological conditions in the aquifer to stimulate the microbial degradation of contaminants under anaerobic conditions to harmless end products.
- Monitored natural attenuation consists of a range of naturally occurring physical, chemical, and biological processes that attenuate contaminant concentrations in groundwater to achieve remedial goals within a reasonable timeframe and protect human health and the environment.
- Phytoremediation is a treatment technology that uses vegetation and its associated microbiota, soil amendments, and agronomic techniques to remove, contain, or reduce the toxicity of environmental contaminants.

EX-SITU

- Biopiles constitute a technology where excavated soil or sediment is placed in piles onto an impermeable base or pad equipped with aeration to optimize and control the rate of biodegradation.
- Composting is used to treat excavated soils and dredged sediments contaminated with a variety of pollutants. Soil is mixed with bulking agents and organic amendments such as mature compost, wood chips, hay, manure, and vegetative (e.g., potato) wastes and organic material is added to maintain thermophilic temperatures during the degradation process.
- Constructed wetlands are used to promote the action of natural, physical, geochemical, and biological processes to mineralize organic contaminants, immobilize inorganic contaminants, and remove suspended particulates. They are considered a type of phytoremediation technology.
- Landfarming involves using agricultural practices to promote biodegradation of organic contaminants so that soils or sediments are spread in thin layers across a large open space, allowing natural processes to degrade and immobilize the contaminants.

2.1.5 Other technologies

- Excavation and off-site disposal. Contaminated material can be removed and transported to permitted off-site treatment and/or disposal facilities. Some pre-treatment of the contaminated media is sometimes required at the project site or the receiving facility to meet land disposal restrictions.

2.2 Selection of remediation alternatives

Considering the large number of existing remediation technologies, it seems convenient to have a methodology for assessing each of the alternatives, considering technical, economic, temporary, social, safety and health and environmental criteria, and choosing the most suitable for the specific case (Emgrisa, 2011).

For each of the aforementioned criteria, the evaluation of a set of subcriteria is proposed that will allow determining the technology of choice. In some cases, minimum scores are established which, if they are not achieved, would leave the corresponding technology out of choice.

Technical criteria (maximum 32 points):

- Definitive or palliative solution to the problem, both for the degree of contamination and for the number of contaminants considered (10 points, minimum 4 points)
- Guarantees of achievement of the objective (10 points, minimum 4 points)
- Solution durability (6 points)
- Simplicity of execution and commercial availability of the technique (3 points, minimum 1 point)
- Compatibility with other techniques (3 points)

Economic criteria (maximum 30 points):

- Total infrastructure cost (25 points, minimum 5 points). Cheapest solutions, highest score.
- Possibility of splitting the investment over time (5 points)

Deadlines (maximum 13 points):

- Solution lead time (10 points)
- Speed of start of execution (3 points)

Social criteria (maximum 10 points):

- Social rejection of the technique (5 points, minimum 3 points)
- Interferences/annoyances to the population (5 points, minimum 3 points)

Safety and Health and environmental criteria (maximum 15 points):

- Risk for the workers themselves (5 points, minimum 3 points)
- Risk to third parties (5 points, minimum 3 points)
- Environmental risk (5 points, minimum 3 points)

3 Methodology for decision making

Considering the high number of sites affected by contamination by HCH or lindane and the different characteristics of each of them, it may be useful to apply a classification tool that allows to prioritize the remediation actions towards their Sustainable management. To this end, the model based on the assessment of the **availability of remediation technologies**, the **quantification of risks**, the **availability of fund**s and the **awareness of the interested parties** (site features) allows an orderly cataloguing of the affected areas to be established (Langervoort, Rijk, Fokke, & van der Wijk, 2013). It is evident that decision-making will also be based on aspects not considered in this article, but the proposed system is robust enough to become a first-order factor both for the proper solution of the problem and for its subsequent monitoring.

3.1 Availability of remediation techniques

A list of available technologies for the HCH remediation has been exposed in section 2, together with a methodology for the selection of the most suitable proposal.

Although there is a wide variety of existing remediation technologies, HCH removal is not usually simple, because of its presence in different forms, distribution and matrixes, together with the complexity of the sites. Due to that, some technologies might not be yet available for use, and need a period for research and / or development.

3.2 Quantification of risks

Carrying out an analysis of risks to human health and the ecosystem, considering the different migration pathways, is greatly facilitated if a conceptual site model (CSM) has previously been developed.

3.2.1 Development of a CSM

A CSM is a representation of a site that describes the distribution, release mechanisms, exposure pathways and migration routes and potential receptors of contaminants of concern. This is usually visualized by organizing and presenting data in such a way that it is easy to understand (TAUW, CDM Smith and Sarga, 2021).

