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SHARP

Strengthened International HeAlth Regulations & Preparedness in the EU

Best practice for public health surveillance for chemical health threats: A global literature review

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Version History

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Version 0.2		Changed title - reviewed headings	All authors
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		Updated following comments by RDD	
Version 0.13	09/10/23	Corrections to number of papers reviewed and missing references	OO, AL
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Executive Summary

The SHARP Joint Action aims to strengthen preparedness in the EU against serious cross-border threats to health and support the implementation of the International Health Regulations (2005) (World Health Organization, 2016). Surveillance is a key activity required under the International Health Regulations (IHR). Tested surveillance systems are required for the detection, verification, and risk assessment of the impact of chemical events of (potential) health concern as part of a multi-hazard surveillance strategy. The aim of this work was to review the global tools, systems, and strategies currently available for the public health surveillance of chemical health threats, including incidents, events, and exposures with the potential to impact health.

The published literature was searched for relevant articles and reports that demonstrated good practice. Using indexing databases, Medline, Web of Science and Embase databases, and grey literature indexing sources, a total of 4066 titles were extracted, of which 175 articles and reports were included in this review. The material identified was divided into nine themes; acute surveillance, event-based surveillance, industrial surveillance, occupational surveillance, oil spills, environmental contamination surveillance, maternal/paediatric surveillance, system approaches and other surveillance and tools (for miscellaneous titles that did not fit into a theme). These were further synthesised into four key themes: acute surveillance, industrial and occupational surveillance, environmental contamination surveillance and system approaches.

In conclusion, different chemical incident surveillance tools are used for identifying and responding to chemical incidents, and for protecting public health and the environment. Various systems and reporting tools are available for chemical health threat surveillance for public health purposes. Through ongoing monitoring and collaboration, these systems can help to prevent and mitigate the impact on health of chemical incidents and promote safe and responsible practices in the use and handling of hazardous materials. In addition to the importance of surveillance, it is critical to take proactive measures to prevent chemical incidents from occurring in the first place. This can include efforts to improve safety regulations, increase awareness of the risks associated with chemicals, and promote the use of safer chemicals and production processes.

Overall, the risk to health of unintentional chemical exposures and chemical incidents underscores the need for ongoing vigilance and coordinated efforts to protect public health and safety. By developing and implementing effective surveillance and prevention strategies, we can help mitigate the risks associated with chemical incidents and reduce their impact on individuals, communities, and the environment.

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1 Introduction

Surveillance is a key activity required under the International Health Regulations (IHR) (2005) core capacities and the EU decision on cross-border health threats (Dec 1082/2013/EU), now EU Regulation 2022/2371 on serious cross-border threats to health (European Parliament and Union, 2022). As outlined in the IHR (2005), "surveillance refers to the systematic ongoing collection, collation and analysis of data for public health purposes and the timely dissemination of public health information for assessment and public health response as necessary". Tested surveillance systems are required for the detection, verification, and risk assessment of the impact of chemical events of (potential) health concern as part of a multi-hazard surveillance strategy.

This review provides an overview of the literature on public health surveillance for chemical health threats, covering examples of different surveillance, reporting systems, surveillance systems and how they are used to monitor the impacts of chemical incidents and exposures. The review also highlights good practice and existing gaps in chemical health threat surveillance.

1.1 What is SHARP?

The SHARP Joint Action aims to strengthen preparedness in the EU against serious cross-border threats to health and support the implementation of International Health Regulations (2005). "SHARP" stands for ***Strengthened International HeAlth Regulations and Preparedness in the EU***. The SHARP Joint Action started in March 2019 and will run until September 2023; it is a collaborative action of 26 countries and 61 partners, co-funded by the Health Programme of the European Union.

SHARP Work Package 9: 'Chemical safety and chemical threats' focusses on strengthening preparedness and supports implementation of IHR in terms of chemicals. Among the tasks of WP9, a part of milestone M33 is for conducting a literature review on best practice for chemical health threat surveillance. This report is the result of the literature review undertaken to inform chemical surveillance guidance and SOPs to provide a background for the activities on chemical surveillance and other tasks in WP9.

2 Aims and objectives of the literature review

The first step of responding to a chemical incident or chemical exposure is the detection of the incident. There are a variety of ways to do this, but a common approach involves designing and deploying a surveillance strategy (a strategy for the continuous, systematic collection, analysis, and interpretation of health-related data on chemical incidents and exposures). The systems and strategies available for communicable disease surveillance are numerous and well-established. However, this is often not the case for non-infectious disease and chemical incidents and exposures. There are very few dedicated resources and many of the tools used in chemical health threat surveillance were designed with biological agents in mind.

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The aim of this work was to review the global tools, systems, and strategies currently available for the public health surveillance of chemical health threats, including incidents, events, and exposures with the potential to impact health.

Objectives:

- Provide an overview of the current landscape with respect to surveillance of chemical health threats, incidents and exposures
- Collect and showcase good practice of public health chemical surveillance
- Outline the types of methods for chemical health surveillance, identification of systems, processes, and resources in place
- Identify the benefits of chemical surveillance and prevention in relation to public health threats
- Improve awareness of current systems and promote linkage between relevant authorities such as Poison Centres and national public health authorities
- Evaluate the efficacy of current public health chemical surveillance (with respect to capturing risks to health from chemical exposures), in relation to international frameworks such as IHR, surveillance evaluation criteria (e.g., USCDC/ECDC), and include papers which evaluate surveillance systems.

The literature search focused on papers on the following topics:

- Public health surveillance
- Chemical incidents
- Chemical exposures
- Public health preparedness.

3 Methodology for literature review

Literature search strategy

Search terms were developed for the Medline, Web of Science and Embase databases with the key words below (see Table 1). These terms were further refined into queries for each database with the support of the UKHSA Library services team (see Appendix 1).

Table 1. Search terms used for literature review

	Topic	Searches/key words
1	Public Health Surveillance	Surveillance, detection, indicator-based, event-based, toxicosurveillance/toxicovigilance, syndromic, multi-hazard, international, European, capacity, 'environmental public health', chemical, tracking
2	Chemical incident	Chemical, chemical incident, chemical event, chemical release, chemical spill, chemical accident, industrial accident, chemical health threat, environmental, injury, death

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3	Chemical exposure	Chemical exposure, chemical injury, chemical-related illness, environmental, metals, heavy metals, gases, air water, land, contamination, environmental monitoring
4	Public health preparedness	Poisons centres, environmental public health tracking, emerging public health threats, networks, planning, data review, 'watching brief', database, horizon scanning, Emergency Preparedness Resilience and Response (EPRR)

The search, conducted in May 2022, produced 4,066 titles, which were loaded into Rayyan (an online interactive software for collaborative reviews) for the team to review. Titles, abstracts, and keywords were screened based on the inclusion criteria below.

A blind pilot sample screening process was conducted by each member of the reviewing team on 202 titles and abstracts, and the results were compared. Conflicts were discussed and decision made as to their inclusion. After all conflicts were resolved the selection criteria was amended and the remaining papers were screened through the allocation of 644 titles and abstracts to each reviewer (NI, TG, HC, MI, KB, AJ). Each paper initially selected through the systematic search was assessed for relevance based on the content of their corresponding titles, abstracts and keywords. Weekly meetings were held for all reviewers to discuss any issues or confusion. If the paper was found to be relevant to the review, a label was attached to it denoting a theme or topic for that paper in relation to the review. Each reviewer was given their own allocation to screen as well as another reviewers', to ensure each 644 allocation was double screened. 502 abstracts were reviewed at the full-text level by NI, TG, HC, AL, MI, KB, MP, DM, and VG, these were allocated between reviewers based on the themes that had been assigned in the titles and abstract screening. Literature screened at each stage was retained in an Endnote file.

Some reviewers added extra literature, found through manual searches in the full-text screening stage. This has been accounted for in the results. All reviewers involved at the full-text screening stage contributed to the writing, editing, and reviewing of this report. NI was responsible for allocating all sections and managing the full text screening for all reviewers.

Inclusion criteria

Studies were only be included in the review if they meet the following criteria:

- Paper describes good practice for surveillance, either describing surveillance data or a system or designing surveillance.
- Paper's focus should be on chemical surveillance for public health purposes, particularly looking at systems for surveillance, early warning systems, alerting systems, chemical exposures, related health outcomes and so on.
- When papers are looking at chemical incidents, they must have caused a health impact, or have the potential to cause a health impact to be included in the review. This includes incidents with injuries or deaths, but also non-physical impacts, such as mental health outcomes.

Exclusion criteria

Studies were excluded if they met the following criteria:

- If the paper’s focus was on any non-chemical surveillance (for example, communicable disease, radiation, non-chemical environmental, e.g., weather, heatwaves, flooding etc.).
- The paper focuses on chemical incidents/exposures which do not involve potential health impact, injury, or death (public health chemical incidents are defined as having health effects).
- The paper focuses on animal studies and not human health.
- The paper focuses on one-off epidemiology studies, for example time series analysis of air pollution, one-off study on chemicals in water, and other similar research studies. One-off epidemiology studies are not surveillance.

4 Results

4.1 Search results

4,066 titles were extracted in total from Embase, Medline and Web of Science. 175 papers were included in the review (see Fig 1).

Figure 1. Flow chart of literature screening process, after (Haddaway et al., 2022)

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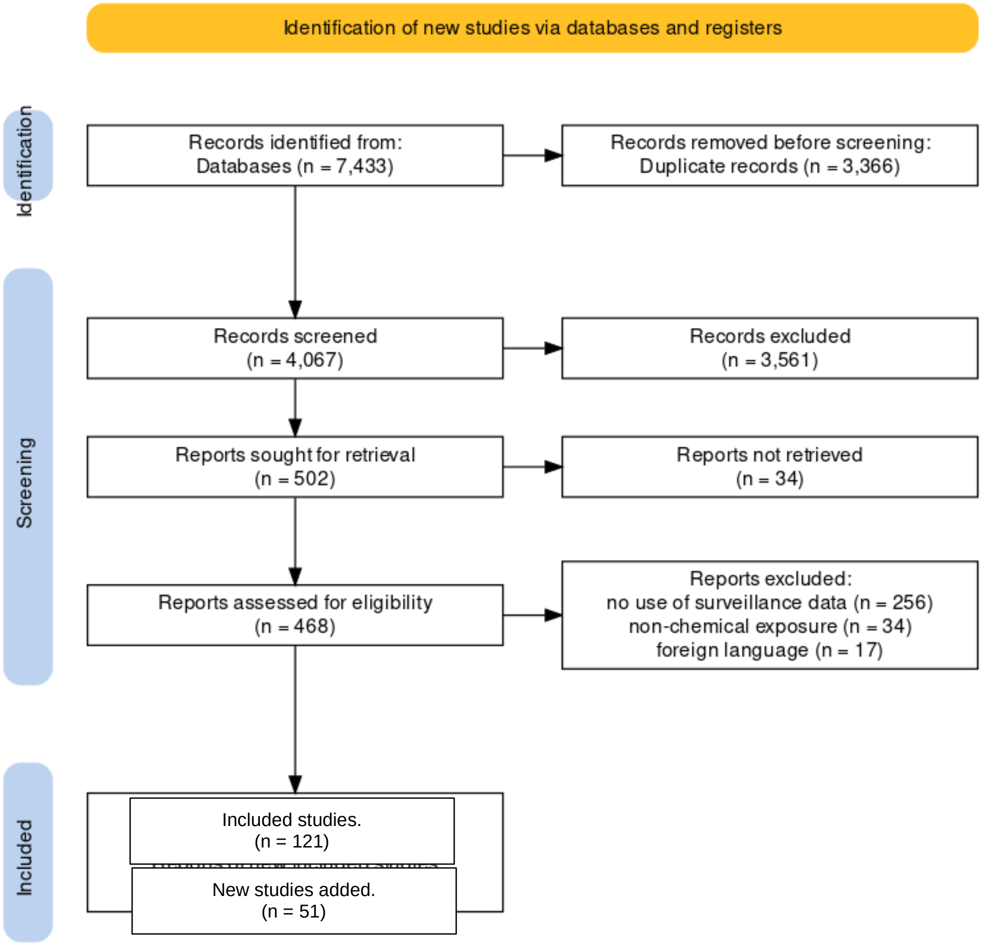

Themes of the literature

The literature screened at full-text level were divided into nine themes; acute surveillance (including poison centre surveillance, toxicovigilance and event based surveillance); industrial surveillance; occupational surveillance; oil spills, environmental contamination (air pollution surveillance and chemicals in water surveillance studies); pesticide exposure surveillance; maternal and paediatric surveillance; system approaches (including environmental public health tracking systems and evaluation of chemical surveillance systems); and other (these were later added into the appropriate themes). Acute surveillance and system approaches were the most populous themes (Table 2), followed by pesticide exposure surveillance, environmental contamination surveillance and oil spills. The least populous theme was industrial surveillance and occupational surveillance. After further consideration, some of these themes were combined into four key themes: acute surveillance, industrial and occupational surveillance, environmental contamination surveillance and system approaches. The results of the review were categorised by these four themes, with the remaining five sub-themes being included in each of these themes as deemed appropriate.

Table 2. Table shows the theme names, number of papers allocated to each theme, number excluded, additional papers or references, manually searched and added to each theme.

Theme	No. included from search	No. excluded	No. added	Total included
Acute surveillance	24	107	3	27
Industrial surveillance*	4	13	1	5
Occupational surveillance*	4	17	13	17
Oil spills*	5	45	5	10
Environmental contamination surveillance	23	31	10	33
Pesticide exposure surveillance*	8	43	6	14
Maternal and paediatric surveillance*	19	28	3	22
System approaches	34	131	10	44

*these were later put into the relevant topic sections

5 Literature Review

5.1 Acute surveillance

5.1.1 Poison centre surveillance/toxicovigilance

Poison centres are an important repository of chemical exposures and chemical incidents and undertake an important function in the surveillance of poisonings and chemical exposures. Poison centres provide members of the public and/or healthcare professionals (depending on the country) information about poisons and clinical treatment of poisoning. For example, for a chemical substance reporting symptoms of illness with the aim of identifying a chemical aetiology, or to report a chemical incident occurring (Wolkin et al., 2012). Poison centres have a fundamental role in toxicovigilance, which is defined as the active observation and evaluation of toxic risks and phenomena in the community – an activity that should result in measures aimed to reduce or remove risks (Veale et al., 2013).

