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OVERVIEW

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The role of forensic science in the generation of intelligence to address environmental water contamination problems

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Abstract

Water contamination is a growing concern in society. New environmental laws are being enacted to define intolerable human activities, and their enforcement is increasingly supported by forensic science. However, water contamination is a broader security issue that is not only caused by illegal human behavior. Risk-based approaches are needed to prevent (re)occurrence of incidents and minimize their negative consequences. This can be achieved through the formalization of a monitoring process producing intelligence (i.e., actionable knowledge), crucial to detect recurring incidents, and guiding decision-makers in their choice of preventive and responsive actions. In this perspective, forensic science has a key role to play in integrating vestiges from water-contaminating activities (i.e., traces) in such a problem-solving process. Information conveyed by traces allows detecting similarities among contamination events (i.e., patterns), inferring common causes, and better understanding of mechanisms and consequences of water contamination. The different stages of the process will be described and illustrated through a real case example. Current barriers to the implementation of such a process are then discussed, showing how systemic issues and complexity may prevent the establishment of links across contamination events, thus negatively impacting the generation of intelligence. To overcome these obstacles, we underline the importance to initiate local and size-limited approaches by implementing relatively simple and flexible systems. New knowledge can be used to improve local situations and help stakeholders to understand the benefits of such a process; then, by a bottom-up iterative learning process, the approach can be given a greater ambition at a larger scale.

This article is categorized under:

Forensic Science in Action/Crime Scene Investigation > Special Situations and Investigations

Crime Scene Investigation > From Traces to Intelligence and Evidence

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KEYWORDS

environment, forensic science, monitoring, pollution, water security

1 | INTRODUCTION

Beck (1992) defined the modern society as a risk society. In his theory, new risks—that is, situations involving exposure to hazards—are proliferating as side effects of society's own development (e.g., risks related to car accidents, nuclear powerplant incidents, cyber-attacks, pandemics, climate change, and pollution). These risks and their perception have broad social consequences. They change the size and nature of security problems, which must be handled to prevent potentially harmful events from (re)occurring and to mitigate negative consequences when they do happen. The identification and reduction of risks are thus increasingly seen as an essential function in a very wide range of human-related activities (Ericson & Haggerty, 1997; Garland, 2001; NIST, 2018; Steffen et al., 2015; Zedner, 2007). From this perspective, security problems related to water are a major concern as this essential resource is increasingly affected by human activities and climate change (Bakker, 2012; Grey et al., 2013; Hall & Borgomeo, 2013; Pahl-Wostl et al., 2016). Water-related risks are associated with several categories of chronic and episodic hazards that include water shortage, water excess (flooding), and water contamination (Garrick & Hall, 2014; Hoekstra et al., 2018; OECD, 2013). When the risk is considered unacceptable or when a risk materializes and provokes damages, the problem needs to be addressed. Environmental agencies carry out regulatory chemical monitoring to detect and manage such problems (see, e.g., FOEN, 2013).

Forensic science is generally absent from this debate because it usually assists in the reconstruction of singular past activities to facilitate investigative processes and judicial decisions (Estoppey, 2022; Mudge, 2008; Petrisor, 2014; Spikmans, 2019). Its role of bringing evidence to court is essential, especially given the development of environmental law[1] and the growing sense that human behavior needs to be better regulated in this area. However, it remains unclear how law enforcement models and forensic science could more efficiently address persistent and recurring problems. Water contamination incidents often have (multiple) sources that are not only caused by direct illegal human behavior. Although overlapping, law enforcement is often in tension with risk analysis because the immediate objectives are different. Risk analysis is used to protect systems by anticipating harmful situations, while law enforcement focuses on individual violations of a set of rules after the incident occurred. If forensic knowledge is to be useful in addressing security issues, it must be considered in a different framework. Policing systems have also been concerned about the inadequacy of their reactive (law enforcement) approach, and tend to better align toward the trend of risk analysis to more proactively deal with security issues (Weisburd & Majmundar, 2018). For example, problem-oriented policing is a proactive process involving the detection, analysis, and response to recurrent, similar, and persistent incidents grouped under the term “problems” (Goldstein, 1990). This type of framework provides the opportunity for forensic science to expand its role through what is known as forensic intelligence. This idea has been successfully implemented operationally to address serial incidents, such as high-volume and organized crimes, serial homicides, false identity documents, or recurrent fires (Bruenisholz et al., 2019; Ribaux et al., 2022). By analogy, we support that water contamination issues can be approached in a similar way, where forensic intelligence can complement and enrich existing risk analysis processes and provide a bridge to investigative and law enforcement activities.

Forensic intelligence relies on the information conveyed by traces—that is, the remnants of past activities—to understand criminal and other anomalous events of public interest (Roux et al., 2022). Water polluting activities are events of interest for forensic intelligence. They alter the normal course of events by introducing anthropogenic contaminants into water at a level that produces adverse effects in living organisms (Heath, 1995; Nicolle-Mir, 2013; Tarazona, 2014), leaving traces that initially did not belong to the space where they were transferred. These traces can either be material (e.g., chemical substances) or digital (e.g., communication signals); they sometimes are invisible to the naked eye (e.g., micropollutants), but are not necessarily of small size (e.g., large volumes of oil) (Buzzini et al., 2019; Margot, 2017;

[1]See, for example, the Stockholm Convention that aims at controlling the production, use, trade, and disposal of substances termed as persistent organic pollutants (POPs), or the European Directive 2004/35/CE that establishes a framework of environmental liability based on the “polluter-pays” principle, to prevent and remedy environmental damage.

Roux et al., 2022). Contaminants themselves (e.g., chemicals or microorganisms), as well as other remnants of water-polluting activities (e.g., dead fishes, morphological deformities), constitute traces that can be systematically monitored. Through their ability to be measured and compared, they can contribute to detecting similarities (patterns) among recurrent water contamination events. By formulating hypotheses about the potential causes of the observed patterns (abductive reasoning) and by testing these hypotheses through the detection of additional traces or patterns (deductive reasoning), knowledge can be generated based on recurrent cause-effect observations (inductive reasoning) (Crispino, 2008; Ribaux & Caneppele, 2017). The generated knowledge can then guide a variety of decision-makers (not only judges, but also regional agencies and other stakeholders) in their choice of actions to address persistent problems, thus preventing contaminant releases from being repeated or continued (Estoppey, 2022; Ribaux et al., 2022).

This article reviews how traces can be integrated into a global problem-solving process allowing the detection and analysis of environmental[2] water contamination problems. It describes the various steps proposed to generate actionable knowledge (intelligence) from traces, based on a trace-based operational monitoring process described in the forensic literature (Ribaux et al., 2022). Current barriers to knowledge production and use, as well as ways to overcome them, are also discussed from a joint environmental and forensic perspective.