Building a CSM involves different experts and disciplines, such as soil scientists, hydrologists, toxicologists, and remediation engineers. With regard to environmental and health risks, important aspects of a CSM are the source(s) of contamination, the source-receptor pathway(s) and the receptor(s).

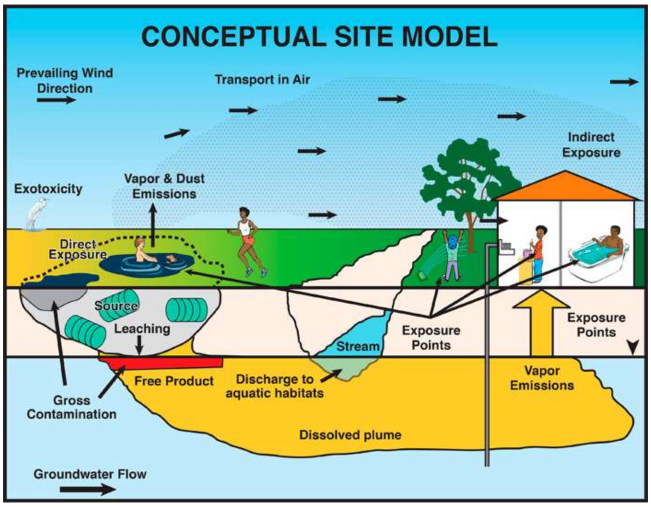

Figure 6 Example of a CSM (ITRC, 2018)

A CSM is built in various stages, with the first stage being an Initial CSM (ICSM) made with the information available. The second stage is the update of the ICSM to a CSM. This is based on a gap analysis of the ICSM and the data collection and interpretation for bridging the gaps.

Potential source areas of contamination can be classified as follows:

- Areas where contaminants are used, handled and/or stored.
- Areas where contaminants enter the soil, surface water and / or groundwater.

For each potential source, consideration needs to be given to whether a pathway exists, through which the contamination can migrate and spread from its original source area to the surroundings. Typical potential pathways for soil and groundwater contamination are spreading through air, groundwater; surface runoff, surface water, physical contact with the contamination and uptake in the ecosystem. Regarding humans, some examples of pathways are soil ingestion, inhalation of dust, uptake by food plants and direct -dermal- contact with the contamination.

Potential receptors for contamination are any plants, animals and/or human beings that might come into direct contact with or take-up the contamination. In most cases, receptors are also pathways for a contamination. The potential receptors are not necessarily in and around the site; they might be a considerable distance away, if potential pathways are thought to exist.

Typical potential receptors for soil and groundwater contamination at, near and around the contaminated site are for example humans (visitors, users, workers and general); animals including livestock (cattle, poultry and pet animals); fish and other aquatic organisms; subsoil fauna (living organisms in the soil); vegetation (growing crops); and the ecosystem in general (soil, groundwater and/ or water bodies). It is key to identify potential receptors, so that in further investigation receptors can easier be identified depending on the type and amount of contamination.

3.2.2 Risk analysis

The objective of the risk analysis is the categorization of the identified risks for human health, ecosystem and contaminant migration. The categorization is based on the likelihood of exposure to contaminants and the expected magnitude of impacts.

A method is proposed here with the purpose of getting a score that can be used in the method for decision making explained in section 3.5 (TAUW, CDM Smith and SARGA, 2020).

Thus, for the proposed method the following four risk categories are defined:

- Direct risks having high likelihood and, if occurring, have high impact.
- Potential risks having low to medium likelihood and, if occurring, have high impact.
- Probable risks having high likelihood and, if occurring, have low to medium impact.
- Latent risks having low to medium likelihood and, if occurring, have low to medium impact.

In order to establish an objective assessment of the risks detected, values are established for the probability and for the expected impact, according to the following Table:

Class	Likelihood (L)	Score	Class	Impact (I)	Score
1	Not likely	>1 & <2	1	Very small	>1 & <2
2	Possible	>2 & <3	2	Small	>2 & <3
3	Likely	>3 & <4	3	Reasonable	>3 & <4
4	Probable	>4 & <5	4	Large	>4 & <5
5	Very likely	>5 & <6	5	Very large	>5 & <6

Table 1 Probability and impact assessment used in risk analysis

Risks are scored by multiplying likelihood by impact. The total risk of the site is the sum of the score of each analyzed risk (risk for human health, the ecosystem, risk of migration of the contaminant, …).