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Logs of the calls/enquiries directed to poison centres can be analysed and trends can be found in the frequency of calls for a specific agent or incident. This process can also identify emerging outbreaks in real-time, such as outbreaks of poisonings via synthetic cannabinoids. In one such case in the US, an initial report of an outbreak in Missouri resulted in a nationwide investigation into synthetic cannabinoids in the US (Scalzo and Rivera-Sepulveda, 2018).

Although there are extensive systems in place for pharmacovigilance (surveillance of pharmaceuticals and their adverse effects), many countries have limited capacity for the routine monitoring of adverse health effects relating to exposure to non-pharmaceutical compounds, particularly pesticides (Perry et al., 2014).

The UK's National Poisons Information Service (NPIS) has four major centres in the UK and is commissioned by the UK Health Security Agency (UKHSA). NPIS also maintains TOXBASE, which provides online clinical toxicological information for thousands of products to UK health professionals (National Poisons Information Service, 2023). In the UK, TOXBASE can be accessed (although requires an account) by public services and health professionals in hospitals and primary care. In the case of pesticides, the UK NPIS scanned their repository of enquiries on poisoning cases over a 9-year period and found 7,804 incidences where a member of the public was exposed to a pesticide. The NPIS then extracted information from each enquiry to gain an understanding of pesticide exposure, frequency, and severity in the UK. The NPIS also recorded a much higher number of pesticide exposures detected than other equivalent systems in the UK (Perry et al., 2014).

The data held within poison centres can also identify who is at most risk from certain chemical agents. For instance, the US Texas poison centre compared the rates of poisoning by pesticides between adults and adolescents. It was found that the most common exposure was to insecticides and exposure was more frequent among males than females and that the study also recommended separate policies or guidelines for reducing exposure to pesticides for adults and adolescents (Forrester and Bojes, 2016).

Poison centres can identify clusters of poisoning where the cause is unknown, for instance via a covert release, where illness is the first sign of exposure. These can be difficult to diagnose and through consultation with a poison centre, signs and symptoms may be recognised as having a chemical origin, speed up the diagnosis and suggest an aetiological causative agent (Patel et al., 2006). This vigilance extends to natural disasters as well as intentional incidents, as poison centre surveillance was employed during the Deepwater Horizon oil spill in 2010. Based on the calls received about potential exposures around the area of the spill, the national poison data system at the time collated this data and via the US Centre for Disease Control (US CDC), situational reports were distributed to authorities in the surrounding areas, tracked exposed individuals and provided public health advice messages to the public (Wang et al., 2018a). In the aftermath of Hurricane Ike in the US in 2008, the Texas poison centre evaluated the calls received in the aftermath; they found that while many calls decreased (due to evacuation of the affected areas) there was an increase in calls regarding gasoline and carbon monoxide exposure. They were also able to compare the calls received to previous hurricanes to evaluate the severity of the health effects caused after the hurricane had passed (Forrester, 2009).

Poisoning data may come from other sources other than Poison Centres, a study on deaths by poisoning from the coroner's service in New Zealand was able to provide trends in

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compounds causing death, with carbon monoxide, despite a reduction in frequency of poisoning cases over time, it continued to be the most common causative agent of death by poisoning (Fountain et al., 2019).

Poison centre surveillance can identify trends in the type of poisoning and the causative agent(s) involved and suggest preventative measures to mitigate exposure. When looking at rates of poisoning with laundry detergent capsules, Rigaux-Barry et al. (2017) identified a higher exposure for children under 6 years of age and suggested measures to prevent exposure in this age group, including a reformulation of the laundry detergent capsules with less dangerous ingredients and a lower viscosity formulation (Rigaux-Barry et al., 2017).

The US currently operates a near-real time surveillance system. Poison centres automatically upload data from calls directly into the National Poisons Data System (NPDS) in just a few minutes after receiving them (Gummin et al., 2019). Users of the system can access regional and national data on current poisonings to facilitate management of outbreaks and incidents involving chemicals shortly after they have occurred.

The data collected by poison centres can be strengthened by creating networks between poison centres and national health institutes to enable early detection of unexpected or sentinel incidents involving chemicals. This has been done in Italy (Giordano et al., 2022), is practised in the US with the near-real time surveillance system (Gummin et al., 2019) and has been trialled in Europe with the systems set up through previous EU-funded projects. These include a rapid alerting system for chemicals (RAS-CHEM), a reporting system between poison centres and chemical incident experts across Europe where chemical exposures, incidents or outbreaks were posted onto an online system where they could be discussed and evaluated by this network and reported to the European Commission (Schaper et al., 2012). However, it is important to note that this system is currently not operational, and the EC is exploring ways of incorporating the system into the EU Early Warning and Response System (EWRS).

The literature reviewed here provides multiple examples of the ways poison centre surveillance/toxicovigilance can be used to raise situational awareness of chemical incidents, identify emerging chemical incidents, provide recommendations to policy/guidance for managing exposures from chemicals and provide an overview of the substances which pose a risk to public health. This review highlights the initial measures being taken in some countries to integrate poison centre surveillance into a national surveillance system, working towards real time surveillance.

5.1.2 Event-based surveillance

Event-based surveillance (EBS) is a functional component of the early warning and response process and encompasses the organised collection, monitoring, assessment, and interpretation of mainly unstructured information (from formal and informal sources, e.g., official news websites and social media) regarding chemical incidents or hazards, which may represent an acute risk to human health (Gaulton et al., 2021). EBS can be used to enhance situational awareness of current chemical incidents occurring globally (i.e., types of agents involved and their health effects). While this methodology is most commonly used for surveillance of infectious disease outbreaks, it is also highly useful for the monitoring of chemical incidents, such as poisoning incidents, explosions and fires, water/food contamination and also environmental incidents that present a hazard to public health, such as natural disasters (earthquake, storms etc.) which release toxic chemicals and expose members of the public (Fox et al., 2009) as many of the same reporting sources are used for both biological and chemical surveillance.

In Europe, the drive for establishing systems such as EBS arose from terrorist attacks in the early 2000s (e.g. world trade centre attacks and the London bombings of 2007) and the lack of formal systems which existed at the time to detect, respond to and share information on chemical threats to public health (Schaper et al., 2012).

The World Health Organization (WHO) has a surveillance system which includes chemicals, as well as infectious diseases. The Global Outbreak Alert and Response Network (GOARN) was founded in the year 2000. It was established to identify and describe the frequency, nature, and geographical location of acute public health chemical incidents of potential international concern, which countries must report to WHO under the International Health regulations (IHR, 2005) (Olowokure et al., 2005). This paper also discusses the importance of utilising sources that were originally intended to scan for incidents involving infectious diseases, as there are very few resources dedicated to chemicals.

Gaulton et al. (2021) describe an EBS system used in the UK Health Security Agency to identify chemical incidents from around the globe. The system uses a list of websites which are used for scanning for biological incidents of infectious disease but can also include chemical incidents (for example, MediSYS, ProMEdMail and GPHIN) as well as standard tools like Google News and Google alerts. Incidents which meet a set of criteria (e.g., involves a chemical, involved health effects to members of the public, potential for the incident to spread) were recorded on a database and later analysed. This system detected almost 1600 incidents between November 2014 and June 2020 and was able to identify which agents caused the most deaths/injuries, which were the most common incidents (and which chemicals were involved in these incidents) and where these incidents occurred around the world (Gaulton et al., 2021).

The EBS methodology also has the potential to be adapted to a variety of specific incidents or chemical agents. For instance, during the Covid-19 pandemic, an adapted EBS method was used in the UK to monitor injuries caused by exposure to chemicals which were linked to the pandemic and subsequent national lockdowns around the globe. For instance, the study found that injuries caused by the use or misuse of hand sanitiser increased, methanol exposure caused by an increase of home-brewed alcohol due to border closures increased. These closures were also thought to contribute to an increase in opioid-related deaths in Canada and two industrial accidents in India, on sites which were unattended or improperly shut down due to lockdown measures (Cook and Brooke, 2021).

While useful for acute chemical incidents (‘big bang’ incidents which can be over very quickly from the time of release), EBS is also utilised for routine monitoring of chronic incidents or certain types of commonly occurring incidents, for instance, exposure to pool-cleaning chemicals (Esschert et al., 2019). These smaller scale incidents make up the bulk of injuries incurred from chemical incidents, as they are far more frequent than big bang incidents.

Similar systems have been in place in other countries for some time, for example in the USA the US Centre for Disease Control (CDC) Hazardous Substances Emergency Events

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Surveillance (HSEES) system that was established in 1990. The system describes the distribution and characteristics of hazardous substance emergencies, the health effects caused, any risk factors for these health effects and any strategies which may reduce these health effects from the release of hazardous substances (Ernst et al., 2005). Ernst et al. found that most injuries arising from pool chemicals came from improper mixing of chemicals and in response, an increase in available information and awareness-raising around the dangers of improper mixing of chemicals were produced and distributed. The HSEES system is also used to identify which industries account for the most chemical-related injuries and which releases are most likely to occur from these industries (Anderson and Wu, 2015). Anderson also found that the most common form of death or injury was related to the transport of chemicals via road and suggested the means to reduce such accidents in the future. In other studies, the HSEES system was used to develop a list of key chemical hazards to public health on a state-by-state basis, allowing for enhanced preparedness to chemical incidents in each state (Orr et al., 2015). The HSEES system was replaced with the National Toxic Substance Incidents Program (NTSIP) in 2010 and helps states to collect surveillance data and to promote cost-effective, proactive measures such as promoting safer designs, developing geographic mapping of chemically vulnerable areas and adopting the principles of green chemistry (design of chemical products and processes that reduce or eliminate the generation of hazardous substances) (Orr et al., 2015).

There is also a global terrorism database (GTD) which collects information on all detected terrorist attacks from across the globe since 1970. It is managed by the Centre for Terrorism and Intelligence Studies and the University of Maryland National Consortium for the Study of Terrorism and Responses to Terrorism (START), a US Department of Homeland Security Center of Excellence (Santos et al., 2019). Santos et al. analysed 45 years' worth of data from the GTD and found that 0.2% of the recorded incidents involved chemicals, although the number of recorded incidents involving chemicals has increased from 2 to 25 since 1970 (Santos et al., 2019).

The data gathered by EBS systems can be used in a variety of ways, such as increasing situational awareness due to chemical incidents, identifying trends in the chemicals which cause the most health effects in humans and mapping where these incidents have occurred (Gaulton et al., 2021, Cook and Brooke, 2021). It can also inform decision-makers in planning and mitigation activities, for instance for chemical spills. Bryant and Abkowitz (2007) developed a tool for chemical spill management based on the lessons learned from previous chemical incidents.

Recommendations for prevention of further incidents can be put forward based on the collection and analysis of EBS data. For example, Dursun analysed a series of incidents in Turkish mines from 2010 to 2017 and found that methane explosions accounted for 68% of the incidents, with a mortality rate of over 92% (Dursun, 2020). The study identified safety problems with existing procedures, errors made at the sites and subsequent measures which could reduce further incidents from occurring (Dursun, 2020).

The EBS method can also be enriched with other sources of data, for example the New York Department of Health and Mental Hygiene developed an on-site system of data collection at various chemical incidents. The data was sent back to their headquarters where the data was analysed and allowed for real-time analysis and mapping of the incidents (Eplan, 2005). This

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system allowed the rapid collection of detailed information on the incidents, helping to improve response times of first responders and reducing casualties caused by chemical incidents.

Olowokure et al. (2005), highlights the lack of sufficient data on chemical incidents of international concern and how this can hamper planning for major incidents. A robust EBS system can also contribute to improving public health preparedness and assist in the estimation of the frequency and geographical distribution of chemical incidents of potential international concern. EBS can contribute to the increased situational awareness of organisations, departments, and individuals of the current trends in chemical health threats, which agents are responsible for most of the injuries caused by chemical incidents and where these incidents are occurring. This awareness and knowledge can be used to address gaps in the preparedness and response to chemical incidents, inform policy and work towards reducing the health burden of chemicals around the globe.

5.2 Industrial and occupational surveillance

5.2.1 Industrial surveillance

Industrial surveillance refers to the monitoring of industrial processes and facilities using various methods to ensure safety, security, and compliance with regulations. It involves the use of sensors, cameras, and other equipment to collect and analyse data for potential risks, events or anomalies.

This can play an important role in preventing industrial accidents and disasters by identifying potential hazards, monitoring equipment and processes, and detecting anomalies and events that may indicate a potential risk. An industrial disaster is defined as the release or spill of a hazardous material from an industrial source that results in an abrupt and serious disruption of the functioning of a society, causing widespread human, material, or environmental losses that exceed the ability of the affected society to cope using only its own resources (Keim, 2011). Industrial accidents can happen due to fires, explosions, spills, and the release or leakage of substances. These incidents can be sudden or prolonged. Dealing with industrial disasters poses distinct difficulties for responding to public health emergencies.

In the US, the Idaho National Engineering and Environmental Laboratory (INEEL) has developed a comprehensive and quantitative risk model framework for environmental management activities at the site. The Environmental, Safety and Health Risk Assessment Program (ESHRAP) is designed to give the best estimates for environmental, safety and health risks. It includes two basic types of risk assessments: risks from environmental management activities, and long-term legacy risks from wastes/materials (Eide and Wierman, 2002). ESHRAP can have a significant impact on industrial surveillance by improving the identification, assessment, and control of environmental, safety, and health risks associated with industrial activities.