2 | A TRACE-BASED OPERATIONAL MONITORING PROCESS

The concept of intelligence implies that accurate and reliable knowledge is made available in a timely manner for rational decision-making (Arndt et al., 2020; Lum & Koper, 2017; Sherman, 1998). Decision-makers (e.g., managers, policymakers, governments) need to be informed by the "best available knowledge" to decide on the most suitable course of action and instruments to address (security) problems in real-time, even when a rapid response to a series of detected incidents is required (Ratcliffe, 2016; Williamson, 2008). The production of intelligence must constantly adapt to its legal, political, administrative, economic, or operational environment. Thus, problem-solving processes integrating traces and producing intelligence must comply with all these constraints. In a monitoring function, these processes are ideally considered as a cycle (Aepli et al., 2011; Gillson et al., 2019; Giordano et al., 2008). Their iterative nature allows generating (continuous) knowledge to guide sound decisions, and to assess the effects of implemented actions, while allowing adaptations to improve outcomes (Rist et al., 2013; Summers et al., 2015; van Assche et al., 2020). This so-called trace-based operational monitoring process, as described in forensic literature, is illustrated in Figure 1 for water pollution (Ribaux, 2014; Ribaux et al., 2017; Ribaux & Caneppele, 2017).

This process follows several stages—acquisition, integration, detection, analysis, decision, evaluation—that feed a memory. This memory can be defined as the current shared knowledge about the problem that evolves through new observations, external input, and analysis. Although it is usually implemented within a computerized database, the concept goes beyond this, as it is also composed of various types of accessible knowledge that feed the process (e.g., scientific literature or informal information).

Such a process has similarities with "adaptative monitoring" described in the environmental literature (Lindenmayer et al., 2011; Lindenmayer & Likens, 2009; Summers et al., 2015) but it differs from it in explicitly expressing traces and their specificities as a central source of information. Hence, traces (such as contaminants) are considered together with other case data (such as pluviometry data or river flow rates) to detect patterns as signs of recurrent water contamination events (see Figure 2). Relevant traces—usually detected when (potentially) contaminated areas are under investigation—may translate into signs of a more global problem, for example, when it results in the repeated detection of a given contaminant at places or times that share common characteristics (e.g., industrial zones). Knowledge can be extracted from the detected pattern by inferring potential causes that produced the dissemination of the contaminant (e.g., leaching of a contaminant from the same kinds of industries). When used by decision-makers in the definition of actions to reduce recurrent water contamination events, the acquired knowledge becomes intelligence (e.g., type of industries that need to improve their waste treatment).

The following sections first illustrate the concept of traces in water contaminating problems. Then, each step of the trace-based operational monitoring cycle is described and illustrated with the problem of polychlorinated

[2]Another security issue caused by water contamination is related to intentional poisoning of drinking water, for example, in the course of terrorist attacks against critical infrastructure (Gleick, 2006). Although systematic monitoring can contribute to reducing the risk associated to these issues, this paper does not claim to address this problem; it tackles the problem of recurrent environmental water contamination.

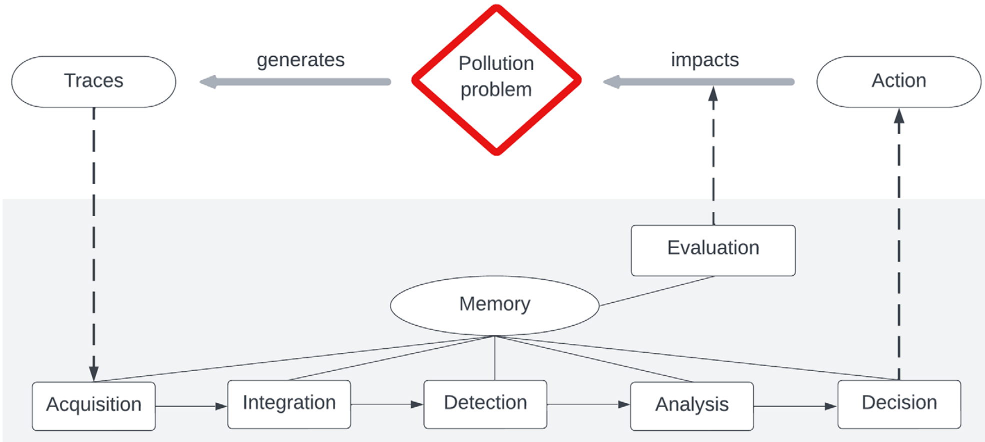

FIGURE 1 Trace-based operational monitoring process (Adapted from Ribaux, 2014). Traces generated by a pollution problem are integrated into a problem-solving process that includes several stages—acquisition, integration, detection, analysis, decision, evaluation—and feed a structured memory that represents the current knowledge on the problem. The process optimizes the production of intelligence that guides decision-makers in their choice of actions to act on the problem.

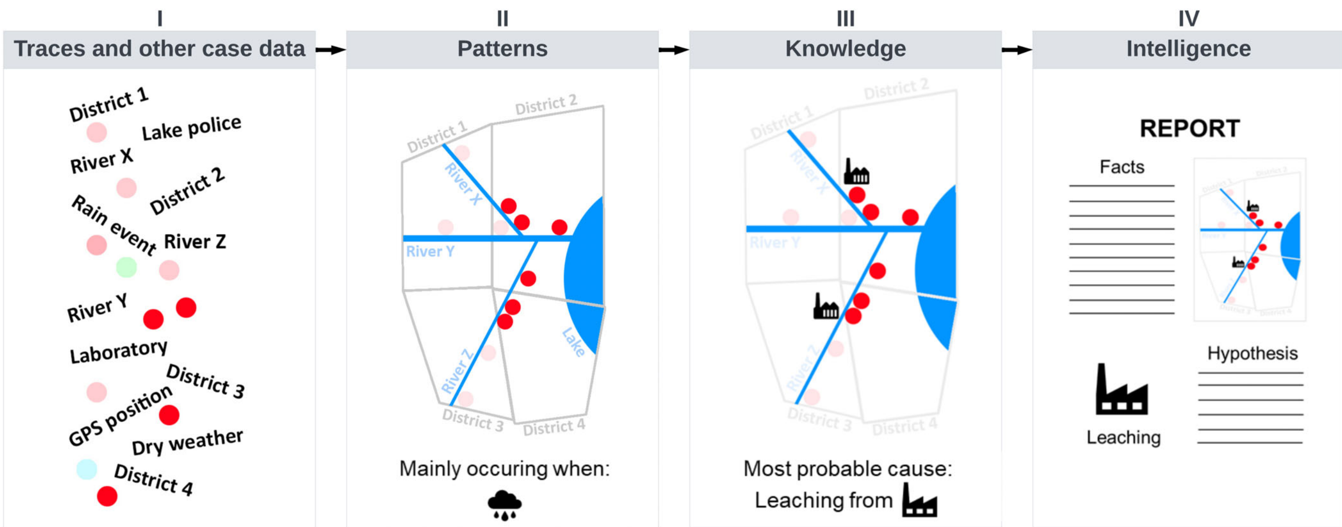

FIGURE 2 Example of how (I) traces and other case data can contribute (II) to the detection of patterns (as signs) of recurrent water contamination events. The analysis of these patterns leads (III) to the production of knowledge through the inference of potential common causes and (IV) provides decision-makers with intelligence to act on the problems.

biphenyl (PCB) contamination of Lake Geneva (Estoppey et al., 2019; Estoppey & Medeiros Bozic, 2019; Pfeiffer et al., 2020).