Nº	Risk description	S	P	R	Risk score	Human health		Ecosystem		Contaminant migration	
						L	I	L	I	L	I
		Total risk score:									

Table 2 Total risk score for the analyzed site

3.3 Availability of funds

Usually, the remediation, monitoring and subsequent care of sites contaminated by HCH and/or lindane entail high costs that can hardly be fully assumed by the administration at the local, regional and even national level. The "Polluter Pay" principle is difficult to apply in this case (Vijgen, de Borst, Weber, Stobiecki, & Forter, 2019), since a large part of the discharges were carried out in accordance with the legislation then in force, the owners are bankrupt or are former governments (as is the case in some Central Europe). Therefore, it is necessary to find financing to face the costs associated with the environmentally sustainable management of the sites.

3.4 Awareness of the interested parties

Considering the technical, environmental, economic and social aspects related to contamination by HCH and/or lindane, it is necessary to have the coordinated participation of all interested parties in solving the problem. In this sense, it is worth mentioning the initiative of the Aragon Government (Spain), with the drafting of a Strategic Plan (Aragón Government, 2016) and the creation of a Management Section for the Comprehensive Decontamination of Lindane. This Section has the support of three Committees:

- Scientific Committee, made up of experts from recognized prestige that underpins and improves the rationale and relevance of the objectives established and the measures carried out in the different areas of action, including the R&D processes required to the final solution of the challenge. Its eight members cover the areas of hydrogeology, engineering chemical, biosanitary, soil restoration and agronomy.
- Monitoring Committee, which ensures the coordination between the different areas of competence related to the challenge and its solution. It has twelve representatives of the Hydrographic Confederation of the Ebro, Department of Health, Civil Protection, SEPRONA, municipal administrations and Alto Aragon Irrigation system.
- Social Committee, which articulates the participation of civil society and facilitates the flow of information as well as the communication process. It is made up of twenty-one representatives of environmental associations, workers' unions, the Organization of Agricultural Producers, business associations and the Council of Nature Protection. In July 2016 Representatives from all parliamentary groups have joined to ensure the presence of all sensitivities.

The proposed strategy responds to a local/regional scheme, but given the magnitude of the problem, it is necessary to expand its scope to a higher level. In this sense, the expansion of networks such as LINDANET both at the national level, to create effective cooperation with all other affected regions, and at the European level, establishing a dedicated EU legal framework for soil protection, which addresses soil pollution in a comprehensive manner, would expand the range of parties involved, sharing knowledge to work together towards the improvement of the HCH and/or lindane contaminated sites.

3.5 Methodology development

Each one of the four site features described in the previous sections is classified into five levels: uncontrolled, minimum controlled, semi controlled, controlled and completely controlled, rated from zero to four according to the following Table:

Level	Class	Site feature			
		Availability of technique	Risk control	Availability of funds	Awareness profile
4	Completely controlled	All risk control measures are readily available and feasible	Direct, potential and latent risks controlled	Funds available, including monitoring and aftercare	All stakeholders take their responsibilities
3	Controlled	Risk control measures can be designed site specific	Direct and potential risks controlled	Funds available on the short and mid term	Receptors, local and national decision makers are aware of risks and responsibilities are allocated
2	Semi controlled	Direct risk control measures are available	Direct risks controlled	Funds available on the short term	Receptors and local decision makers are aware of risks
1	Minimum controlled	Emergency measures are readily available	Emergency measures implemented	Emergency block grant available	Receptors are aware of risks
0	Uncontrolled	Risk control measures are not available	No risks controlled	No funds available	Stakeholders do not take their responsibility

Table 3 Site classification by categories: technique, risk, funds and awareness

The level of Availability of the technique can be easily obtained from the score calculated in section 2.2, changing the scale from 35-100 (being 35 is the minimum score) to 0-4.

In the Quantification of risks section, a risk assessment model was proposed that can be used to classify sites in level 4 in case of very low risk control and 0 in case of high risk control, and distributing the rest linearly. In the case of a single site, the assessment is subjective and should be adjusted to what has been stated in Table 3.

Although the assessment on the Availability of funds and the Awareness profile is more subjective, Table 3 features guides on how to place the site at the appropriate level.

The final result of the application of the model awards 0 points to the uncontrolled sites and 16 to those completely controlled, which allows their classification, having the advantage of providing guidance on the characteristics of the site that constitute an obstacle to its sustainable management, and **allowing efforts to be oriented in the right direction**. To achieve this the following circumstances should occur:

- The rehabilitation of the site should be fostered by a person or group with the power and willingness to do so and with a clearly defined schedule.
- There should be a socio-economic incentive. Improvement of the socio-economic situation is a powerful driving force for any chosen solution.
- Apply simple and effective solutions using natural processes and locally available resources that add value to the future surrounding land use.
- Balance civil engineering and green rehabilitation. It is essential to exchange knowledge within the project setting and also at a broader scale.