It is important also to develop a multi-hazard risk assessment toolkit applicable to chemical disasters, which helps identify, evaluate, and prioritise the risks posed by chemical disasters (e.g. a large spill of chemicals stored in seismic vulnerable tanks) (Brunesi et al., 2019). These

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toolkits can have a positive impact on industrial surveillance by improving the identification and management of potential risks, reducing the likelihood of incidents, and promoting a culture of safety and preparedness within the organisation. One of the well-known toolkits is The Strategic Tool for Assessing Risks (STAR). It presents an encompassing and user-friendly toolkit for all types of risks. It allows national and subnational governments to swiftly carry out a strategic, evidence-centred evaluation of health risks. This aids in organizing and prioritizing health emergency preparedness and managing disaster risks. The tool's effectiveness was confirmed through 64 initial workshops and a worldwide discussion organized by the WHO Region of the Americas in November 2019. An uncomplicated STAR data toolkit has been designed to generate pertinent risk details upon input of data into designated sections (World Health Organization, 2021).

Damage to oil and gas pipelines can lead to accidents in the form of a rupture or, more frequently, latent damage that can result in failure later (Biezma et al., 2020). To learn from the experience of documented pipeline failures, a database of pipeline incidents is needed. The European Gas pipeline Incident data Group (EGIG) was created to manage pipeline incident data. The EGIG database has 5 categories of pipeline failure causes: corrosion, external interference (failures provoked by digging, piling, and groundworks), construction defect/material failure, ground movement (dike break, erosion, flood, landslides), and other/unknown causes. A similar database is managed by the Pipeline and Hazardous Materials Safety Administration (PHMSA) in North America. Pipeline accidents reporting is required by law, but in Europe, the reporting is not mandatory (Biezma et al., 2020). The use of pipeline incident databases can have a positive impact on industrial surveillance by improving the identification and management of potential risks associated with pipeline infrastructure, reducing the likelihood of incidents, and promoting a culture of safety and responsible pipeline management within the organisation.

Oil Spills

Oil spills can be defined as the release of liquid raw/natural petroleum hydrocarbons into the environment, especially into the sea (Wexler, 2014). Although coastal oil spills tend to be highly publicised, crude oil spills in the United States affect inland areas relatively often. Spills to inland areas often affect sensitive environments and can have greater impacts to health and welfare than spills to coastal areas.

In 1992, Emergency Response Branch (USA, covering the states of Illinois, Indiana, Michigan, Minnesota, Ohio and Wisconsin) staff started to develop an Inland Sensitivity Atlas (ISA) to track threats and vulnerabilities. The threats examined were storage tanks, oil, and oil product pipelines, roads, and rail lines with the potential for oil transport, and shoreline lengths of navigable waterways. Geospatial vulnerabilities included populations using drinking water intakes, natural areas, and sensitive species (Brody et al., 2012). Unlike tanker spills in oceans, inland spills originate from industrial and municipal lands, including production sites, local product stores, and transportation corridors. In Ontario, Canada, the Spill Action Centre (SAC) was established to record spill events and other urgent environmental events on a daily basis, initiate or coordinate a response as required, and provide support to municipalities (Cao et al., 2013).

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In the case of oil spills, public health can be directly and indirectly threatened. The health of individual groups of the population may be at risk to a greater extent.

Vulnerable populations include:

- Natural resource dependent communities,
- Response and clean-up workers,
- People living on or near the coast,
- Children, pregnant women, and elderly in spill-affected communities,
- People with chronic illness, health or socio-economic disparities in spill-affected areas (Sandifer et al., 2021).

Effective surveillance systems require a basic understanding of exposure pathways, which includes identifying the contaminant source, available environmental media, exposure points, exposure routes, and the at-risk population. It is important to understand why certain populations are at risk for developing particular short- and long-term adverse health effects (Institute of Medicine (US), 2010).

The Deepwater Horizon (DWH) oil spill in 2010 is the only declared Spill of National Significance in US history, and it significantly impacted the health of people and communities in the Gulf of Mexico region (Sandifer et al., 2021) This event resulted in 11 deaths, 17 injuries, and the largest marine petroleum release in history. Over the following three months, more than 4.9 million barrels of oil were released into the Gulf of Mexico. Although the oil well was capped on July 15, 2010, thus stopping the flow of oil into the ocean, the released crude oil has had prolonged negative effects on marine biota. The proximity of the well to the fishing industry of the Gulf States, coastal tourist attractions, and estuarine, marsh, and protected ecosystems placed these resources in jeopardy of contamination and destruction (Buttke et al., 2012). The Gulf of Mexico Research Initiative (GoMRI) was established in 2010 with $500 million in funding provided by British Petroleum over a 10-year period to support research on the impacts of the Deepwater Horizon oil spill and recovery (Eklund et al., 2019).

Five US states (Alabama, Florida, Louisiana, Mississippi, Texas) reported two types of active public health surveillance: syndromic surveillance and reporting surveillance. **Syndromic surveillance** involves collecting data on sets of symptoms that may be exposure related (e.g., respiratory symptoms) and investigating case clusters. Data for syndromic surveillance come from the Department of Defence (DoD) and Veterans Affairs (VA) treatment facilities as part of the Centers for Disease Control and Prevention's (CDC's) BioSense Program and from hospital emergency rooms and urgent care centres participating in other surveillance programs (e.g., Florida's ESSENCE program).

Reporting surveillance involves collecting data from poison control centres, physician clinics, and other sources, and investigating unusual clusters of symptoms that could be exposure related (Institute of Medicine (US), 2010). States also proposed several improvements of surveillance, among them; there is no validation of exposure reports, monitoring systems that capture relevant data for examining long-term health effects need to be developed; mental

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health surveillance needs improvement; syndromic surveillance system must differentiate between resident and worker status.

A Community Assessment for Public Health Emergency Response (CASPER) was conducted on August 27 and 28th, 2010, in Mobile and Baldwin counties in Alabama because public health officials were concerned that some health effects, particularly mental health outcomes of the Deepwater horizon incident, were not adequately captured by the surveillance systems. A two-stage sampling method was used to select households, and a questionnaire including the Centers for Disease Control and Prevention's Behavioural Risk Factor Surveillance System (BRFSS) was administered. Weighted cluster analysis was conducted, and BRFSS questions were compared to the most recent BRFSS reports and the 2010 results. Overall, mental health symptoms were higher in the three assessment areas compared to BRFSS reports, but lower than 2010 surveys. These results suggest that mental health services are still needed, particularly in households experiencing decreased income since the oil spill (Buttke et al., 2012).

Several studies analysed seafood contamination linked to the Deepwater Horizon (DWH) spill. Xia et al. (2012) analysed 278 seafood samples and compared polycyclic aromatic hydrocarbons (PAH) levels detected by the National Oceanic and Atmospheric Administration (NOAA) Mussel Watch program for the prior 10 years and found no significant difference in concentration of PAH. Dickey and Huettel (2016) found concentrations of potentially harmful oil components were at pre-spill levels soon after the end of the spill, however, residual oil not captured in clean-up in the waters and sediment could provide risk to ongoing exposures (Eklund et al., 2019).

While the DWH incident led to some reactive surveillance, there is a clear need for an effective industrial safety management decision support system alongside robust proactive surveillance for accident prevention at oil and gas drilling sites, specifically for onshore and offshore oil and gas industries during drilling operations. This industrial safety management system will be used for the identification and elimination of potential hazards associated with drilling activities at onshore and offshore drilling sites with an appropriate hazard controlling strategy (Asad et al., 2019).

It's important to note that while industrial surveillance systems are effective preventive tools, they should be complemented by a comprehensive safety management system that includes proper training, risk assessment, data collection, emergency preparedness, and regular safety inspections. Surveillance systems alone cannot guarantee prevention, but they support prevention work and provide valuable insights on real-time monitoring capabilities that enhance overall safety practices in industrial settings.

5.2.2 Occupational surveillance

Hazardous substances in the workplace can cause a variety of occupational injuries and diseases. The term work-related diseases refer to a set of conditions (from chemical, physical

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or biological agents) which may develop in workers who are exposed to hazardous risk factors in their workplace (Centers for Disease Control and Prevention, 2021). To ensure the health and safety of workers, it is essential to introduce appropriate preventive measures in the workplace. These measures should not only aim for the prevention of work-related disease, but also ensure that the workers' health and safety is being maintained and promoted (Proper and van Oostrom, 2019).

Surveillance is a core activity in the practice of occupational health. Two broad groups of surveillance are commonly performed—Occupational hazard surveillance and Occupational health surveillance.

Occupational hazard surveillance

The focus of hazard surveillance is on hazards in the workplace. It has been defined as "the process of assessing the distribution of, and the secular trends in, use and exposure levels of hazards responsible for disease and injury" (Koh and Aw, 2003). For this type of surveillance to be considered, a clear 'exposure–health outcome' relation must already have been established. The surveillance of hazards should result in action to reduce exposure in workplaces where indicated. This will eventually reduce the disease burden arising from hazardous exposures.

In the investigation of occupational chemical exposures, it is essential to have collaboration between poison centres and occupational health and safety teams. Data from poison centres can provide overviews of accidents with hazardous substances at work. Poison centre data also has exposure information that may be useful for managing the incident, or for surveillance and follow-up. Such data is particularly useful in occupational epidemiology and surveillance as chemical exposure data is often lacking in traditional health surveillance. This exposure data could then be used to investigate a variety of occupational issues or groups (Tustin et al., 2018, Schenk and Oberg, 2018). More examples as well as comparisons between poison centre and traditional forms of surveillance will be discussed in the section on poison centre surveillance.

Occupational Health Surveillance

Occupational health surveillance is the ongoing systematic collection, analysis, interpretation and dissemination of occupational health data for the purpose of prevention (International Labour Office, 1998). It may be required by law for workers potentially exposed to hazardous substances such as solvents, fumes, dusts as well as biological and other hazards.

Information on incidence and prevalence of occupational disease and injury provides a basis for prevention and control. Public health surveillance can lead to discovery of new associations between occupational agents and accompanying disease (Koh and Aw, 2003). Occupational health surveillance is important for:

- early detection of ill-health effects because of exposure to a hazard
- helping employers evaluate potential health risks at their workplace by providing them with essential data

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- offering employees the space to raise concerns about their health in the workplace
- highlighting errors and gaps in workplace control measures, therefore providing invaluable feedback to the risk assessment
- providing employees with an opportunity to reinforce their training and education (Health & Safety Authority, 2023).

The surveillance programme should be set up only if it is established that it improves the prevention of, and protection from, work-related risks. To determine this, four criteria must be met:

- need,
- relevance,
- scientific validity,
- effectiveness (European Agency for Safety and Health at Work, 2023).

To prevent work-related and occupational diseases, the European Union (EU) Directive 89/391 has addressed occupational health surveillance, recommending that workers are provided with access to health surveillance at regular intervals (Council of the European Union, 1989). However, the concept of occupational health surveillance has not been explicitly defined nor carried out across the European Union. The EU's regulatory framework is designed to accommodate a diversity of perspectives and considerations. This flexibility allows for a range of practical applications, even within the context of a single regulation. However, this can also lead to inconsistencies and a lack of harmonisation. To address this issue, efforts are needed to promote greater alignment and consistency in the interpretation and implementation of EU regulations (Colosio et al., 2017).

There are several approaches which can be used to help identify and monitor the exposures to hazards and their related health effects. It is important to emphasise the ethical considerations when handling any health-related data. It is essential to ensure that the privacy of the workers is being protected, and that occupational health surveillance is not being used in any prejudicial manner or for any discriminatory purposes. This means that the system for the collection, processing and use of health-related data needs to be well-controlled (Verity and Nicoll, 2002).

Hazard exposure in the workplace and related health effects can be identified and monitored through occupational health surveillance, using:

- medical health checks, which are tailored to the exposures and conditions of the workplace
- biological tests (including biomonitoring) for specific indicators of risk.

Medical Health Surveillance

Medical health checks refer to periodic clinical and physiological assessment of employees. Such screening may include symptom review, clinical assessment, medical examination, special investigations, and determination of immunity status. Medical health checks may help detect early effects of exposure to occupational hazards. If any of such are found, workers should be removed from further exposure, to reverse early subclinical changes (Aw, 1999).

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If atmospheric or biological monitoring shows that there could be effects on the health of a worker because of exposure to chemicals at work, medical surveillance is necessary. Exposure to the following types of chemicals may be appropriate for medical surveillance:

- Chemicals that have a recognised systemic toxicity, i.e., an insidious poisonous effect
- Chemicals known to cause chronic effects, e.g., occupational asthma
- Chemicals known to cause severe dermatitis
- Chemicals that are known or suspected carcinogens
- Chemicals that are known or suspected teratogens or mutagens, as science develops
- Other chemicals where there is a likelihood that the disease or effect may occur under particular conditions of the work activity (International Labour Organization, 2004).

Biological Tests and Biomonitoring

Biological tests can play a role in health surveillance via exposure assessment when a chemical risk factor is present. There are two kinds of biological tests which can be used for health surveillance purposes: biological monitoring, and biological effect monitoring.

Biological monitoring refers to the measurement for the presence of a chemical (or its breakdown products) in a biological sample, usually urine or blood, to indicate how much of the chemical has entered the body. For example, biological monitoring can be used to measure the presence of lead in the blood of workers who are exposed to lead dust.

Biological effect monitoring refers to the measurement of biological effects, which occur because of the absorption of a certain chemical. For example, biological effect monitoring can be used to measure the presence of cholinesterase in the blood of workers exposed to organophosphorus pesticides.

As such, biological monitoring and biological effect monitoring can play a role in health surveillance by helping to evaluate control measures and manage risks to workers' health (Health and Safety Executive, 2023, Lele, 2018).

Recent advances in molecular biology can aid health surveillance by identifying molecular biomarkers for exposure, response, and genetic susceptibility. These include measurements for gene damage, variation, and products in cells and body fluids, such as oncogenes, tumour suppressor genes, DNA adducts, genetic polymorphisms, and metabolic phenotypes in exposed populations (Koh and Aw, 2003).