2.1 | Water contamination problems and traces

Recurrent water contamination events constitute a security problem when they have severe consequences (e.g., oil spill) or occur very frequently (e.g., discharges of insufficiently treated wastewater from industries). Individual activities releasing specified amounts of contaminants into water may be legal (because they are considered as an unavoidable consequence of human activities) but can still result in security issues due to the cumulative emissions from several contributing sources (resulting in total amount exceeding the legal threshold). For this reason, it is essential to monitor the environment through the continuous collection of information (e.g., through the analysis of a wide variety of contaminants not necessarily regulated by the law) to better understand water security problems. At this stage, it is worth defining the terms "contaminants" and "pollutants." Whereas "contaminants" are the anthropogenic substances introduced into water, "pollutants" are contaminants present at a level that produces adverse effects on living organisms, including (but not limited to) humans. In a legal context, contaminants are thus considered as pollutants only above numeric or narrative criteria (i.e., thresholds) (Heath, 1995; Nicolle-Mir, 2013; Tarazona, 2014).

At the beginning of a trace-based operational monitoring process, the understanding of specific water contamination problems is only partial, meaning some effects (traces) may have been detected (e.g., high numbers of dead fish), but the causes remain unknown. The process requires to iteratively acquire new traces (e.g., manure in water and on soil) and other data (e.g., witness testimonies, meteorological conditions) to continuously generate information that will contribute to a better understanding of the problems. To adequately understand and define a problem, it is essential to differentiate the effects (i.e., traces that reveal the existence of the problem such as a high number of dead fishes) from the causes (i.e., the problematic activities at the source of the traces such as manure spills in water) (Aepli et al., 2011; Goldstein, 1979). Using hypothetico-deductive reasoning, hypotheses of potential causes are first formulated (based on initial observations) and then tested (based on newly detected traces). Multiple levels of causes exist and can be inferred and addressed, from direct causes (e.g., oxygen depletion in water) to higher-level ("root") causes (e.g., discharges of manure from storage facilities caused by defective or insufficient storage capacities). Understanding the risk of these recurrent contaminations for our society and environment is also an important part of the problem definition and solving approach. Answering questions such as "what is the frequency of manure contamination due to insufficient storage capacity?" or "what is the gravity of these contaminations for aquatic ecosystems and humans who depend on them?" will help decision-makers to take actions to efficiently reduce the frequency and gravity of such contaminations.

2.1.1 | Case example

Level of PCBs and other persistent organic pollutants in fishes and sediments from the Lake Geneva basin were shown to exceed limit values, leading to the prohibition of the consumption of certain species of fishes (Babut et al., 2019; Casado-Martinez et al., 2016; Edder et al., 2013; Edder & Klein, 2015; Loizeau et al., 2017; Schmid et al., 2010). Forbidding fish consumption was a temporary "crisis" solution (i.e., action) decided upon before (root) causes could be investigated and ideally minimized.

2.2 | Acquisition

At this stage of the process, the partial understanding of a problem is used to search for new traces that can bring additional explanatory elements (Estoppey, 2022). For example, if amounts of an industrial contaminant exceed legal thresholds in a lake, relevant information is likely to be obtained from monitoring this contaminant in tributaries that cross industrial areas. The acquisition step requires setting priorities and making methodological choices within contextual constraints because a compromise has to be found between the information required and the resources available to acquire this information (Rossy, 2011). For example, the use of methods providing highly resolved trends of contaminant concentrations (such as automated sampling or in situ instrumental analysis) may not be affordable for large-scale monitoring (Kot et al., 2000; Lohmann et al., 2012; Vrana et al., 2005), and the analysis of a whole class of contaminants may not be necessary to identify their sources (Estoppey et al., 2019; Pfeiffer et al., 2020). Taking advantage of existing opportunities and dividing the collection tasks between several actors (e.g., environmental protection agencies, water bailiffs, lake police officers, academic researchers) is a valuable option to continuously acquire traces and data from a high number of contamination problems (Ribaux, 2014), thus maximizing chances to detect patterns at a later step of the process (see Section 2.4). However, such a decentralized acquisition absolutely needs to be coordinated to generate data that can be reliably compared (Milman et al., 2020).

Characteristics that can be directly extracted (i.e., observed or measured) in situ from traces without using analytical techniques (e.g., color, odor, basic physicochemical parameters such as pH or conductivity) can be acquired by decentralized stakeholders (e.g., first responders). Decentralization allows to collect more data, but the reliability of the data must be controlled to be relevant in further steps of the process. Regarding characteristics that require more sophisticated analytical tools to be extracted, the use of specialized central laboratories may be a more efficient approach to ensure an adequate comparability of results, but is not an ultimate condition as long as interlaboratory comparisons are organized (Lohmann et al., 2017). As the process is iterative, parameters of the acquisition step (e.g., methods, sites, involved actors) can be adapted to keep an equilibrium between the information needed and the available resources.

2.2.1 | Case example

To bring new explanatory elements on the problem of PCB contamination in Lake Geneva, an operational monitoring was initiated in 2018 with the support of the International Commission for the Protection of the Water of Lake Geneva (CIPEL; Figure 3; Estoppey et al., 2019; Pfeiffer et al., 2020). The acquisition of new traces focused on PCBs in the water phase because information provided by PCBs collected in other matrices is hardly exploitable to infer potential causes (e.g., high uncertainty related to mobility of fishes) (Estoppey, 2022). Passive sampling—that relies on the free flow of contaminants from water to a polymer—was chosen to measure PCBs in the water phase. This method overcame the main limitations of grab sampling (lack of representativeness) and automated active sampling (higher cost), and offered a good compromise between provided information and invested resources (Booij et al., 2014; Estoppey et al., 2016; Lohmann et al., 2017; Vrana et al., 2005). Indeed, passive samplers can be deployed at a high number of selected sites as they are cheap and do not require electricity. They allow in situ accumulation and integrative sampling, thus providing average concentration that takes fluctuating concentrations into account (Lohmann et al., 2017; Salim & Górecki, 2019). A central laboratory prepared the passive samplers before deployment and carried out the quantification of contaminants after sampler retrieval. During the first monitoring campaign, local environmental protection agencies around the lake were trained with the objective to decentralize the field deployment during subsequent