4 Conclusions

The problem of pollution generated by the production of HCH and lindane is far from being solved. The current estimates of the amount of contaminant present in soil and water and the verification -of a limited scope- of the existence of numerous contaminated sites in the territory of the EU show the enormous pending work.

A multitude of remediation techniques have been briefly described, although a greater effort is required on the part of the chemical industry to develop procedures that allow the recycling of HCH and the use of 70% of the chlorine of which it is composed. Confinement techniques are discouraged, as they do not constitute permanent solutions, but actions that transfer the problem to future generations. Spanish legislation establishes that "Recovery actions must guarantee that they materialize permanent solutions, prioritizing, as far as possible, in-situ treatment techniques that avoid the generation, transfer and elimination of waste" (State Official Newsletter (consolidated legislation), 2005).

The monitoring of the sites contributes, in a fundamental way, to the development of a CSM and to an adequate risk assessment. It allows an iterative process to be carried out that improves knowledge of the site situation, and should lead to the immediate treatment of direct risks, due to their high probability and high impact. The control of risks in the long term requires the permanent support of the interested parties, which can decline if definitive solutions are not taken.

The effort made by the Government of Aragon to achieve the involvement of the different stakeholders has been highlighted. It has also become clear that the different actions must cover local/regional/national/European levels, given the magnitude of the problem, and the expansion of the LINDANET network can constitute the better meeting point.

Finally, based on the information obtained or described in the previous sections, a tool for classifying sites according to their characteristics has been discussed. Given that the circumstances of each site are changing, the tool should be applied cyclically for the proper prioritization of actions and for determining the progress made in the locations where actions have been carried out. The tool can be used to analyze the situation of a site with respect to any type of waste, so it could be applied, for example, and in a preventive manner, to the list of substances subject to review for their possible identification as priority substances or as priority hazardous substances (Official Journal of the European Union, 2008).

The production of HCH began in the 1940s and that of lindane in the 1950s. More than 70 years later, the residues from its manufacture continue to generate problems for human health and the environment that are far from being solved. There is an important legislative development and a great amount of information about it, new techniques have appeared, the concern of society has increased and, consequently, the public sector has reacted. But, as J. Vijgen stated (IHPA, Aragón Government and Sarga, 2015), “Delay is not without consequences: still more than one million tons of obsolete pesticides are to be eliminated, the contaminants continue to spread, affecting soil and groundwater, wild life and crops. But there is also a growing impact on human health: effects on food quality, long term effects on health. It should scare us: how do obsolete pesticides contribute to increased cancer risks and decrease of human fertility? Why does it seem that we don’t want to invest to know these answers? And even for those who want to close their eyes for the impact on environment and human health we have an economic message. One day you will have to agree that the increased risks and effects, the damages and losses have to be restored and compensated and at that time at higher costs than today. Penny-wise will turn out to be pound-foolish”. Stop acting is the worst and most expensive solution.

References

Aragón Government. (2016). Strategic plan for the comprehensive fight against pollution of waste generated by the manufacture of lindane in Aragón. 1-108.

Aragón Government. (n.d.). *Stop Lindano*. Retrieved January 21, 2022, from http://www.stoplindano.es/

Bensaïah, C., & Fokke, B. (2021). The use and legacy of HCH in the EU. A guide to identify potentially impacted sites. 1-26.

Chen, H., Gao, B., & Wang, S. (2015). Microbial Degradation od Hexachlorocyclohexane (HCH) Pesticides. *ResearchGate*, 181-209.

Emgrisa. (2011). Study of technical alternatives to solve the environmental problems of the Sardas landfill, T.M. Sabiñánigo (Huesca). 1-114.

European Commission. (2021, November 17). EU Soil Strategy for 2030. Reaping the benefits of healthy soils for people, food, nature and climate. 1-26.

European Union. (n.d.). *Life Surfing Project*. Retrieved January 21, 2022, from http://www.lifesurfing.eu/

European Union. (n.d.). *LIFEPOPWAT*. Retrieved January 11, 2022, from https://cxi.tul.cz/lifepopwat/home

European Union. (n.d.). *Lindanet Interreg Europe*. Retrieved January 25, 2022, from https://www.interregeurope.eu/lindanet/

Federal Remediation Technologies Roundtable. (n.d.). *Technology Screening Matrix*. Retrieved January 21, 2022, from https://frtr.gov/matrix/default.cfm

Fernández, J., Arjol, M. Á., & Cacho, C. (2011). HCH contamination in the Sabiñánigo's environment. *11th International HCH and Pesticides Forum*, (pp. 117-121). Azerbaijan.