Hahn et al. (2012) argued the importance of including human biomonitoring in national chemical surveillance programmes as part of the German Chemicals Act. Human biomonitoring data is extremely valuable for low-dose exposures. In chronic low-dose level exposures, the scientific assessment of related health impairments is often not possible without existing human biomonitoring data. For adequate surveillance of poisonings, ingestion by children, workplace chemical exposures and incidents, we must establish nation-wide programmes for monitoring human exposures which keep pace with the progressive production of new chemicals. This must be done in close co-operation with physicians, poison

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centres, government safety organisations, and environmental health specialists and must be based on proven expert judgement tools and available human biomonitoring data. Researchers from Russia (Kromerova and Bencko, 2019), also argue that human biomonitoring was crucial for population surveillance of xenobiotic poisoning.

Occupational health surveillance is conducted in two ways: by periodically assessing workplaces to evaluate potential hazards and by regularly examining workers to detect early signs of reversible ill health effects. The data gathered from such surveillance can offer crucial insights into possible emerging patterns regarding workplace hazards and illnesses. However, such data is only useful if it is followed by preventative action, as well as an evaluation of the effectiveness of the interventions taken.

5.3 Environmental contamination surveillance

5.3.1 Air pollution surveillance

Stationary site air quality monitors can provide the levels of air pollution over time, showing a diurnal pattern. This can infer the exposure to air pollutants for populations, assuming that everyone in that population is breathing in, or exposed to, the same level of air pollution.

In reality, the level of air pollution that people breathe varies. Vulnerability also affects the relationship between air pollution and health. Surveillance can provide intelligence on these relationships and the burden on health. Air pollution surveillance can thus include how air quality varies, both spatially and temporality, but also include factors on vulnerability and how that varies, burdens on disease, mortality, and morbidity. Surveillance often accounts for changes over time of the effect of air pollution on mortality and morbidity, often using time series.

From the literature, an example in Turkey, looked at mortality risk with methane exposure from mines and mining incidents. Over the period 2010-17, the mortality rate was 93% due to coal mine incidents, whereas the death toll caused by methane explosions and other gas-related accidents was 68% (Dursun, 2020). Data on mining incidents were analysed for fatalities, methane explosions and other gas-related accidents. It was concluded that both the highest number of injuries and deaths in Turkey's underground coal mines was caused by gas exposures. The group analysed annual coal production (activity in the mines) as a proxy for exposure. This surveillance and analysis of mortality over time allowed for the identification of the largest cause of death as gas related.

A key challenge for all air pollution surveillance is that the surveillance and reporting systems are non-existent or less than complete. Dianat and Nazari (2011) conducted a study to investigate the characteristics of unintentional carbon monoxide (CO) poisoning in Northwest Iran. They used a combination of surveillance data from emergency medical transport records and death reports, as well as a household survey to assess risk factors associated with unintentional CO poisoning. Over the course of two years, a total of 1,005 and 95 non-fatal and fatal poisonings were confirmed to be due to CO exposure. These non-fatal CO poisonings contributed to 17.6% of all poisonings in the region. Non-fatal cases occurred the most among females aged 25-44, while fatal cases were most common among those over 64. The survey identified domestic gas appliances such as water heaters and cookers, as the

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primary source of all CO poisonings (98%), with the mechanism being due to poor installation and defective devices. 48% of these cases occurred in the bathroom. Most (57%) incidents occurred in owner occupied homes, with fewer (40%) in rented homes. Most households were not aware of the hazards of CO exposure. Due to limitations of the reporting systems available, only non-fatal data of individuals requiring patient transport and emergency department treatment was available, excluding those who did not seek treatment or were treated in outpatient clinics. Although the use of surveys allowed the researchers to learn more about their population that would have otherwise been unattainable, the use of surveys is subject to potential biases in recall and reduces the ability for public health programmes to react timely without consistent and accurate baseline measures of risk factors and prevalence.

In the US, two key air pollution surveillance programs are the Agency for Toxic Substances and Disease Registry (ATSDR) acute hazardous substance release surveillance programs and the Centers for Disease Control and Prevention (CDC) National Centre for Environmental Health Tracking Program (Mukhopadhyay et al., 2018). Although there is overlap in the sources they use, the programs play complementary roles to each other. Mukhopadhyay's group demonstrated some key differences in their investigation of CO-related incidents between 2005-2014 (Mukhopadhyay et al., 2018). Using ATSDR data, they were able to identify all but 16% of the source of CO among those injured by CO poisoning. The three most common sources of CO were HVAC systems, generators, and motor vehicles. Only 2.6% of incidents were missing information on the primary causal factor in the poisoning. However, the ATSDR collects more information on the actual chemical incident itself, while the CDC program collects clinical data that is key for epidemiologists in ensuring individuals meet the case definition for a particular air pollution exposure surveillance. As a result, cases would only meet the Council of State and Territorial Epidemiologist's definition of a suspected poisoning, due to the lack of medical charting that is collected in ATSDR.

In emergency responses, air pollution surveillance has been used to monitor carbon monoxide (CO) exposures. When Hurricane Ike struck Texas, US in 2008, the CDC used five disparate surveillance sources (poison centre calls, emergency department visits, hyperbaric oxygen treatment database, disaster mortality surveillance) to monitor and characterise CO exposures. During the surveillance period, generator misuse comprised 82-87% of CO exposures, depending on the data source (Centers for Disease Control and Prevention, 2009). In contrast, a report of CO exposures during Hurricane Sandy in 2012 reported only 4 of 263 case deaths from CO exposures, based only on poison centre calls (Centers for Disease Control and Prevention, 2012). CO exposure-related deaths were likely under-reported based on larger numbers reported by the media during the hurricane event.

Having established surveillance systems allows for comparisons between emergency and non-emergency settings. In Maine, US, a state surveillance system was established using hospital discharges, emergency department, outpatient, and mortality data that allowed estimation of state-wide incidence and trends of CO poisonings over time (Graber and Smith, 2007). The state group emphasised identifying exposures in occupational settings, using a multi-layered approach that searched for payment codes labelled as worker's compensation and injury codes which potentially identified occupational settings. Newspaper searches were also used to supplement information on the place and type of exposure as secondary diagnosis codes labelling external causes of injury are not always utilised. During 5 years of surveillance, 60% of the 740 cases were seen in the emergency department, while 34.3%

were seen in outpatient clinics. The remaining 6.4% were hospitalised. Nearly a quarter (23.1%) of patients aged 16 or older were classified as occupational exposures.

An ice storm in 1998 left half of the state of Maine (US) without commercial electrical power. During that 3-week period, their surveillance systems were able to detect 193 excess monthly outpatient cases and 10 excess monthly hospital admissions. In comparison to the rest of the surveillance period, a higher percentage of cases during the disaster period were age 65 and older (12.0% vs 4.3%) and female (61.8% vs 45.2%). Only 2 CO-related deaths were identified during this period. It was difficult for researchers to ascertain the source of exposures in many cases due to non-mandatory reporting of CO exposures in electronic medical record (EMR) data. In addition, the researchers were unable to characterise certain demographics, particularly ethnicity data due to how the records were de-identified in Maine (Graber and Smith, 2007).

Monitoring of air pollution has also been historically important for suicides and self-harm. In England and Wales, gassing accounted for 5.2% of suicides between 2001-2011 (Gunnell et al., 2015). While gas suicides had a 53% reduction during this time, this was primarily attributed to a reduction in car exhaust and other CO poisonings where new policy measures reduced the concentration of CO produced from motor vehicle exhausts. In contrast, increases were seen in alternative and newer methods of gassing, particularly in helium (17-fold increase) and barbecue charcoal (10-fold increase). Deaths involving these newer methods tend to be from individuals of wealthier socio-economic groups and were younger. Although suicide data was systematically obtained from the Office of National Statistics (ONS) via ICD-10 codes, free-text searching of coroners' reports was required to obtain information about the specific gases used and their sources. Only 40% of deaths had this additional information (Gunnell et al., 2015).

Forensics data has been used in other countries as a form of air pollution surveillance. In the Czech Republic, researchers used autopsy data from 1947-2006 to examine cases of CO poisoning (Janik et al., 2017). They found that accidental poisonings exceeded suicidal poisonings (45% vs 40%), with most fatalities from coal gas inhalation. Researchers were able to quantify the level of exposure by looking at measurements of mean blood carboxyhaemoglobin (COHb), although COHb levels were highly variable (66% +/- 16.74%, min 3%, max 98%) across all cases. Alcohol was involved in many cases; over one third (37%) of all cases examined had a positive blood ethanol concentration. Lastly, there was a positive correlation with winter months and accidental poisonings ($p<0.05$).

In Toronto, Canada, death data obtained from coroner's office charting was stratified into three groups: suicides by compressed gases such as helium or nitrogen, charcoal burning, or motor vehicle exhaust (Sinyor et al., 2019). A ten-fold increase in helium-related suicides and five-fold increase in charcoal-burning related suicides was seen when comparing deaths between 1998-2003 and 2010-2015. There was a large decrease in suicides due to car exhaust (78%). Furthermore, only 26% of cases were able to determine the source of the compressed gases.

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The work conducted in Canada, the UK and the Czech Republic highlights how data from coroners or forensic pathologists can be used in air pollution and health risk surveillance, rather than using environmental monitors. However, the Canadian study highlights the need for better reporting requirements and linkage. With nearly 75% of sources of compressed gases not known, it is difficult to determine what public health actions and policy need to be taken to reduce the risk of exposure. Basic demographic data should be easily linkable from other sources to better examine their associations with key health outcomes.

Surveillance with environmental air quality monitoring

Collaborating with different programmes and utilising their datasets can improve the impact of air pollution surveillance. In California, US, Wilhelm et al. (2008) combined health survey data with routine air monitoring and traffic data to examine associations between pollutant concentrations with reported asthma symptoms and emergency room visits/hospitalisations (Wilhelm et al., 2008). Annual concentrations of CO, NO2, O3, PM10, and PM2.5 from the nearest monitoring station within five miles of each subject's home was used. The group observed 2.29 times increase in the odds of daily/weekly asthma symptoms for 1 part per hundred million (pphm) increase in annual average of O3, after controlling for ethnicity, PM10 exposure, and poverty level. There were also positive associations between living close to heavy traffic and reported ED visits and hospitalisations. Their work highlights the benefits linking routine environmental monitoring to survey work. Linking to surveys allows for important confounding variables, such as the subject's time-activity (i.e., time spent in vehicles, school) patterns, to be assessed in air pollution exposure analyses.

In Canada, air quality monitor measurements of PM2.5 were used along with forest fire and pharmaceutical data to examine the associations between PM2.5 exposure and asthma reliever dispensations in fire and non-fire affected populations (Elliott et al., 2013). Using time series models adjusted for temperature, humidity and temporal trends, the group found that fire season related PM2.5 was positively associated with increased asthma medication dispensations in fire affected populations. On extreme fire days, there was a positive association with dispensations (prescriptions) regardless of whether the population was affected by fire or not.

The data captured by air pollution surveillance also provides opportunities to improve environmental models as well as develop tools that help public health practitioner decision-making. For instance, the USCDC Environmental Public Health Tracking (EPHT) network and Environmental Protection Agency (EPA) used existing air quality monitoring data to develop hierarchical Bayesian models to predict PM2.5 and Ozone concentrations for the entirety of the US (Hao et al., 2012, Vaidyanathan et al., 2013). This was valuable because monitoring data at the time was limited to certain regions or was infrequent. In 2005, fewer than 20% of US counties were monitoring PM2.5, with most of their monitors only operating every third day (Vaidyanathan et al., 2013). This model was eventually combined with routine hospital data to assess associations between PM2.5 and respiratory emergency department visits (Strosnider et al., 2019).

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Air pollution surveillance data can also be used to improve the tools that public health practitioners use in decision-making. The US CDC used air quality data, combined with other key databases about health, population vulnerability, and forest fire/burn severity to create a real-time vulnerability assessment tool for wildfire smoke hazards (Vaidyanathan et al., 2018). This tool provided public health practitioners with the tools to better identify impacted communities and those particularly vulnerable, assess exposures at the population level, and inform what interventions to use during wildfire events.

There are opportunities to improve surveillance through finer examination of the air pollutants themselves. Canadian researchers developed a new method of estimating the risk of mortality due to PM2.5 using satellite image estimates (Crouse et al., 2016). By modelling the proportions of the components of PM2.5 (sulphate, nitrate, organic mass, black carbon, and mineral dust) with the total concentration of PM2.5 together, they achieved a superior predictor of mortality and were able to better characterise the toxicity of PM2.5 in its entirety.

As shown above, there are many approaches to air pollution surveillance. The sources and skills required to analyse and share findings already exist within our current public health systems. The challenge is having policy makers and public health practitioners recognize the significance of air pollution surveillance as a key public health issue, and dedicating resources to help public health surveillance standardise data collection and analysis. Continued access to vital statistics and other routine health data is needed to support the necessary surveillance that sets future standard setting and identification of emerging environmental exposures and health outcomes (Thurston et al., 2009). National governments should adopt standardized variables for individual health records for important health conditions associated with environmental exposures, while ensuring data is available at appropriate spatial and temporal resolutions. By investing into air pollution surveillance, it improves our capacity to plan and evaluate public health actions, our ability to respond to emergencies, and ability to foster collaboration across different environmental, toxicological, and health programs (Graber et al., 2007).

5.3.2 Chemicals in water surveillance

Safe, clean water is the most important precondition for human life. The quality of water bodies is affected by natural and anthropogenic factors. Contamination can derive from various sources, such as industrial and domestic discharges, agricultural run-off, natural disasters, and incidents. These events can pose a serious threat for human health and ecosystems. It is fundamental that there is continuous, vigilant, and effective surveillance and quality control of drinking water supplies for the protection of public health.

An integral part of any drinking water monitoring programme is surveillance of all steps in a drinking-water supply chain, from catchment to consumer, including water quality monitoring with laboratory samples across drinking water sources and all parts of the drinking water network. Monitoring must be carried out according to drinking water regulations, with inspection and sampling occurring regularly and planned at specified intervals. In the case of contamination events, sampling must be based on the risk assessment results.