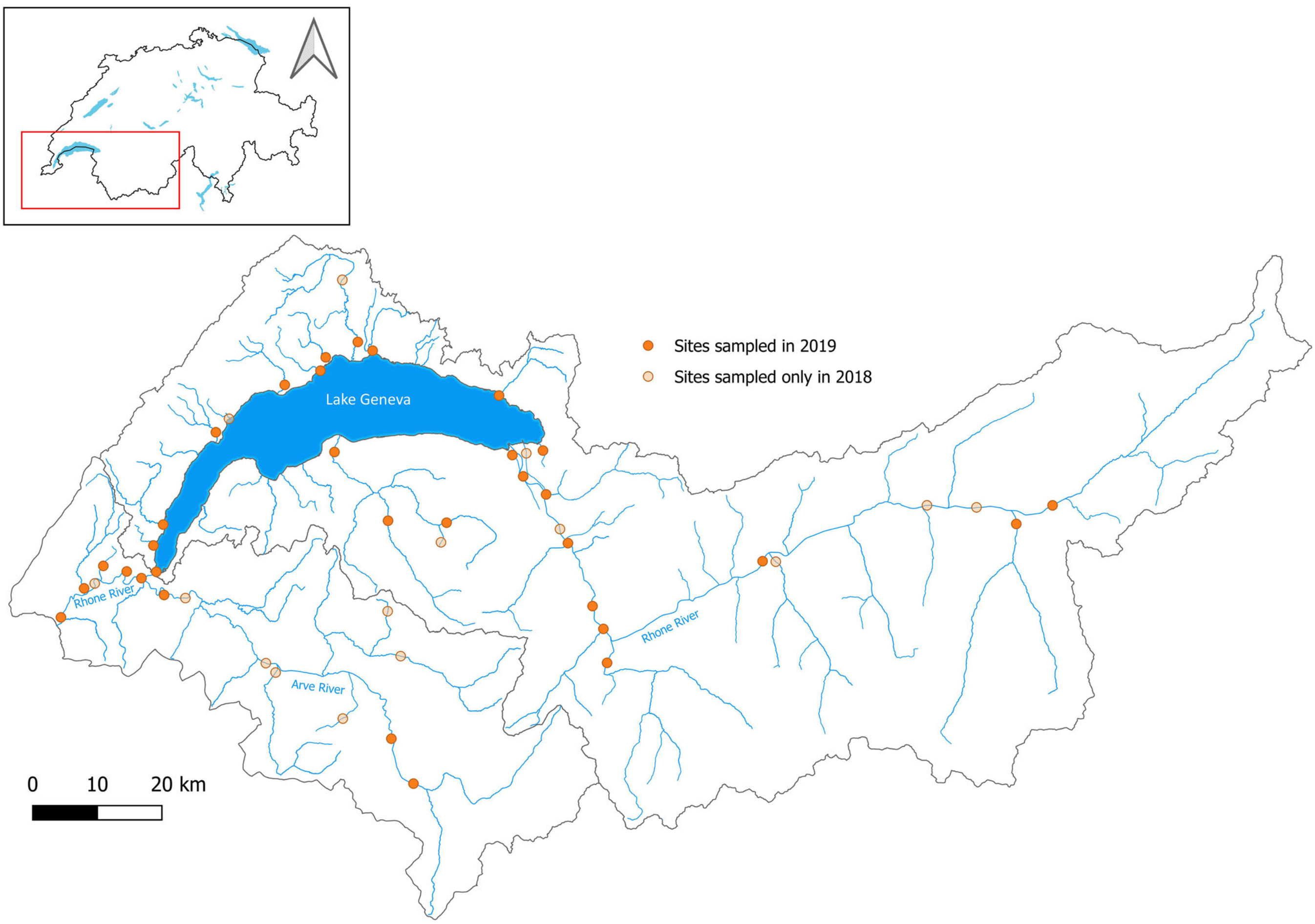

FIGURE 3 Sites in the Lake Geneva basin where amounts of PCBs dissolved in water (i.e., traces) were acquired using passive sampling during the operational monitoring carried out in 2018 and 2019 (Estoppey et al., 2019; Pfeiffer et al., 2020).

iterations of the process. After the first iteration, the acquisition was adapted: some sites were prioritized, new sites were added and the methodology was optimized (Estoppey et al., 2019; Pfeiffer et al., 2020).

2.3 | Integration

While characteristics are extracted from the acquired traces, they are integrated into a structured memory that represents the current knowledge on the problem (Ribaux et al., 2017). Such a memory needs to be carefully devised (Rossy, 2011): characteristics of traces (e.g., color, odor, identity, amount, profile of contaminants) and information about trace collection (e.g., type of locations or time of year at which traces were collected) are required to be transposed in the memory using the same encoding, formatting, and structure. Scientists in charge of database conception and feeding should thus be equipped with computer skills (e.g., format management, uniformization, automation) (Fortin et al., 2019), but generalist skills are also required to efficiently select characteristics that are integrated in the memory. This selection should be based on the relevance of characteristics to provide the expected information (Morelato et al., 2014), as well as the transversality of said characteristics (i.e., their measurability in all investigated problems, and their comparability within the database). A few general criteria relative to the characteristics themselves must be considered (Baechler et al., 2015). First, characteristics should be sufficiently discriminant to allow distinction between the different types of contaminating activities (i.e., high inter-source variability). The profile (i.e., the proportion) of co-released contaminants is an example of characteristic that can be specific to a type of contaminating activities; it can indeed depend on the production, the use, and the disposal of the substances (e.g., profiles of per- and polyfluoroalkyl substances (PFAS) are different whether they were used in fire suppressant or PFAS-coated paper) (Glüge et al., 2017; Langberg et al., 2021). Second, selected characteristics should also be as stable as possible (limited influence from processes such as microbial degradation or photo-oxidation) to allow linkage between traces generated by the same type of activities (low intra-source variability). Third, characteristics should be complementary to each other: time can be gained if characteristics that have little chance to increase the discrimination among contaminating activities are not integrated (e.g., profile based on dozens of PCBs may provide only slightly more information than a profile based on a few representative ones). The selection of characteristics should also consider criteria relative to the observation/measurement methods (Baechler et al., 2015). Characteristics whose observation/measurement require simple, fast, and low-cost methods should be prioritized (provided they offer sufficient discrimination) to maximize the chances to feed the memory with sufficient information in a long-term sustainable monitoring process. In addition, the results must have a minimal dependence on the analytical process (good robustness) to ensure that characteristics measured at different places and times can be compared.

2.3.1 | Case example

In addition to information such as location and time at which PCB traces were collected, the following characteristics were integrated in the memory (for the purpose indicated in brackets; Estoppey & Medeiros Bozic, 2019):

i. The concentration of PCBs in pg/L (detection of sites presenting the highest risks in terms of exposure to PCBs),
ii. the load of PCBs in μg/day (detection of the main contributors to global lake contamination),
iii. and the profile as relative proportion of PCBs in % (information on the type of pollution sources affecting the rivers).

Some characteristics were added after the first iteration to refine the subsequent steps of the process, such as the industrialization of the location (defined in terms of the number of industries and polluted sites) or the pluviometry (amount of rain per unit of time) (Pfeiffer et al., 2020).

2.4 | Detection of patterns

Links between characteristics of traces are searched to detect patterns (e.g., relationships or correlations) as the potential sign of similar sources of contamination. For example, concentrations of PFAS were shown to be systematically higher in surface waters that share similarities (e.g., high number of military areas) and in particular weather conditions (e.g., pluviometry) (Kurwadkar et al., 2022; Nguyen et al., 2022). The shared memory should be organized in a way that provides stakeholders with sufficient access and flexibility to seek similarities between situations and repetitions in time or space (Ribaux, 2014; Rossy et al., 2013). Comparison metrics and scores proved very useful to highlight (dis)similarity between traces (Baechler et al., 2015; Morelato et al., 2014). Correlation measurements can be used to establish links between contaminant profiles, grouping those that are potentially generated by similar activities. Comparison of average values can be used to determine which sites present significantly higher concentrations or loads of contaminants, thus highlighting surface bodies that should be prioritized (Estoppey, 2017). The detection of patterns can be supported by (spatiotemporal) visualization tools that help make information perceivable (see Figure 4; Estoppey, 2022; Rossy, 2011).