IHPA. (n.d.). *IHPA library*. Retrieved January 22, 2022, from http://www.ihpa.info/resources/library/

IHPA, Aragón Government and Sarga. (2015). Key messages of the 13th International HCh & Pesticides Forum. 1-19. Zaragoza.

Interstate Technology & Regulatory Council. (2011). Integrated DNAPL Site Strategy. 1-209. Washington, D.C.

Langervoort, M., Rijk, I., Fokke, B., & van der Wijk, M. (2013). From uncontrolled to controlled final sink. *2nd International Conference on final Sinks*, (pp. 1-14). Espoo, Finland.

Ministry for Ecological Transition. (2019). National Plan for the Application of the Stockholm Convention and Regulation (EC) No. 850/2004, on Persistent Organic Pollutants. 1-135.

Official Journal of the European Communities. (1978, December 21). COUNCIL DIRECTIVE of 21 December 1978 prohibiting the placing on the market and use of plant protection products containing certain active substances. 33/36-40.

Official Journal of the European Communities. (2000, October 23). DIRECTIVE 2000/60/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 October 2000 establishing a framework for Community action in the field of water policy. 327/1-72.

Official Journal of the European Union. (2004, June 29). REGULATION (EC) No 850/2004 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 29 April 2004 on persistent organic pollutants and amending Directive 79/117/EEC. 158/1-49.

Official Journal of the European Union. (2008, December 24). DIRECTIVE 2008/105/EC OF THE EUROPEAN PARLIAMENT AND THE COUNCIL of 16 December 2008 on environmental quality standards in the field of water policy. 348/84-97.

Official Journal of the European Union. (2019, June 25). REGULATION (EU) 2019/1021 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 20 June 2019 on persistent organic pollutants. 167/45-77.

State Official Newsletter (consolidated legislation). (2005, January 18). ROYAL DECREE 9/2005, of January 14, which establishes the list of potentially polluting activities of the soil and the criteria and standards for the declaration of contaminated soil. 1-21.

State Official Newsletter (consolidated legislation). (2011, July 29). Law 22/2011, of July 28, on waste and contaminated soil. 1-57.

State Official Newsletter. (2011, January 22). Royal Decree 60/2011, of January 21, on environmental quality standards in the field of water policy. 6854-6870.

State Official Newsletter. (2020, July 8). Royal Decree 646/2020, of July 7, which regulates the disposal of waste by landfill deposit. 48659-48721.

TAUW, CDM Smith and SARGA. (2020, April 28). Pilot project to evaluate and address the presence of Lindane and HCH in the EU (ENV.D.1/ETU/2019/0023) – Inception Report.

TAUW, CDM Smith and Sarga. (2021). HCHinEU project: part 1. History and Usage of HCH. 1-2.

TAUW, CDM Smith and Sarga. (2021). HCHinEU project: part 2. Conceptual Site Models (CSM), environmental and health risks of HCH-contaminated sites. 1-3.

UNO environment programme. (2019). Stockholm Convention on persistent organic pollutants (POPS). 1-79.

Van de Cortelet, G. (2021). Inventory of sites that are potentially impacted by HCH in EU member states. 1-43.

Vega, M., Romano, D., & Uotila, E. (2016). Lindane (persistent organic pollutant) in the EU. Study for the PETI Committee. 1-138.

Vijgen, J. (2006). The Legacy of Lindane HCH Isomer Production. A global Overview of Residue Management, Formulation and disposal. 1-26.

Vijgen, J., & Egenhofer, C. (2016). Obsolete (lethal) Pesticides, a ticking time bomb and why we have to act now. 1-38. Tauw Group bv, The Netherlands (on behave of IHPA).

Vijgen, J., de Borst, B., Weber, R., Stobiecki, T., & Forter, M. (2019). HCH and lindane contaminated sites: European and global need for a permanent solution for a long-time neglected issue. *Environmental Pollution*, 696-705.

Vijgen, J., Lal, R., Li, Y.-F., & Forter, M. (2011). Hexaclorocyclohexane (HCH) as new Stockholm Convention POPs - A global perspective on the management of Lindane and its waste isomers. *Environmental Science and Pollution Research*, 152-162.

Vijgen, J., Li, Y.-F., Forter, M., & Lal, R. (2006). The legacy of lindane and technical HCH production. *ResearchGate*, 899-904.

Vijgen, John; Fokke, Boudewijn. (2021). EU guidance for sustainably managing HCH impacted sites. Outline of a strategy to resolve the legacy of Lindane production in the EU. 1-16.