The guideline values for chemicals in drinking water are available in the WHO Guidelines for drinking water quality (World Health Organization, 2017). Most of them relate to a level of exposure that is regarded as tolerable throughout life. Acute toxic effects are considered for a limited number of chemicals. The amount of time it takes for exposure to a chemical far in excess of the guideline value to cause adverse health effects will vary depending on the specific contaminant. If a guideline value is exceeded by a significant amount or for more than a few days, it may be necessary to act rapidly to ensure that protective health action is taken and to inform consumers of the situation so that they can act appropriately (World Health Organization, 2017).

Accidental chemical water pollution can occur for several reasons and situations. Spills can contaminate the surface, surface water, and groundwater, leading to a decline in the quality of drinking water. Even in small quantities, spills could affect the long-term toxicity levels in ambient waters (Cao et al., 2012). Moreover, floods can also have multiple environmental and health consequences. These may include direct contamination of homes, contamination of drinking water sources, and disruption of drinking water and sewage systems. During floods, chemicals from sources such as fuel storage, agricultural phytopharmaceuticals, agricultural runoff from fields and livestock manure, and street runoff can enter water bodies and contaminate drinking water.

Geospatial-analysis tools are very useful for monitoring water quality in complex supply or stream networks. Geographic information systems (GIS) have been broadly adopted for use in spatial data management and analyses and for organising geographic data into layers and relating sets by geography. GIS tools aid in identifying, responding, and mitigating the effects of chemical release incidents. Geospatial-analysis tools help to analyse stream networks by modelling the transport of contaminants from a spill to a receiving stream and significant changes between background and potentially impacted sites (Agarwal et al., 2020, Martin et al., 2004).

Long-term environmental monitoring and health data are crucial for better preparation in dealing with impacts of future chemical contamination of water incidents. There are regions around the world where major environmental disasters occur repeatedly, such as hurricanes and floods, that result in chemical contamination of water. Monitoring is needed in order to fully understand the magnitude of effects and better prepare for the impacts of future disasters. In addition to health data, the report suggested monitoring for exposures to contaminants, toxins, organisms, and conditions associated with disasters would be an important future component of the Gulf of Mexico Community Health Observing System (Sandifer et al., 2020).

Harmful Algal Blooms

Microscopic planktonic algae and cyanobacteria are present in all aquatic environments (Hallegraeff et al., 2004). The rapid growth of plankton algae is referred to as algal blooms. Most of such algal blooms are an essential part of marine habitats, as they present an important food source for bivalve shellfish (oysters, mussels, scallops, clams), and larvae of commercially important crustaceans and finfish. As such, they are hugely beneficial for aquaculture and wild fisheries operations. However, there are some algal blooms which have been found to be harmful - not only to the environment and to other animals, but also to humans. These are so-called **harmful algal and cyanobacterial blooms**, or HABs (National Ocean Service, 2021). Contact, inhalation, or ingestion of contaminated water or seafood can cause symptoms such as skin reactions, eye irritation, ear irritation, liver damage, and

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gastrointestinal, respiratory, and neurologic dysfunction (Centers for Disease Control and Prevention, 2023a).

A collaborative group for Ligurian syndromic algal surveillance in Italy (Durando et al., 2007), launched clinical, epidemiological and environmental investigations in Genoa after emergency number of patients admitted to hospital after spending significant time on the beach. A case definition of HAB-related illness was developed:

- presence at the seaside (< 90 m from the shoreline), in concomitance with *Ostreopsis ovata* algal bloom,
- seeking medical care in a hospital emergency department,
- presenting with at least two of the following symptoms: cough, dyspnea, sore throat, rhinorrhea, fever >=38°C, headache, lacrimation, nausea/vomiting, and dermatitis.

After initial investigations proved successful, an **algal syndromic network** was set up which included staff from regional epidemiology centres, hospitals, and local public health units. The surveillance was then continued in 2005-2006 to investigate the occurrence of these diseases more. It's unclear if this surveillance system is still in place as no further studies were found.

Other examples of surveillance of relevance included the usage of remote sensing for the identification and tracking of HABs globally via satellite ocean colour imagery (Maguire et al., 2016). It has proven to be particularly useful over the past decade and has quickly become an essential tool for chlorophyll-a retrieval algorithms, estimation of phycocyanin, capturing spatiotemporal patterns of cyanobacterial blooms, red-tide detection, and the time-series analysis of algal blooms (Khan et al., 2021).

HAB forecasting has also been useful in alerting coastal managers to the presence of blooms before they cause serious damage. HAB forecasting can be divided into short-term forecasting (i.e., once, or twice weekly), and long-term forecasting. Short term forecasts can identify which blooms are potentially harmful, along with their size, location, and where they are most likely headed. By contrast, longer-term (or seasonal) forecasts predict the severity of HABs for the bloom season in a particular region. Early warning through HAB forecasting provides health officials, environmental managers and water treatment facility operators with essential information to focus their testing to guide beach and shellfish bed closures or water treatment in a more appropriate timeframe (National Centers for Coastal Ocean Science, 2023).

In an effort to improve early warning systems of bordering regions, the European Union Interreg Atlantic Area project PRIMROSE (Predicting Risk and Impact of Harmful Events on the Aquaculture Sector) connected partners from the EU Atlantic Area (including Spain, Portugal, France, Ireland, and the UK). Their objective was to enhance and expand upon the management and flow of data from existing HAB and biotoxin monitoring programs, as well as to improve the coordination and development of HAB sampling and modelling systems (Ruiz-Villarreal et al., 2022).

Moreover, new technologies are building our abilities to assess harmful algal blooms remotely and rapidly in the field, and to simultaneously detect species and toxins but not many of these systems are incorporating public health surveillance. These technologies open new doors for researching and monitoring HABs and, ultimately, build the potential for prediction and mitigation of these damaging events. Still, despite the promise that emergent technologies hold for scientists and coastal managers, these need to be put together with health professionals to ensure best usage of these systems so, everyday beachgoers, and boaters

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with their eyes on the water who play an important role in HAB monitoring, can also get effective and prompt treatment and preventive advice (Seltenrich, 2014).

In summary, in cases of chemical surveillance for public health, the need for surveillance of water quality and routinely collected samples to establish pre-incident baselines and extended, long-term post-incident monitoring are important issues. Preparation of surveillance and monitoring guidelines for different accidental water contaminations is crucial (Kirby and Law, 2010). In particular, emergencies caused by accidents where chemicals cause massive contamination of drinking water supply need comprehensive guidance. However, every incident is unique and monitoring programmes must be adjusted accordingly. The surveillance of chemicals in water provides important information on the identification and quantification of relevant contaminants, as well as elucidating the cause-and-effect relationships between contaminants and their adverse effects (Altenburger et al., 2019).

5.3.3 Pesticides exposure surveillance

Pesticides are substances or mixtures of substances that are widely used in agriculture (in crop production, disinfecting facilities, and preventing arthropod infestation in animals), in industry (as a disinfectant), and in urban residential areas (applied to yards, public spaces and homes), mainly to control pests. The excessive and widespread use of pesticides are associated with environmental pollution as well as with increased numbers of human intoxications that occur accidentally, unintentionally, and intentionally (Kalkan et al., 2003, Ghanem et al., 2021, Langley and Mort, 2012). Pesticides are toxic and exposure to pesticides remains a significant public health issue worldwide. The health risk to people depends on the toxicity of the pesticide and the amount and way of exposure. They may enter the human body through ingestion, dermal absorption, inhalation, and absorption through the eyes.

Acute severe pesticide poisonings due to unintentional and intentional misuses are a worldwide problem (Langley and Mort, 2012). In low- and middle-income countries intentional pesticide poisoning is a major clinical and public health problem in agricultural communities. Bans and restrictions of highly hazardous pesticides reduce the number of suicides (Ghimire et al., 2022). Studies in developed countries have related long-term pesticide exposure to cancer, adverse reproductive effects, and damage to the immune system. In developed countries acute pesticide poisoning less of a problem despite the bulk of pesticide use in e.g. Japan, North America and Europe (Nesime et al., 2004).

In most countries worldwide, pesticides are subjected to specific pre-marketing authorization processes, which are supported by prospective risk assessments (OECD, 2018). In the EU, active substances used in plant protection products and biocides must be approved according to the regulation concerning the placing of plant protection products on the market ((EC) No 1107/2009). The European Union (EU) have implemented monitoring programs, including measuring actual pesticide residue levels in food, and the European Human Biomonitoring Initiative (HBM4EU), a large-scale human biomonitoring survey in adults and children across five European countries, between 2014 and 2021 included pesticide monitoring (EEA, 2023). Both methods confirmed a drastic reduction in exposure levels from 2016 onwards (Tarazona et al., 2022). Using data from both systems, supported by a literature search, acceptable daily intake (ADI) of the organophosphate insecticide chlorpyrifos has been reduced several times

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following risk assessments by the European Food Safety Authority (EFSA) in the last decade, resulting in its final ban in 2020.

Due to the adverse health effects of pesticide exposure, it is essential to develop public health surveillance systems that efficiently monitor the trends and outcomes of **Pesticide Related Illness** (PRI). PRI surveillance systems are useful for identifying emerging pesticide related diseases, detecting outbreaks associated with new pesticides or new uses of long-used pesticides, and evaluating public health interventions to mitigate dose and adverse health effects.

Surveillance of PRI in the United States is conducted on a state-by-state basis. Data sources used for PRI surveillance include reports from agriculture and environmental protection agencies (data about careless exposures, use and misuse of pesticides), as well as records from workers' compensation claims, poison control centres, death certificates, emergency medical services, hospital discharge, and emergency department visits. Data on PRI can also be found on the Centers for Disease Control and Prevention's National Environmental Health Tracking Network website[a]. As part of PRI surveillance efforts, 30 states in the United States require mandatory reporting of acute PRI from physicians, laboratories, or hospitals to state health departments (Kyeremateng-Amoah et al., 2020).

Langley and Mort (2012), evaluated different data about exposures to pesticides— including calls to poison control centres, emergency department visits data, hospitalizations, and deaths. The data from poison control centres on exposure calls include information about the reason for the call, age group of the exposed (<6, 6–19, >19 years), which pesticide, indication of treatment in a healthcare facility, and the outcome of the exposure.

Walters et al. (2009), described the scope and magnitude of acute illnesses associated with Pyrethrin and Pyrethroid used products in the states of Oregon and Washington from 2001-2005. Data were collected from two similar PRI surveillance systems operated by the Washington Department of Health and the Oregon Public Health Division. Over 5 years, 407 cases fitted their case definition. Cases peaked seasonally, with the largest number of cases occurring in the summer months. Both Oregon and Washington had increasing incidence rates for acute pesticide poisonings from pyrethrin and pyrethroids. State-based surveillance programs turned out as a valuable tool used to estimate the magnitude of the problem.

In South Korea, the magnitude of acute pesticide poisoning is higher than that in other developed countries (Cha et al., 2014). Most pesticide poisoning deaths were the result of intentional poisoning. Elderly suicide by pesticide ingestion in rural areas was found to be a serious social problem. Easy access to pesticides and the lack of management of suicide by pesticide ingestion in rural areas are suggested as major factors related with the high rate of pesticide poisoning in South Korea.

[a] https://ephtracking.cdc.gov/

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In Turkey, the State Institute of Statistics and Ministry of Health did not have data on the morbidity and mortality from poisoning. Poisoning cases are considered as a forensic case therefore these data are collected at the Institute of Forensic Medicine. However, all acute pesticide poisonings may not have been reported to the forensic institutes, and therefore it is difficult to obtain reliable information on the morbidity and mortality resulting from poisoning (Nesime et al., 2004).

Pesticide exposure surveillance is a complex system that still does not work well in many countries. However, examples in the US, Turkey, and China show how pesticide surveillance could be conducted. The US' state-based surveillance programs are a valuable tool that are being used to estimate the magnitude of the problem. An active substance can be approved if it is safe for human health and does not have unacceptable effects on the environment. However, limitations in testing methods, data availability and obligations to communicate approved pesticides' adverse effects (i.e. post-marketing surveillance) imply that such effects may only be recognised after many years (Science Advice for Policy by European Academies, 2018).

In general, whilst there are many examples of pesticide surveillance, the current risk assessment paradigm is fragmented and fails to capture cumulative and combined exposure to pesticides, and the resulting impacts on human health and ecosystems (Sousa et al., 2022). This paradigm is also limited in terms of assessing risks from other potentially toxic substances contained in pesticides, such as co-formulants and adjuvants (Science Advice for Policy by European Academies, 2018).

5.3.4 Maternal and paediatric surveillance

Maternal and paediatric surveillance is an important tool to utilise, for understanding future chemical threats and highlighting very prevalent chemical threats in some of the most vulnerable groups in any population. Currently, the WHO has a maternal health unit that operates a maternal and perinatal death surveillance and response system (MPDSR) (World Health Organization, 2023). This surveillance system is defined as an essential quality improvement intervention which permits the identification, notification, quantification, and determination of causes and avoidance of maternal and neonatal deaths and stillbirth with the goal of orienting the measures necessary for their prevention. This definition also includes confidential enquiries, maternal death reviews, perinatal death reviews, maternal and perinatal death reviews and maternal death surveillance and response.

The primary goal of MPDSR (World Health Organization, 2023) is reducing future preventable maternal mortality through a continuous action and surveillance cycle followed by the interpretation of the aggregated information on the findings which is used for recommended actions that will prevent future deaths. MPDSR can also strengthen quality of maternal and new-born programmes as well as routine data systems such as Civil Registration and Vital Statistics (CRVS) and routine health information systems (RHIS).

In the UK, paediatric chemical surveillance systems include elevated lead exposure in children in England and Wales, for example the Lead Exposure in Children Surveillance System (LEICSS) for England (UK Health Security Agency, 2022). This is a passive surveillance system that integrates reports of incident (newly detected) cases of lead exposure in children from two sources. The first source is cases reported to UKHSA directly from a UK

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Accreditation Service (UKAS) accredited testing biochemistry or toxicology laboratory. The second source is from searching the national case management database for cases first reported from a non-UKHSA source (for example, the managing clinician or an environmental health officer) to a local UKHSA Health Protection Team (HPT), or from other UKHSA departments (for example, UKHSA Radiation, Chemicals and Environmental Hazards Directorate) and not reported to LEICSS by laboratories participating in surveillance. Case notification to UKHSA is voluntary but encouraged for case management and surveillance purposes. Annual reports are published by UKHSA regarding the epidemiological trends of these cases reported[b].