Detected patterns are treated in sub-problems (potential groups of similar contaminating activities) (Estoppey, 2022). New iterations of the process (i.e., acquisition of new traces and potential integration of new characteristics) bring additional information on sub-problems. For example, most contaminated river sections can be shown to be situated near specific areas or buildings (e.g., fire training sites—such as airports—for PFAS) (Ahrens et al., 2015; Kwadijk et al., 2014; Langberg et al., 2022; Nguyen et al., 2022). The better the sub-problems are characterized, the more relevant will be the hypotheses on their causes in the next stage.

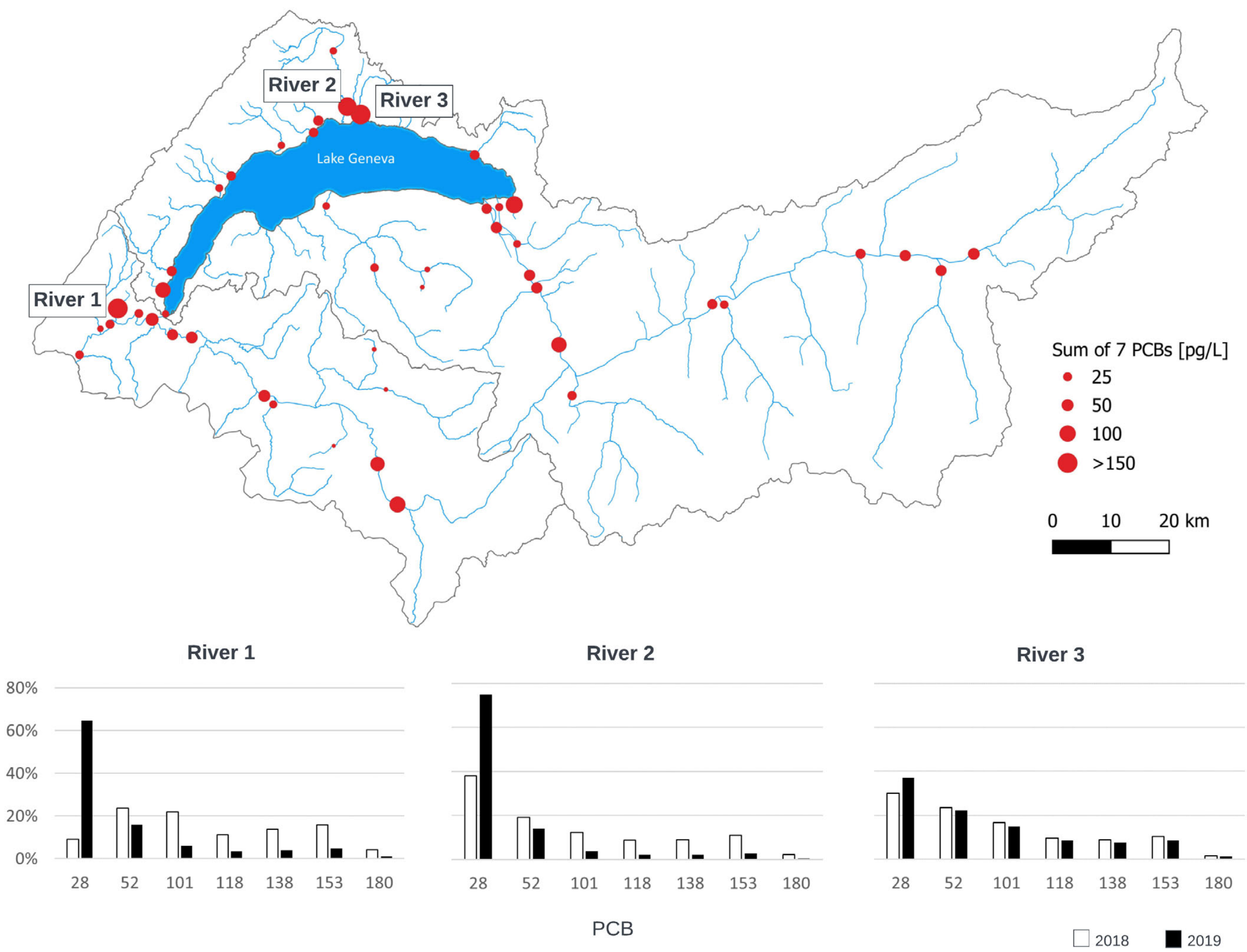

FIGURE 4 Concentration of the sum of PCBs 28, 52, 101, 118, 138, 153, and 180 (dissolved fraction) measured at 46 sites during the first monitoring campaign in 2018 (upper panel). Profile of PCBs in the three rivers presenting the highest concentrations (lower panel). The profiles in these rivers were generally richer in low chlorinated PCBs (i.e., PCBs 28 and 52), particularly when precipitations were heavier in 2019.

2.4.1 | Case example

Comparisons and classifications of PCB concentrations (e.g., "below" vs. "above" threshold values), loads (e.g., relative contribution to lake contamination), and profiles (e.g., profile rich in "low-chlorinated PCBs" vs. "high-chlorinated PCBs") were carried out to search for similarities among contaminations (Estoppey, 2022). Two main patterns were detected in Lake Geneva tributaries and thus, subdivided as sub-problems: rivers presenting the highest concentrations of PCBs flowed through highly industrial areas and often had a profile rich in low-chlorinated PCBs, particularly when precipitations were heavier in 2019 (sub-problem 1; see Figure 4); rivers presenting the highest loads of PCBs flowed through mountainous areas and often had a profile rich in more highly chlorinated PCBs (sub-problem 2; Estoppey, 2022).

2.5 | Analysis

The analysis intends to give meaning to sub-problems by inferring potential causes of observed patterns (Rossy, 2011). First, hypotheses of potential causes are generated based on the patterns (abductive reasoning; Crispino, 2008). For example, if it is shown that many cases of acute fish mortality involve manure contaminations near farms in winter (pattern), potential causes could be (i) ruptures, (ii) overflows, or (iii) deliberate emptying of manure storage facilities; these causes are themselves explained by the exceedance of storage capacity limits in winter (manure spreading on water-saturated soils being forbidden in many countries). The generated hypotheses are then tested by collecting traces and other data from new similar contamination cases (or new traces/data from past contaminations; deductive reasoning) (Crispino, 2008). For example, traces on (or close to) manure storage facilities (e.g., cracks, manure spills, luminescent markers) can be used to exclude some potential causes and refine the other hypotheses. Depending on the degree of uncertainty that can be tolerated, the hypothetico-deductive process can be reprocessed as many times as necessary to sufficiently stabilize the confidence in the hypotheses. This cyclic process interpretation adds value to the information provided by the patterns; the (sub-)problem is better understood, and the frequency and gravity of potential new similar contaminations (and thus, the risk) can be better assessed. The produced knowledge is then communicated to decision-makers to achieve its full potential in the next stage (Ribaux, 2014).

The analysis involves knowledge from a multitude of transversal and specialized disciplines. For example, explaining why high aqueous contaminant concentrations are detected in areas with similar activities (e.g., similar kinds of crops or buildings) requires knowledge of the use of these chemicals (e.g., rate and time of pesticide application or years of use and concentrations of flame retardants in building materials) as well as on physicochemical properties influencing the environmental behavior of these contaminants (e.g., hydrophobicity and persistence) (Estoppey, 2022). Thus, this stage involves different fields of expertise, using knowledge arising from different disciplines including field practitioners. Research, intellectual, and interpersonal skills are essential to identify and find the knowledge necessary for interpreting information (i.e., generating and testing hypotheses).