Maternal surveillance

Maternal surveillance can include surveillance of pregnant women, newborns and maternal outcomes. LaKind et al (2001), argued that the key difficulties in determining chemical exposures to babies via breast milk were due to a lack of a standardised surveillance programmes in place for monitoring exposures in breast milk in the USA. These difficulties included inconsistent sampling and analysis protocols, incomplete reporting of sampling methods, non-representative sampling (geographic, parity, age), duration of sampling, limited number of study participants and the number and types of chemicals analysed. A more recent study (Basu et al., 2017) looked into a more efficient way of using dried blood spots from new-borns to determine methylmercury exposure, suggesting that there still wasn't an effective surveillance system in place for maternal exposures to new-borns (Basu et al., 2017).

The active use of surveillance data for maternal outcomes from chemical exposures were found in Iran and Spain. Karimi et al. (2020), accessed the Foundation of Martyrs and Veterans Affairs database which had listed the 1,100 war veterans who served in Ahvaz, Iran, and was used to identify those exposed to sulphur mustard during the Iraq-Iran war. A significant increase in secondary infertility, spontaneous abortions and congenital anomalies was associated with wives of veterans who sustained injuries affecting more than half of their body.

The aim of the Spanish birth cohort study (Llop et al., 2017) was to investigate the effects of environmental exposure to pesticides, diet, and genetics on foetal and child development in a cohort of pregnant women and their offspring in Spain. Pregnant women were recruited at the beginning of their pregnancy (10–13 weeks of gestation) (2003–2005, n = 855). These women were followed up until the third trimester of pregnancy (n = 794). The final study population consisted of 573 pregnant women with complete data on organophosphate pesticides (OPs) exposure. The urine OP metabolite detection frequencies and the concentrations observed in their study population were low, compared with previously published studies. The concentrations were positively associated with maternal intake of fruits and vegetables during pregnancy, especially the intake of green and fruit vegetables, stone fruits, kiwis, and apples and pears.

[b] https://www.gov.uk/government/publications/lead-exposure-in-children-surveillance-reports-from-2021

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Paediatric surveillance from poison centre data

In the UK, an example of a toxicovigilance study on acute childhood (<12 years old) exposures and outcomes to pesticides is by the National Poisons Information Service (NPIS) through its online poisons information system TOXBASE (Adams et al., 2009). From this, they found that permethrin (insecticide), malathion (head lice treatment) and metaldehyde (slug killer) were the most common exposures for the 1,123 children who were captured in the surveillance system from 2004 to 2007.

A comparison of paediatric poisoning (5 years and younger) from laundry detergent packs against traditional laundry detergents in Texas, US, utilised surveillance data from the Texas poison centre network (Forrester, 2013a). This is a network of 6 centres that service the State that use a common database (Toxicall) to input information as standardised by the Association of American Poison Centers (see Table 3 below). 91% of exposures were from ingestion with a greater risk from packs to traditional detergents for children aged 5 and under.

Table 3. Medical outcome classifications used by the Texas Poison Centre Network (TPCN), extracted from Forrester (2013)

TABLE 1. Medical Outcome Classification Used by the TPCN

Medical Outcome	Definition
No effect	No symptoms owing to exposure
Minor effect	Some minimally troublesome symptoms
Moderate effect	More pronounced, prolonged symptoms
Major effect	Symptoms that are life threatening or cause significant disability or disfigurement
Death	
Not followed (judged nontoxic)	Symptoms not expected
Not followed (minimal effects)	No more than minor symptoms possible
Unable to follow (potentially toxic)	Moderate or major symptoms possible
Unrelated effect	Symptoms unrelated to exposure
Not serious	No effect, minor effect, not followed (judged nontoxic), not followed (minimal effects)
Serious	Moderate effect, major effect, death, unable to follow (potentially toxic)

Surveillance data from the same poisons centre network in Texas was also integral for investigations of insecticide chalk exposure, bombina toads' poisonings and demographic determinants of poisonings (Forrester, 2013b, Forrester, 2018, Trueblood et al., 2018). Pesticide exposure data from Texas between 1997-2000 has also been used to look into clinical manifestations in the 47 counties in the Texas-Mexico border region and found that almost 100% of children reported suffered from acute, unintentional pesticide exposures (Belson et al., 2003). In other parts of the US, there has also been utilisation of prescription records collected by poison centres, where the frequency and magnitude of buprenorphine exposures were compared with methadone (Rege et al., 2020). Poison centre data in the USA was also used to find that products with lamp oil exposures are the most common in children while at home (Sheikh et al., 2013). Belson et al. (2003), described childhood pesticide exposures in an agricultural area on the Texas–Mexico border. Their data suggest that agriculture-related pesticide exposures are rare among young children residing in the Texas border counties. Poison centre coding criteria suggest that most of these exposures occurred in the household rather than in a workplace or a crop field and that the exposures primarily involved household pesticide products.

In other parts of the world, similar utilisation of poison centre surveillance data has been used to investigate herbicide poisoning in Taiwan, where they found a 33.3% mortality rate in children (Hsieh et al., 2013). The only other example found was in Saudi Arabia to investigate the severity of oral poisonings in toddlers (Alanazi et al., 2016).

Paediatric surveillance from other sources of data

Brink et al (2016) accessed the Kansas environmental public health tracking network (from US CDC) for data on children under 3 years old tested for elevated blood lead concentrations. They mapped addresses of cases relative to their proximity to the nearest lead emitting industry, marked as a toxic release inventory (TRI) site. In China, researchers were able to deduce epidemiological trends of pesticide poisonings in children from the Occupational Disease Surveillance and Reporting System (Center for Disease Control, China). They found organophosphate and carbamate insecticides as the leading cause of poisoning in Zheijang province (Yimaer et al., 2017).

Wang et al. (2018b), used data on pesticide poisoning cases registered with the Occupational Disease Surveillance and Reporting Systems (ODSRS) in Jiangsu Province, China, to describe the whole epidemiological features of childhood pesticide poisoning. Pesticide poisoning among kids aged 0-5 years was most common and in the farming season. This may be due to their inherent curiosity and the high “hand-to-mouth” activity. On the other hand, pesticide-related self-harm and suicide is a significant social issue for adolescents in some Asian countries, including China, where most intentional cases are in the 11–14 age group. Similar results in Taiwan found that while younger patients had accidentally swallowed paraquat, older patients had intentionally ingested paraquat (Hsieh et al., 2013).

More recently, Forrester (2022), utilised data from the National Electronic Injury Surveillance System to investigate the number of paediatric lamp oil-related injuries from 2000-2018. Most injuries occurred via ingestion in domestic settings in 1–2-year-old males. Others have made use of hospitalisation data to determine those that were pesticide-related in children and teenagers. Once again, there was a higher level in males with an overall prevalence of 2.1 per 100,000 population (Trueblood et al., 2016).

Kaiser et al (2008), used administrative datasets in a population sample and found that childhood exposure to lead is a big risk for developmental disabilities (measured via ‘special education status’). A retrospective study in Russia exploited information available in archived autopsy reports to understand trends of lethal poisonings in children and adolescents in 2009 to 2018. They found 438 cases diagnosed with lethal poisoning, predominantly in boys with carbon monoxide poisoning being the most common cause recorded (Plis et al., 2022).

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Utilising poison centre data for paediatric surveillance of chemical exposures seemed to be the most common method used by researchers, whilst other methods such as an established environmental public health tracking network were less common, highlighting the lack of these tracking networks on a global scale. Whilst in 2019, the WHO reported 81% of countries reported a national policy or guideline requiring notification of all maternal deaths within 24 hours and 83% of countries reported a national policy or guideline requiring review of all maternal deaths. This review found no critical review of the potential chemical exposures of these, if reported.

Overall, there were few papers from this search that focused on maternal and paediatric surveillance within the literature search (19/47). More research needs to be published in this theme, specifically on the maternal surveillance of chemical health threats.

5.4 System approaches

5.4.1 Systems for chemical incident surveillance

Chemical incidents, whether accidental or intentional, have the potential to cause harm to public health and the environment. Unintentional chemical exposures can occur due to chemical releases from industrial plants, transportation accidents, or other sources. Chemical emergencies may also arise from deliberate acts such as terrorism or criminal activity. Chemical incidents can severely affect the population, infrastructure, environment, and economy.

To monitor and respond to chemical incidents, many countries have established their own tools (i.e., **Chemical Incidents Surveillance systems**). Surveillance data enable public health and safety professionals to better understand the patterns and causes of these incidents, which can improve prevention efforts and preparation for future incidents (Orr et al., 2015). These systems enable rapid detection and response to chemical incidents, helping to prevent or mitigate the impact on public health and the environment.

Chemical emergencies, chemical incidents, and disease outbreaks as a result of the incident represent important public health issues. While some countries are implementing systems to detect and respond to chemical releases, not all are able to do so. In August 2002, the World Health Organization began preparing an international database of chemical incidents of public health importance. After the pilot phase, they realised that this database would eventually provide valuable information on the global scale of chemical incidents, as well as an indication of their public health impact. It would also provide information and evidence on which to base chemical safety capacity-building activities in developing countries (World Health Organization, 2004). In the EU, the WHO database was successfully replaced by eMars, (European Commission, 2020) where accidents are reported to the European Commission in compliance with Seveso Directive (European Parliament and Council of the European Union, 2012) which aims at prevention, preparedness and response to accidents involving dangerous substances in industry in the EU.

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An important aspect of incident surveillance is determining the severity of the incident. Assessment of the environmental consequences of a chemical accident is a demanding and complex task. During the planning process, a broader strategy is needed to predict the environmental consequences of potential accidents. The **Environmental-Accident Index (EAI)**, a simple tool based on such a strategy, has been developed to facilitate consideration of the multitude of influencing variables (Andersson et al., 2005). To manage the risk of chemical spills and risks to human health and the environment, a screening tool was developed in the United States to assess the immediate threat to human and environmental receptors from chemical spills on land. As part of this development effort, a modified Delphi survey was used to identify the most important factors that moderate this risk and the relative importance of these factors (Bryant and Abkowitz, 2007).

Although not a true surveillance system, Belgium uses a **Decision Support System (DSS)** that has been developed to assist public health and other regional and local officials in identifying appropriate actions in case of chemical incidents, particularly those with dermal exposures (Dotson et al., 2015). The DSS is set up in a way to provide a flexible and structured decision tree, but it is important that they also involve experts in decision making. In operation, the DSS and associated instruments provide a valuable addition to existing protocols and specifically protect public health interests (Smolders et al., 2014). The DSS could eventually be set up to operate in a surveillance capacity.

In the US, the Hazardous Substances Emergency Events Surveillance System (HSEES) was established by the Agency for Toxic Substances and Disease Registry (ATSDR) to collect and analyse data that would allow researchers to describe the public health consequences associated with hazardous-substance-release events that occur in facilities or during transportation and to develop activities aimed at reducing the harm from such releases. Acute chemical incidents can result in serious public health consequences, including the need for evacuations, morbidity, and mortality (Centers for Disease Control and Prevention, 2005, Keim, 2011, Anderson and Wu, 2015). The HSEES Program concluded in 2009. The National Toxic Substances Incidents Program (NTSIP), which began in 2010, is modelled partially on HSEES, with additions suggested by stakeholders to have a more complete program. NTSIP collects and combines information from many resources to protect people from harm caused by spills and leaks of toxic substances (ATSDR, 2018).

The **Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH)**, aims to improve the protection of human health and the environment from the use of chemicals by encouraging cooperation between EU member states, including cross-border cooperation, the creation of modules within the EU mechanism and the consideration of reinforcement between member states as precautionary measures, such as in major international events (Domres et al., 2009, Stewart-Evans et al., 2014). REACH registration allows surveillance of chemicals in use and potential health effects.

Having networks that improve international cooperation and coordination to environmental disasters allows for the potential of a unified strategy and methodology in future incident surveillance. To support the response to natural hazard-related and human made disasters, the Rapid Risk and Impact Assessment Tool was developed by the European Multiple Environmental Threats Emergency NETwork (EMETNET) project that the EU co-founded. The methodology and tool were developed to support and strengthen interdisciplinary collaboration in response to environmental emergencies. Such a network removes geographical barriers for international response to supporting countries that are facing an environmental emergency in its early phase. This methodology considers the short-, medium- and long-term impact of a disaster on the environment and public health and aims to provide a coordinated approach to risk and impact assessment, while other tools consider environmental impacts with limited public health aspects (Goode et al., 2021). One of this is the **Flash Environment Assessment tool (FEAT)**, which is the first tool that addresses environmental incidents via an integrated human health, environmental and long-term impact assessment (Posthuma et al., 2014).

Data collected in chemical incident surveillance could be used to improve incident response tools. For example, 'The Coastal Ocean Monitoring and Prediction System' was established in 1997 as an ongoing regional coastal ocean observing program operating along the Gulf of Mexico's west Florida coast in the United States. Consisting of a numerical circulation model and a Lagrangian particle transport model, it rapidly produces simulations that alert authorities to high-impact areas following the introduction of hazardous material into the area (Havens et al., 2009). Observations, data, and West Florida coastal ocean and estuary model products are available for dissemination in real-time by various means including the internet to the general public, as well as federal, state, and local emergency management officials (University of South Florida's College of Marine Science, 2023). Feeding chemical incident surveillance data into these systems could improve their models, better predicting potential risks and hazards, and improve response strategies.

5.4.2 Environmental public health tracking

The surveillance of environmental exposures, hazards and the resultant health impacts involve **Environmental Public Health Tracking (EPHT)** techniques, a concept first introduced in the late 1990s by the US Centers for Disease Control and Prevention (CDC). The CDC define EPHT as 'the ongoing collection, integration, analysis, interpretation, and dissemination of data from environmental hazard monitoring, and from human exposure and health effects surveillance' (Centers for Disease Control and Prevention, 2023b). The US has been leading the development of EPHT in practice since its inception in 2000.

An effective environmental public health surveillance system utilises hazard, exposure, and health outcome data to provide public health professionals a picture of the relationship between the environment and health. Environmental monitoring data and health surveillance systems that currently exist are generally not compatible with one another. There exists a lack of common standards in how data are collected, including where data are collected, the frequency of collection, the characteristics collected, and data formats. Among other uses, Charleston (Charleston et al., 2008) suggest that an EPHT Network can address weaknesses and gaps associated with utilising and linking these types of data, including chemical health threats and exposures.

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Having a well-defined purpose for systematically collecting relevant data is key. State and local programs play a crucial role in conducting meaningful surveillance and connecting it with evidence-based outreach and interventions. Since 2000, the US congress has funded the US CDC to build a national EPHT network to support US States' environmental public health surveillance (Shire et al., 2011). Although capacity has improved, fragmentation was still found within occupational health surveillance, prompting further funding to develop environmental occupational health surveillance over the past decade. The US EPHT programme and funded states programmes often provide the best practice for EPHT and Tracking hubs.

Some examples of EPHT for chemical health surveillance include:

- The first surveillance system for acute chemical incidents was developed in Wales in 1993-1995. A multi-agency community-based surveillance system captured the frequency, nature, and locations of incidents. This is the forerunner of subsequent UK systems including SWEISS (south west England) and the UK Health Security Agency's Environmental Public Health Surveillance System (EPHSS) for England (Bowen et al., 2000)
- New York State: Associations between PM2.5 and Ozone and Term low birth weight-used data from the EPHT Network (Talbot et al., 2008)
- The New York State Department of Health developed a user-friendly interactive system to access and link environment and health data, often a challenge because these data are managed by different data stewards, may contain confidential information that must be protected, and have not been collected in a manner to facilitate linkages. Available tools for analysis, visualization, and reporting of these data are either difficult to use or not available through a common user interface. The EPHT system allows for this, while protecting confidential information (Brown et al., 2015)
- National Biomonitoring Network in the US: to harmonize approaches to human biomonitoring in the US, thus increasing the comparability of human biomonitoring data across states and communities (Latshaw et al., 2017)
- In 2017, the US CDC added pesticide exposure and 70 years of climate data to their national EPHT programme (Outin, 2014)
- Chemical hazards in private water supplies –was included as a pilot 'proof of concept' EPHT study in England (Leonardi et al., 2012)
- A local EPHT was set up in Sandwell Metropolitan Borough Council, West Midlands (England), to address the 'environmental health data gap' through systematically linking data on environmental hazards, exposures, and diseases. Existing networks of environmental, health and regulatory agencies developed a suite of innovative methods to routinely share, integrate and analyse data on hazards, exposures, and health outcomes to inform interventions. As a result, horizon scanning systems have been established, at almost zero cost (Saunders et al., 2017).
- The 2001 California Health Interview Survey (CHIS), with reported asthma symptoms and emergency department (ED) visits/hospitalizations, was linked with air quality monitoring and traffic data. This was used to estimate associations between traffic density and outdoor air pollutant concentrations and childhood asthma morbidity, and used to evaluate the usefulness of such databases, linkages, and analyses from the

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Environmental Public Health Tracking (EPHT) network in California (Wilhelm et al., 2008)

- EPHT programmes can include cluster investigation guidance, and a centralized, coordinated response system for cancer cluster inquiries, as a US federal initiative (Kingsley et al., 2007)
- Epidemiological patterns of asbestos exposure and spatial clusters of incident cases of malignant mesothelioma from the Italian national mesothelioma registry (ReNaM), from 1993-2008, found clusters associated with asbestos cement plants, as part of the Italian EPHT programme (Corfiati et al., 2015).

Young et al (2008), utilised data collected as part of the US Environmental Public Health Tracking programme. "If a county consistently has substantially higher Myocardial infarction (MI) rates than can be explained by a model that otherwise describes the association well, the state health department might be interested in a more in-depth study in that county". They said that the process of relating public health to environmental factors, from data collection through interpretation is challenging. Simplifying assumptions are often needed to move forward, and standardized analytical approaches should be adopted if the process is to become routine. As the methodology is refined, the assumptions can be relaxed, and the analyses can become more refined. Young et al (2008) suggested that to advance EPHT, is its use as an optimal analytic approach in which the underlying assumptions are clearly delineated.

Types of data included in EPHT

Several EPHT systems include different types of chemical health threat data. Most common is air pollution surveillance.

An example is the Canadian EPHT system. A review of existing environmental exposure databases and health databases was undertaken (Lavigne, 2012). For environmental exposure data, they reviewed outdoor air quality, water quality and soil contaminants. Health databases included emergency department visits, hospital admissions, cancer and mortality data. National outdoor air quality data could be easily incorporated into an EPHT system while very little data existed on water and soil quality. Boiled water advisories, as a measure of water quality, could be collected nationally to be incorporated in an EPHT system. A national Canadian Health Measures Survey was used as a proxy measure for the distribution of several soil contaminants and chemical products in use in Canada. Health data in Canada was deemed to be good quality and could be easily linked using specific geographical boundaries with environmental exposure data including outdoor air quality and boiled water advisories data (Lavigne, 2012).

Locating data in a EPHT network requires users to be familiar with data types. To help users locate data on the US EPHT Network, Patridge and Namulanda (2008) describes a system of descriptive metadata that provides critical information as to the purpose, location, content, and source of these data. A EPHT Metadata Subgroup, (USCDC) has met since 2003 to initiate the creation and use of descriptive metadata. Efforts undertaken by the group include the adoption of a metadata standard, creation of an EPHT-specific metadata profile, development of an open-source metadata creation tool, and promotion of the creation of descriptive

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metadata by changing the perception of metadata in the public health culture. Other EPHT systems could use this standard as good practice.

An early example of EPHT involved the intelligence gained from reviewing public health response systems in-action, local health departments' experiences with acute and emergency incidents. While each incident is unique, the number and type of response activities are finite. Through comparative analysis, Hunter et al, (2013) identified response patterns that could improve predictions and expectations regarding the resources and capabilities required to respond to future acute events. 120 local health departments were interviewed regarding their recent experiences with real-world acute public health incidents, such as chemical spills and bioterrorism threats. As a result, response profiles and functional and structural response patterns were created with construction of rich, relevant, and practical models of response operations that can be employed to strengthen public health systems.

EPHT examples of developing indicators

EPHT has also been used to analyse public health response systems, create indicators for monitoring environmental health status (Dreyling et al., 2007), develop reproductive surveillance systems (Le Moal et al., 2016), assess potential population exposure to air pollutants (Vaidyanathan et al., 2013), and evaluate conditions for diverse communities around contaminated sites (Burger et al., 2022). EPHT outreach activities involve engaging communities through culturally relevant materials, such as comic books, to raise awareness about pesticide exposures and other environmental health issues (Braggio et al., 2015).

EPHT programmes have developed indicators for monitoring the state of environment health status. The Johns Hopkins Center for Excellence in Environmental Public Health Tracking (US) piloted three pairs of indicators, two of which involved chemicals: 1) air toxins and leukaemia in New Jersey, 2) mercury emissions and fish advisories in the United States, and 3) urban sprawl and obesity in New Jersey (Dreyling et al., 2007). They illustrate the feasibility of creating environmental hazard, exposure, and health outcome indicators, examining their temporal and geographic trends and relationships. They demonstrate how existing environmental health data can be used to create meaningful indicator measures to further the understanding of environment-related diseases and to help prioritise and guide interventions.

To support the research and evidence for a possible causal link between reproductive health and exposure to endocrine disrupting chemicals (EDCs), a reproductive surveillance system was developed in Europe. A multidisciplinary network named HUman Reproductive health and Global ENvironment Network (HURGENT) was created aiming at designing a European monitoring system for reproductive health indicators (Le Moal et al., 2016). 23 potential indicators, based upon a weight of evidence (WoE) approach according to their potential relation with EDC exposure, were developed with the highest scores; prostate and breast cancer incidence, sex ratio, endometriosis and uterine fibroid incidence, indicators related to the testicular dysgenesis syndrome, precocious puberty incidence and reproductive hormone levels. Not only sentinel health endpoints, but also diseases with high burdens in public health are highlighted as prior indicators in the context of EDC exposure. This is the first multi-country reproductive monitoring system found as a good example of EPHT in action.

County level metrics to characterise potential population exposure to PM2.5, from air quality models, were developed as part of the US CDC EPHT network, to help with linkage to health data where air quality monitoring data does not exist. This used a population weighted county centroid containment method in a geo-imputation approach to provide a more spatially and temporally consistent basis for calculating metrics on the tracking network (Vaidyanathan et al., 2013).

Assessing environmental quality often requires selection of indicators. A recent paper suggested creating Environmental Justice (EJ) indicators to evaluate conditions for diverse communities around contaminated sites (Burger et al., 2022). Combining ecological, eco-cultural, and environmental justice parameters as part of a EPHT system can monitor cultural and environmental justices for diverse communities around contaminated sites. They propose that assessment and monitoring include these Eco-EJ indicators, especially for communities near facilities that have extensive chemical or radiological contamination will support monitoring of chemical health threats over time.

EPHT outreach

In Maryland, US, a Behaviour Risk Factor Surveillance System (BRFSS) was used to assess barriers to health care access for Spanish speaking communities. This included pesticide use, of which 30% used indoor pesticides, and 9.2% outdoor pesticides. A Spanish comic book about pesticide exposures was used to engage the Spanish speaking communities in EPHT activities (Braggio et al., 2015).

5.4.3 Evaluation of relevant chemical health surveillance systems

Public-health surveillance for chemical incidents is not a new issue. As far back as 2001, a comment in the Lancet (Kibble et al., 2001) discussed the need for environmental public health surveillance systems for chemical incidents. A pilot active surveillance system in the West Midlands was active since 1995, collecting information on incidents from fire departments, environmental health departments, health authorities, Health and Safety Executive, NHS, and ambulance services. It recorded 52 incidents in 1995 and 300 in the year 2000. Data even then was used to inform public-health decisions, to govern training issues in relation to chemical incidents, and to direct regional publications on hazardous chemicals. The growth of chemical health surveillance since then has been exponential.

Global systems

'**ChemiNet'** is a global public health chemical incident alert, surveillance and response network (World Health Organization, 2003). Initiated by the WHO in 2001 through the International Programme on Chemical Safety (IPCS). This effort emerged from expert consultation with WHO/ILO/UNEP, who recognized that many countries had limited capacity to respond to chemical incidents, incidents which could have the potential for inter-national significance. The 55th World Health Assembly (WHA) in May 2002 expressed concern about the global public health implications of a possible release or deliberate use of biological and

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chemical agents or radio nuclear material. Member States, with the support of WHO, were urged to strengthen systems for surveillance, emergency preparedness and response. Subsequently the 56th WHA in May 2003 revised the International Health Regulations (IHR) to cover not just 3 notifiable diseases but also biological, chemical, or radiological events of international concern, leading to the establishment of ChemiNet. This system provides early warnings, rapid investigation of chemical events, bolster preparedness and response mechanisms, and enhancing local surveillance capabilities. IPCS, as a new joint activity with the WHO **Global Alert and Response (GAR)** team for infectious diseases piloted a system (the **Global Chemical Incident Alert, Surveillance and Response System**) that verifies chemical, biological, radiological, or unknown outbreaks of potential international significance by utilising the GAR team to screen information from a wide range of sources (**Global Outbreak Alert and Response Network (GOARN**), ChemiNet, the **Global Public Health Information Network (GPHIN)**, WHO regional and country representatives, official government sources, WHO Collaborating Centres, non-governmental organizations, inter-governmental organizations, news media, eyewitnesses, and others). These outbreaks may be of chemical, biological, radiological, or unknown origin. Using this information, the team's risk assessment determines the need for government alerts and assistance.

The **Global Chemical Incident Alert, Surveillance and Response System** global database of chemical incidents database is compiled from various sources and includes details: the date the incident occurred; the location and type of incident; the chemical(s)released; the public health impact of the incident; the public health action taken; and whether the incident met the revised IHR criteria for an event of potential international concern. During the first phase of this work, from 1 August 2002 through 30 April 2003, approximately 25 000 events were scrutinized: of these, 364 (1.5%) were identified as being eligible for inclusion in the global database. Of the 364 events, 27 (7.4%) met the criteria for chemical incidents of potential international concern. This database is currently being validated.

Global networking and the role of partners WHO, through IPCS, can provide leadership and a single focal point for a global chemical incident alert, surveillance, and response system. However, a broad partnership is essential for developing, implementing, and maintaining such a system. GOARN provides a means for reporting, investigating, verifying, and responding to communicable disease events of international importance. ChemiNet complements GOARN by fulfilling a similar role in relation to outbreaks of chemical or possible chemical etiology. Networks offer a flexible, robust, and rapid means of responding to events and a way of accessing scarce specialist expertise. In addition, they encourage research and other types of collaboration such as the exchange or provision of financial, technical, and human resources. Thus, partners in ChemiNet play a critical role in mounting an effective response to chemical incidents of public health significance (World Health Organization, 2003).

Rare-events detection

Rare events, especially those that could potentially negatively impact society, often require humans' decision-making responses. Detecting rare events can be viewed as a prediction task in data mining and machine learning communities. By reviewing papers on rare-events, modelling methods including techniques such as data pre-processing, classification algorithms and model evaluation were found. This could be a learning for chemical health

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threats by reviewing good practice from rare-events or learning from the occasions of how these occur and when they can be predicted. The statistics suggested that rare events detection and imbalanced learning are concerned across a wide range of research areas from management science to engineering. Some suggestions from the reviewed papers offer further research directions for the imbalanced learning and rare event detection fields (Guo et al., 2017).