2.5.1 | Case example

To explain the sub-problem 1, the assumption can be made that profiles rich in low-chlorinated PCBs are mainly released from industries dealing with the treatment of old capacitors. They contain PCB oils with similar PCB profiles (Glüge et al., 2017). Small capacitors are not always dismantled from metal structures before grinding in scrap treatment industries (Kuhn & Arnet, 1998). PCBs would thus be dragged by rainwater and would end in rivers via stormwater outfalls. Regarding sub-problem 2, it can be hypothesized that profiles rich in high-chlorinated PCBs come from anticorrosive paint present in penstocks of hydroelectric facilities. Indeed, chlorinated rubber paints used between 1950 and 1974 (e.g., for the inner coating of pipes) contain PCBs (Glüge et al., 2017; Stolz, 2000). These compounds can be released by mechanical abrasion (Stolz, 2000), arriving in watercourses that receive turbined water (Estoppey, 2022). In some situations, sediments highly contaminated by such releases could act as secondary sources (not as sinks) (Chiaia-Hernández et al., 2022; Mustajärvi et al., 2017). These hypotheses may require more data (i.e., repeating or expansion of the acquisition stage) to be adequately tested before moving to the next stages.

2.6 | Decisions and actions

When the produced knowledge (also called "clue" in forensic science) is used in the decision-making process to act on security problems, it is then called "intelligence" (see Figure 2). To facilitate decision-making, the disseminated knowledge needs to be "actionable," that is, to be readily and timely usable by decision-makers to decide if a problem requires actions (i.e., to assess whether the risk posed by such contaminations is inadmissible) and, if so, to define the most appropriate actions to act on the problem (e.g., to reduce the risk) or to acquire more knowledge by additional monitoring actions (Ratcliffe, 2016; Ribaux, 2014; Rossy, 2011). Intelligence can support decision-making at different levels (Aepli et al., 2011; Ribaux, 2014). At an operational level, decision-makers are generally involved in "water management" (e.g., operational managers of environmental laboratories, water protection inspectors, and investigators) (Cook, 2014). At this level, intelligence can, for example, support immediate crisis response in specific situations (e.g., containing oil spill in surface water), investigation of pollution events (e.g., better sampling and laboratory processes), or management of operations addressing persistent problems (e.g., inspection and information toward vulnerable facilities such as manure tanks in winter or building sites). At a strategic level, intelligence guides decision-makers involved in "water governance," such as political authorities, national, or regional legislators, governing bodies of environmental protection agencies or water police commanders. At this level, intelligence can, for example, support changes within a type of facility that was shown to pollute (e.g., addition of micropollutant removal technologies in wastewater treatment plants), the establishment of authorization requirements to own facilities which may pollute water (e.g., construction permits for chemical storage tanks) or the introduction of stricter penalties to deter companies from releasing contaminants into water (e.g., pecuniary penalties higher than the treatment of the waste).

When actions need to be taken, interdisciplinary exchanges between all stakeholders are essential to establish coherence between objectives, constraints, and actions (Aepli et al., 2011; Perman et al., 2003). Objectives should tackle whenever possible the causes (i.e., affliction) and not only the effects (i.e., symptoms) of a problem. Indeed, reducing the effects in a crisis (through containment and remediation) is necessary in the first response stages, but such reactive actions only provide temporary relief and do not solve the problem in the long term, that is, they do not eliminate or reduce contaminant emissions (Aepli et al., 2011; Goldstein, 1979; Okes, 2019). Whenever possible, the root causes should be addressed to mitigate a problem. However, the chosen course of action must take into account all the constraints (pragmatic and contextual) surrounding the problem and will require trade-offs. For example, improving the treatment of pharmaceutical residues and metabolites in wastewater is a more realistic measure to reduce their effects on surface water organisms than stopping the consumption of such chemicals. As resources are insufficient to eliminate all environmental problems, prioritizing problems, and associated actions is necessary (McCarthy et al., 2010); intelligence can help to allocate resources to the most significant problems (i.e., the ones presenting the highest risks; Ribaux et al., 2003).

A wide range of different types of actions can be taken to reduce problems and will depend on the level at which decision-making is done (i.e., operational vs. strategic), the fixed objectives and the case-specific constraints (political, legal, economical, situational). Intelligence helps decide if the approach to address the problem in its current state requires actions that intend to (i) further monitor contaminations to improve the understanding of the problem, (ii) treat contaminants after they have been generated by addressing low-level causes or effects, or (iii) prevent contaminations at the source by addressing high-level causes. Table 1 gives examples of actions at a strategic level by subdividing them depending on whether they impose a certain behavior (regulatory instruments), stimulate the desired behaviors through financial incentives (economic instruments), or encourage desired behaviors (voluntary instruments) (Metz & Leifeld, 2018; Vedung, 1998; Weber et al., 2014).

2.6.1 | Case example

In the case of Lake Geneva, intelligence generated from traces has so far mainly supported actions at an operational level. First, reports presenting the overview of PCB contamination in the Lake Geneva basin (including maps like the one in Figure 4) were provided to local environmental protection agencies and discussed with their representatives during meetings coordinated by the CIPEL. This allowed for prioritizing streams where actions were required, knowing that acting on streams presenting the highest concentration of PCBs (e.g., rivers 1, 2, and 3, in Figure 4) would decrease the risks posed by these chemicals on organisms, whereas acting on streams presenting the highest loads of PCBs

TABLE 1 Example of actions at strategic level, depending on approaches and instruments (Adapted from Metz and Leifeld (2018), Perman et al. (2003), Sterner and Coria (2011), and Taylor et al. (2012)).

		Approach		
		Further monitoring	**Treatment**	**Prevention**
Instrument	Regulatory	• Registries • Reporting	• Best available technique • Technical standards • Disposal requirements	• Substance bans • Restrictions • Authorization
	Economic	• Subsidies for monitoring	• Effluent/emission charges • Subsidies for improved wastewater treatment	• Product taxes • Subsidies for "green" action • Permit trading
	Voluntary	• Agreements on control measures	• Advice • Agreement on wastewater treatment	• Awareness campaigns • Education

(e.g., river Rhone) would significantly reduce the amount of chemicals arriving in the lake, and thus reduce the risk for the lake and the water leaving the lake. Then, specific meetings were organized with the local environmental protection agencies to set up PCB source investigations. The knowledge acquired on the types of sources was used to guide the acquisition of new traces, that is, to include sampling sites upstream and downstream of industries treating metallic waste (sub-problem 1) and hydroelectric companies (sub-problem 2). While the whole process is relatively long, results combined with information on potential sources (e.g., industrial zones, pipe network, discharge line) helped refining the knowledge on the sub-problems and localizing contaminated river stretches and specific sources (similarly to what was done in Estoppey et al., 2015). Finally, the produced knowledge has allowed local authorities to approach some industries to discuss appropriate measures to prevent water pollution (e.g., covering waste to avoid PCBs being leached out by rainwater or monitoring PCB in releases). These measures can, for example, be required for renewal of operating permits.

2.7 | Evaluation

Continuing the monitoring of the problems during and after the implemented actions is essential to evaluate if the actions allowed to significantly reduce or stop the problem (e.g., the release of the monitored contaminants in water) (Aepli et al., 2011; Ferraro & Pattanayak, 2006; Pullin & Knight, 2001). It is necessary to not only assess the *effectiveness* of actions—that is, their ability to achieve objectives—but also their *efficiency*—that is, their ability to obtain maximum effects with a minimum of resources (Kleiman et al., 2000). For each sub-problem, the assessment should ideally be done by monitoring situations where mitigation actions have been taken (target) and comparing evolutions in similar places where no action was taken (control). Such an assessment allows moving toward an evidence-based approach. Periodic evaluations and feedback-based learning involving scientists, investigators and decision-makers—particularly after a change in actions—allow continual adaptation, reduction of uncertainty, and improvement of the monitoring process and decision-making outcomes (Fazey et al., 2005; Giordano et al., 2008; Kleiman et al., 2000; McDaniels & Gregory, 2004; Timmerman et al., 2010; Varady et al., 2016; Walters, 1986).

2.7.1 | Case example

Evaluation requires continuing the monitoring of the Lake Geneva basin over time. One monitoring campaign was done in Spring 2023; it should ideally be repeated at regular intervals in tributaries—particularly at sites close to identified sources of pollution—to evaluate if taken measures to reduce PCBs release from industries treating metallic waste or hydroelectric companies have been successful. The cycle is thus repeated, and adapted, to continuously monitor and act on the problem(s). This iterative process also allows the detection of emerging (sub-)problems.

3 | CHALLENGES IN IMPLEMENTING A TRACE-BASED OPERATIONAL MONITORING PROCESS

3.1 | Current barriers

Although knowledge is recognized as essential to support decision-makers in formulating and choosing a course of action (Aepli et al., 2011; Sterner & Coria, 2011; Timmerman & Langaas, 2005; van der Molen, 2018), complete problem-solving processes such as the presented trace-based operational monitoring often remain complicated to implement in practice (Carter et al., 2014; Cope, 2004; Ericson, 2006). There are still considerable barriers to knowledge production and use, frequently resulting in intuitive reactions guided by societal and political pressures rather than rational decisions guided by scientific knowledge (Aepli et al., 2011; Arndt et al., 2020; Timmerman et al., 2010; Timmerman & Langaas, 2005; Walsh et al., 2015, 2019). It is impossible to identify and monitor all types of risks (Ericson, 2006). A selection is required a priori and may evolve over time. This is not obvious, as sensitivity to certain types of pollution can greatly vary between jurisdictions and over time. In this context, spectacular and visible events are systematically prioritized at the expense of more latent, but potentially more dangerous, problems.

Fragmentation and misunderstanding among stakeholders (systemic issues) also lead to difficulties in detecting and understanding patterns (issues in knowledge production), and prevent efficient decision-making (issues in intelligence use). At both the strategic and operational levels (i.e., water governance and management), responsibility is often dispersed or divided between multiple actors or agencies operating with different priorities at local, regional, federal, and sometimes international levels (Adler, 2009a, 2009b). There is often a lack of clarity of stakeholder roles as well as poor coordination and cooperation between them (Brown & Farrelly, 2009; Eurojust, 2014; Kim et al., 2015; Liu et al., 2019; Xie, 2008). Similarly to crime problems, the fragmentation is amplified by the fact that water security requires a multitude of specialized knowledge (Roux et al., 2012, 2021), and that waterbodies are often shared by several countries or states/provinces (Hill et al., 2008; Kidd & Shaw, 2007; Liu et al., 2019; Nava & Solis, 2014; Pahl-Wostl, 2015). It leads to specialization as well as physical and organizational separation which reduces interactions between stakeholders (Roux et al., 2021; Timmerman et al., 2010).

This fragmentation of the processes often leads to "linkage blindness," that is, the inability to connect and compare investigated problems with each other (Egger, 1984; Margot, 2017). Linkage blindness is particularly affected by issues in the acquisition of the data and in its inappropriate integration in the memory reflecting the available knowledge at a specific time on a problem (see Figure 1). Data may be missing or unreliable. For example, first responders in case of "acute" contamination events (e.g., firefighters, police officers, fishery inspectors) do not always have the specialized knowledge and specific skills to collect appropriate data in environmental offences (Eurojust, 2014; Xie, 2008). Intervention in water contamination cases is one of the many tasks they are assigned, and their lack of awareness and training can lead to missing key traces or inadequate collection. Other stakeholders such as environmental protection agencies have technical expertise and knowledge in water contamination, but their monitoring tasks mainly focus on assessing whether concentrations of target contaminants meet legal thresholds. They can hardly move away from routine protocols to monitor contaminants other than legally or politically predefined target compounds.

Moreover, as water contamination is often monitored in a fragmented manner by the many stakeholders, there can be significant inter-entity differences in methodologies, targeted substances and results especially when waterbodies are shared by several countries or provinces (Behmel et al., 2016; GWP & NBO, 2012; Hering et al., 2010; Roose et al., 2011; UNECE, 2006). The collected data, sometimes over a large-scale area (e.g., a watershed) that seldom corresponds to political boundaries or jurisdictions, is rarely centrally stored and remains mostly unshared or poorly accessible (Hering et al., 2010). This compartmentalization of data between states and organizations reduces the probability to detect patterns, and promotes a case-by-case approach, easier to implement at a local level, but less efficient to resolve global or persistent pollution problems. By forming organizations associating all stakeholders from the same watershed (see examples in Aichinger, 2009; Schmeier, 2014; Schmeier et al., 2016), an integrated approach is expected to promote cooperation, including data-sharing (GWP & NBO, 2012; INBO & UNESCO, 2018), but can be difficult to implement for systemic reasons (Biswas, 2004; Blomquist & Schlager, 2005; Schröder, 2019; Waylen et al., 2019). Indeed, there are significant difficulties in integrating different legal frameworks and policies of riparian nations or states/provinces into an institutional architecture, and the potential lack of flexibility and adaptability of such river basin organization can be responsible for the absence of significant progress (Bréthaut & Pflieger, 2020).

The final argument resides in the complexity to articulate adequately science, justice, liberty and security in the context of risk analysis (Brodeur & Shearing, 2005; Roux & Weyermann, 2020). This is especially evident in the area of water contamination. We have already mentioned the many tensions associated with combining a law enforcement perspective with more proactive models of policing. As another example, policy-makers and managers frequently complain about the lack of useful information provided by scientists whereas the latter complain about the lack of use or understanding of the produced knowledge leading to poorly informed decisions (Dubois et al., 2020; Gibbons et al., 2008; Rose et al., 2020; Timmerman et al., 2010). Such communication difficulties are rooted in the interdisciplinary nature of the problems, requiring a minimum of shared understanding and objectives between the different stakeholders, particularly the policy-makers, the managers, the scientists, the field specialists, the law enforcement services, but also the industries and the population (Arndt et al., 2020; Gibbons et al., 2008; Lindenmayer & Likens, 2010; Rose et al., 2020).