Evaluations of early warning systems

The European Parliament and the Council of European Union recently adopted new legislation that aims to improve the co-ordinated response to cross border health threats (European Parliament and Council of the European Union, 2013). The decision seeks to reconcile this issue for serious threats by linking relevant platforms into one overarching higher level risk management IT platform called the **Early Warning Response System (EWRS)**. The system serves to link other sectors within the European Commission (EC) to public health (e.g., medicines), as well as other EU agencies and international bodies via co-notification features.

A paper reviewed all available alerting systems for cross border environmental health alerts with the view to link other European alert systems to EWRS to facilitate information sharing at both the assessment and management levels (Orford et al., 2014). The paper provides a timely overview of the main systems run by the EC and other international organisations that provide alerts following chemical incidents that have, or may have, the potential to affect public health. The advantages and further considerations of linking these different systems and sectors are highlighted.

The following systems were reviewed:

- Early Warning Response System (EWRS)
- Rapid Alert System for Chemicals (RASCHEM)
- Industrial Accident Notification (IAN) system—cross border industrial accidents
- Major Accident Reporting System (eMARS)
- European Medicines Agency defective product reports
- Illicit drugs and emerging psychoactive drugs (Réseau Européen d’Information sur les Drogues et les Toxicomanies (REITOX)
- The Rapid Alert System for non-food consumer products (RAPEX)
- The Rapid Alert System for Food and Feed (RASFF)

Recommendations are made with the purpose of ensuring that modifications to these systems made to satisfy EU legislation enable a more timely coordinated response and greater awareness of events in Europe, thereby reducing the public health impact from chemical exposures. The authors proposed that a custom-made cross border chemical health surveillance system RASCHEM could meet the needs for timely warning of potential chemical health threats and incidents (Orford et al., 2014).

The RASCHEM[c] system was further developed to improve the speed and effectiveness of public health response to toxic exposures following deliberate or accidental chemical incidents or emergencies. A rapid Alerting System for chemical Health Threats (ASHTII) project developed protocols for dealing with chemical heath alerts and a mechanism as a practical and valuable addition to the European Union and the Health Emergency Operation Facility (HEOF) (Wyke et al., 2010a). The ASHTII project also evaluated standard medical terminology systems to describe symptoms of poisoning to help with chemical surveillance methods (Wyke et al., 2010b). Clinical Effect Profiles (CEPs) were produced to provide concise tabulated summaries of clinical effects reported in the available literature. All clinical effects identified in the review were compared to symptoms reported in internationally standardised terminology systems such as MedDRA, SnoMED-CT, WHO-ART, and poison centre specific terminology such as NPDS and GFKT. From the 118 chemical agents included in the literature review, 1011 clinical effects were identified. 108 individual CEPs were produced; seven were grouped as 'organophosphates' and three as 'cyanides'.

Development of the chemical health threats alerting system RAS-CHEM

It is intrinsically important that both the EUPC Forum and RAS-CHEM can capture the wide spectrum of clinical effects associated with toxic chemical exposure and poisonings. The use of a limited terminology system containing broad definitions of clinical effects may result in reduced sensitivity of the alert system. As a result, an internationally standardised terminology system such as MedDRA or SnoMED-CT has been recommended for inclusion in EUPC Forum and RAS-CHEM. The terminology system[d] chosen for alert systems may become a basis for collation or exchange of cases from poisons centres for different purposes in the future (Wyke et al., 2010b).

6 Discussion

Whilst many robust examples of public health surveillance systems for chemical health threats and exposures were found, alongside many examples of the utilisation of chemicals and environmental surveillance systems for public health use, there were significant gaps identified in the literature.

- One aspect of chemical surveillance that could benefit in improvement is in industrial surveillance. Our review did not find any current surveillance systems monitoring industrial events. However, there are potential opportunities, such as the European Gas pipeline Incident data Group (EGIG) and Pipeline and Hazardous Materials Safety Administration (PHMSA) datasets, which could be used to fill these surveillance gaps.

[c] Although this system is no longer operational and this is currently being replaced, including legislation, by the EC EWRS.

[d] This is also being reviewed and updated.

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There is a clear need for an effective industrial safety management decision support system alongside a surveillance system for accident prevention at oil and gas drilling sites. Apart from the Deep water Horizon oil spill in the US in 2010, that resulted in several reactive surveillance systems being put in place in several US states, our literature review was unable to identify surveillance systems for other oil spill events.

- No examples of long-term proactive water surveillance systems with a public health focus were found. Routinely collected samples to establish pre-incident baselines and extended, long-term post-incident monitoring were key areas where improvement is needed. Where there was an example from Italy (Durando et al, 2007) for harmful algal bloom syndromic surveillance, there was no further information as to whether this system is still ongoing. The Ligurian Syndromic Algal surveillance collaborative group established in Genoa in Italy is a good example of establishment of a surveillance system with public health, clinical and environmental specialists involved. This multi-sector collaboration is key to an effective and impactful chemical surveillance system for public health.

- There were no papers found investigating nor evaluating **land chemical contamination surveillance**. No papers were published or found on describing land contamination registries for surveillance purposes. This suggests a weakness in current chemical surveillance systems, that are not incorporating land chemical contamination as a key surveillance theme. Furthermore, there was a lack of literature describing the systems for chemical surveillance in countries within the global south where there are likely very similar issues yet different challenges in establishing surveillance of this kind.

- There was only one example of the use of registries for public health surveillance of chemicals found in this review. This was the use of the **Intelligence Research in Sight (IRIS)** database in the United States of America. IRIS was accessed to research the demographics, frequency, and visual outcomes of ocular burns. The IRIS consists of a clinical data registry of more than 50 million patients who received eye care nationally (Anchouche et al., 2021).

- While quite a few studies emphasised the importance and need of **biomonitoring** surveillance, only one example from Russia (Kromerova and Bencko, 2019), that utilised biomonitoring surveillance of xenobiotic poisoning for public health and the large **European Human Biomonitoring Initiative (HBM4EU)** was found that attempted to provide more resources in this area.

- There was a lack of studies on paediatric lead surveillance systems which was unexpected. UKHSA's Lead Exposure in Children Surveillance System (LEICSS) publishes annual reports on outputs of this passive surveillance system in England (Lead exposure in children: surveillance reports (from 2021) - GOV.UK (www.gov.uk))

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whereas our literature search did not find other papers on lead surveillance in children elsewhere in Europe, whereas we know they exist (e.g. in France and Slovenia). Evidence was found of a system in the USA (Brink et al, 2016; Kaiser et al, 2008), operating as part of the wider environmental public health tracking system that the US has been developing since the year 2000. The US was also the only country where evidence was found of an **Adult Blood Lead Epidemiology and Surveillance programme (ABLES)**. This programme allowed researchers to access information on lead source exposure, specifically from firearms at work. The ABLES data and the investigations from this data highlighted the seriousness of the lead exposure risk from indoor firing ranges in the USA (Beaucham et al., 2014).

- No studies formally evaluated a chemical surveillance system for public health. This would entail comparing the system against international frameworks, published criteria[e],[f] or against other national chemical surveillance systems for public health. Without studies formally evaluating surveillance systems, it's uncertain what the limitations are and where there is room for improvement. Relatively recently developed systems are still under-used and misunderstood in the context of public health relevance and use.

7 Conclusions and recommendations

In this report, we provide an outline of existing surveillance systems with respect to chemical health threats, incidents, and exposures. We highlighted systems showcasing good practice, outlining their methods, the benefits of system, and examples of practice. We also noted sub-categories where chemical health threat surveillance can be improved.

One of the objectives of this review was to evaluate the efficacy of current public health chemical surveillance (with respect to capturing risks to health from chemical exposures), in relation to international frameworks such as IHR, surveillance evaluation criteria (e.g. USCDC/ECDC) and include papers which evaluate surveillance systems. While we included a couple of examples that outlined appropriate surveillance systems, no papers were found that formally evaluated surveillance system using these criteria and there were not enough comparisons against international frameworks for this objective to be completely met.

It is recommended that future studies need to formally evaluate chemical surveillance systems for public health against the various standards set in international frameworks. A comparison of standards set in international frameworks could also be integral for future work. From this, more formal evaluations against set criteria endorsed internationally could be carried out.

[e] USCDC (2001) Updated Guidelines for Evaluating Public Health Surveillance Systems. MMWR, July 27, 2001/50 (RR13);1-35. Available at https://www.cdc.gov/mmwr/preview/mmwrhtml/rr5013a1.htm#:~:text=The%20evaluation%20of%20public%20health,representativeness%2C%20timeliness%2C%20and%20stability.

[f] ECDC (2014) Data quality monitoring and surveillance system evaluation - A handbook of methods and applications. Available from https://www.ecdc.europa.eu/en/publications-data/data-quality-monitoring-and-surveillance-system-evaluation-handbook-methods-and

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There should be a self-assessment methodology that will allow EU member states or organisations within countries to examine exposure assessment capabilities and surveillance and communication channels between exposure assessors and public health risk assessors for surveillance purposes. Where gaps exist, this self-assessment methodology should provide links to good practices that could improve response, communication and collaboration across local, regional and national boundaries. A network of experts is also needed in the field of chemical health threat surveillance. They provide a clear means of influencing and developing standardised approaches to technical functions and national and international comparability, both of which are goals in the effort to harmonise exposure assessment (Stewart-Evans et al., 2014) and surveillance.

Through several different funding streams, the EU intends to further develop and implement more standardised chemical incident notification and response procedures across the EU to close existing surveillance gaps. It is important to provide appropriate material that provides advice and to support all countries in using the reliable sources that are being established to deal with chemical accidents, surveillance and warning systems (eg RASCHEM and EWRS) (Duarte-Davidson et al., 2014).

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9 Appendices

Appendix 1. Literature search queries conducted

	Search number	Search strategy	Medline	Embase	Web of Science	Scopus
surveillance	1		*Public AND Health AND Surveillance/	*Public AND Health AND Surveillance/	*Public AND Health AND Surveillance/	*Public AND Health AND Surveillance/
	2	1st search 1 AND 2	AND chemical*	AND chemical*	AND chemical*	AND chemical*
	3	1 and 2, then OR 3	OR ("indicator base*" OR "event base*" OR toxicosurvey OR toxicovigilance* OR syndromic OR "poison* cent*")	("indicator base*" OR "event base*" OR toxicosurvey OR toxicovigilance* OR syndromic OR "poison* cent*")	("indicator base*" OR "event base*" OR toxicosurvey OR toxicovigilance* OR syndromic OR "poison* cent*")	("indicator base*" OR "event base*" OR toxicosurvey OR toxicovigilance* OR syndromic OR "poison* cent*")
				*environmental monitoring/		
	4	1 AND 2, then OR 4	OR ((environmental or "public health") adj5 (track* or monitor*OR surveillance OR detect*))	((environmental or "public health") adj5 (track* or monitor*OR surveillance OR detect*))	((environmental OR "public health") NEAR/5 (track* OR monitor* OR surveillance OR detect*))	(environmental OR "public health") W/5 (track* or monitor* OR surveillance OR detect*)
	5	1 AND 2, then OR 5	OR ((track* OR monitor*) adj2 network*)	((track* OR monitor*) adj2 network*)	((track* OR monitor*) NEAR/2 network*)	(track* OR monitor*) W/2 network*
exposures	6	1 AND 2, then OR 6	*Environmental Exposure/	*Environmental Exposure/	*Environmental Exposure/	*Environmental Exposure/
	7	1 AND 2, then OR 7	AND Chemical Hazard Release/	AND Chemical Hazard Release/	AND Chemical Hazard Release/	AND Chemical Hazard Release/
	8	6 Or 7, then AND 8	((chemical OR environmental OR gas OR "heavy metal*" or oil) adj1 (incident* OR event* OR release OR spill* OR accident* OR "health threat" OR expos* OR injur* OR death* OR fatal* OR contaminat* OR hazard*))	((chemical OR environmental OR gas OR "heavy metal*" or oil) adj1 (incident* OR event* OR release OR spill* OR accident* OR "health threat" OR expos* OR injur* OR death* OR fatal* OR contaminat* OR hazard*))	((chemical OR environmental OR gas OR "heavy metal*" or oil) NEAR/1 (incident* OR event* OR release OR spill* OR accident* OR "health threat" OR expos* OR injur* OR death* OR fatal* OR contaminat* OR hazard*))	(chemical OR environmental OR gas OR "heavy metal*" or oil) W/1 (incident* OR event* OR release OR spill* OR accident* OR "health threat" OR expos* OR injur* OR death* OR fatal* OR contaminat* OR hazard*)
	9	6 OR 7, then AND 9	((land OR air OR water OR sea) adj2 (contaminat* or spill*))	((land OR air OR water OR sea) adj2 (contaminat* or spill*))	((land OR air OR water OR sea) NEAR/2 (contaminat* or spill*))	(land OR air OR water OR sea) W/2 (contaminat* or spill*)
	10	6 Or 7, then AND 10	*emergencies/ or *mass casualty incidents/	*emergencies/ or *mass casualty incidents/		
Public Healthpreparedness	11	1 AND 2, then AND 11	Disaster Planning/	disaster planning/	disaster planning/	disaster planning/
	12	11 AND 12	((emergency or disaster) adj1 (respon* OR prevent* OR resilien* or prepare*))	((emergency or disaster) adj1 (respon* OR prevent* OR resilien* or prepare*))	((emergency OR disaster) NEAR/1 (respon* OR prevent* OR resilien* or prepare*))	(emergency or disaster) W/1 (respon* OR prevent* OR resilien* or prepare*)
	13	11 AND 13	((horizon adj1 scan*) OR "watching brief" OR (data adj2 review) OR	((horizon adj1 scan*) OR "watching brief" OR (data adj2 review) OR toxicoinformatics OR EPPR)	((horizon NEAR/1 scan*) OR "watching brief" OR (data adj2 review) OR toxicoinformatics OR EPPR)	((horizon W/1 scan*) OR "watching brief" OR (data W/2 review) OR toxicoinformatics OR EPPR)

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			toxicoinformatics OR EPPR)			