Actions can be efficiently taken by decision-makers only if they are informed of problems in a useful and timely manner (Ribaux, 2014). When risks arise (i.e., when incidents occur), decision-makers are expected to respond as appropriately and timely as possible to mitigate the consequences of incidents (e.g., pollution containment, population protection) and quickly overcome the crisis (e.g., investigations of pollution sources, sensitive site inspection). However, appropriate reactive actions cannot be developed if no learning process is implemented on a large scale, that is, if data from previous similar incidents have not been adequately collected, stored, shared, linked, and analyzed to allow decision-makers to sufficiently understand the extent and magnitude of consequences of new cases. Risk prevention also necessitates intelligence, which cannot be adequately generated without an operational monitoring process. However, successful preventive actions are rarely measurable,[3] often leading to little support from political instances and population. Moreover, certain types of water pollution are often overlooked or minimized because they remain largely imperceptible, and their effects are often far removed in time and space from their source(s).

Unable to act on root causes (hazards), decision-makers are often compelled to address security problems caused by water contamination in a reactive way that involves costly remediation of symptoms (e.g., treatment of contaminants to render them less harmful to organisms or human health) (Damania et al., 2019; Vörösmarty et al., 2010) rather than in a proactive way that requires timely actionable knowledge produced by operational monitoring.

3.1.1 | Case example

Water governance and management of Lake Geneva involves two countries (France and Switzerland) and several regional administrations (three Swiss regions and two French departments). Thus, monitoring networks are largely based on national/regional legislation, sampling methods, and target substances may vary across agencies, leading to heterogeneous data and difficulties to compare at the basin level (Estoppey et al., 2019). In certain cases, data are missing or inadequate because measuring hydrophobic compounds is too time-demanding and challenging for routine laboratories and because information extracted from traces measured in some matrices are difficult to analyze in terms of causal inference (e.g., fishes move along a water body) (Estoppey et al., 2019; Estoppey & Medeiros Bozic, 2019). These data-related issues hamper pattern detection and generation of knowledge on the types of pollution sources around Lake Geneva.

3.2 | Ways to overcome barriers

Problem-solving approaches aim at understanding the extent and mechanisms of water contamination activities at a large scale. However, centralized top-down projects in complex problem contexts can be difficult to implement and maintain (Ribaux, 2019; Rist et al., 2013; Rossy & Ribaux, 2020; Westgate et al., 2013). Finding the right balance between centralized and decentralized elements in problem-solving processes is thus crucial to ensure the process viability; the systems in which the process needs to be implemented must be considered (Aepli et al., 2011; Bréthaut & Pflieger, 2020; Schröder, 2019).

Several studies suggested that, at first, more local and realistic bottom-up approaches in relatively simple systems (rather than centralized top-down projects) are adequate to concretely implement elementary components and connect existing stakeholders (Ribaux, 2019; Rist et al., 2013; Rossy & Ribaux, 2020). Providing processes and intelligence

[3]This is known as the "prevention paradox," because if a harmful event is prevented from happening, it is generally impossible to prove it would have happened if no action had been taken (and thus to justify the implemented resources). While if an event occurs, then it is usual to blame the stakeholders for insufficient action to prevent the event.

products actionable in local situations helps stakeholders to understand their benefits (Carter et al., 2014). Such local approaches can identify when harmonization and centralization of parts of the processes are beneficial (to benefit from scale effects), and when instead decentralized processing and decision-making is the best way to deal with specific local contexts (Ribaux, 2019; Rossy & Ribaux, 2020). Thus, a bottom-up approach should be promoted to rapidly develop and confront knowledge products with the reality of a practical environment. These components, once validated, are then assembled into a more integrated system in which an increasing number of actors are involved and actions at larger scale can be implemented (Rossy & Ribaux, 2020).

3.2.1 | Case example

The International Commission for the Protection of the Water of Lake Geneva (CIPEL) performs an extensive coordination role in the monitoring of the regional water quality and supports the water policy coordination of the lake's basin. It is a Franco-Swiss intergovernmental body composed of elected representatives, senior officials, scientists, and experts. Concerning the water quality monitoring, it does not have deliberative or decisional authority, but it finances monitoring campaigns, raises awareness, and proposes consensus-based solutions and incentives (Estoppey et al., 2019; Muniz Miranda, 2017; Pfeiffer et al., 2020). As the principle of subsidiarity is respected, it allows horizontal cooperation and actions that account for local factors because they are developed by local decision-makers (Adler, 2009b; Helmer et al., 1997; INTERPOL & UNEP, 2016). The trace-based operational monitoring of PCBs (and of other persistent organic pollutants) in the Lake Geneva basin, initiated and supported by the CIPEL, has allowed the generation of intelligence that local protection agencies have mainly used to guide investigations of pollution sources in the most polluted rivers. Convinced by the benefits of such an approach, it has been decided to include new contaminants in the monitoring and to extend it to new sites. It is believed that the success of this implementation will lead to similar approaches in other watersheds. This example illustrates the underlying learning process, which increases the ambition of the process by tending to address a wider range of issues in a bottom-up approach.

4 | CONCLUSION

Traces left by water-contaminating activities convey information that—if monitored and systematically treated—can help generate knowledge on the extent and mechanisms of these activities. Relying on the expertise acquired from the treatment of other types of criminal/anomalous events, forensic science has an important role to play in detecting similarities among contamination incidents and inferring common causes. This paper describes how the production of intelligence can be optimized by using a problem-solving process described in the forensic literature and based on the study of traces, as the vestiges of polluting activities. The fact that operational monitoring process relies on traces is of great importance in providing an appropriate framework for expressing the nature of the data being handled and, consequently, their appropriate interpretation. In addition, it creates an explicit bridge between law enforcement and risk analysis approaches.

The iterative nature of the proposed forensic intelligence process allows for continuous optimization of the main steps involved:

i. efficient acquisition of traces that have a high potential for explaining a problem,
ii. integration of the most relevant characteristics in a structured memory,
iii. detection of patterns and treatment of those in sub-problems,
iv. analysis through hypothetico-deductive reasoning to infer potential common causes,
v. transfer of the generated knowledge in actionable—that is, intelligence—to support decision-makers in the designing of tailored actions.

However, the integration of traces in a problem-solving process requires overcoming some current barriers, often due to systemic issues, that prevent the establishment of links among cases. Similarly to other criminal phenomena and security problems, examples of successfully implemented monitoring systems are extremely important to convince scientists and decision-makers of the benefits of such approaches. To this end, we suggest favoring iterative bottom-up approaches through horizontal cooperation, rather than starting directly by complex centralized top-down projects. By doing so, we are convinced that intelligence can be timely generated to act on highly concerning problems that the population is becoming aware of.

AUTHOR CONTRIBUTIONS

Nicolas Estoppey: Conceptualization (lead); data curation (lead); supervision (lead); writing – original draft (lead); writing – review and editing (lead). **Fabienne Pfeiffer:** Data curation (lead); writing – review and editing (supporting). **Vick Glanzmann:** Conceptualization (lead); writing – review and editing (supporting). **Naomi Reymond:** Writing – review and editing (supporting). **Ines Tascon:** Writing – review and editing (supporting). **Sofie Huisman:** Writing – review and editing (supporting). **William Lacour:** Conceptualization (supporting); writing – review and editing (supporting). **Olivier Ribaux:** Conceptualization (lead); writing – review and editing (lead). **Céline Weyermann:** Conceptualization (lead); supervision (supporting); writing – review and editing (lead).

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CONFLICT OF INTEREST STATEMENT

The authors have declared no conflicts of interest for this article.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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