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Analytical issues in monitoring drinking-water contamination related to short-term, heavy rainfall events

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Heavy rainfall events, increasing in frequency and intensity with climate change, impact on the quality of the water resource used for drinking-water production. Small-scale water suppliers are particularly sensitive because of their management and the related difficulties of adapting treatment to variations. Decision-support systems, based on monitoring and analytical tools, need to be developed to improve crisis-management procedures related to such events. After presenting the issues related to heavy rainfall events, the article summarizes the tools currently used for quality control of drinking water within this framework, the need for developments and other requirements.

Keywords: Analytical tool; Climate change; Contamination; Decision-support system; Drinking water; Monitoring; Quality control; Rainfall; Small-scale water supplier; Water treatment

1. Introduction

For half-a-century, worldwide political awareness of river-water quality issues has been increasing substantially. For example, the Water Framework Directive (WFD) asks European Union (EU) member states to ensure the necessary protection for the bodies of water identified with the aim of avoiding deterioration in their quality in order to reduce the level of purification treatment required in the production of drinking water [1]. Moreover, within the framework of the WFD Common Implementation Strategy, EU member states may establish safeguard zones for these water bodies by following the guidance on Groundwater in Drinking Water Protected Areas [2]. In this context, water-safety plans (WSPs) aim to ensure the safety of a drinking-water supply through the use of a comprehensive risk-assessment and risk-management approach [3].

The first step of this approach is identification of hazards and hazardous events, the first of which comprises the meteorology and the weather patterns associated

with rapid changes in source-water quality. This point is very important, because freshwater resources have the potential to be strongly impacted by climate change, with wide-ranging consequences for human societies [4]. According to the 2007 IPCC report [5], it is likely that the frequency of heavy precipitation events has increased over most areas, particularly in Europe and North America, and that available research suggests a significant future increase in heavy rainfall events in many regions. Regarding the change in rainfall patterns, the increase in frequency of intense rainfalls of short duration is already being observed. Fig. 1 presents a synthesis of the different types of events, from light rain to flash and plain floods on a local or regional scale.

Resulting changes in flow regimes will influence the chemistry, hydromorphology and ecology of water bodies [6]. In particular, associated with the type of heavy rainfall events, the impacts on the quality of water resources can be severe for surface water and karstic groundwater, through run-off transportation of

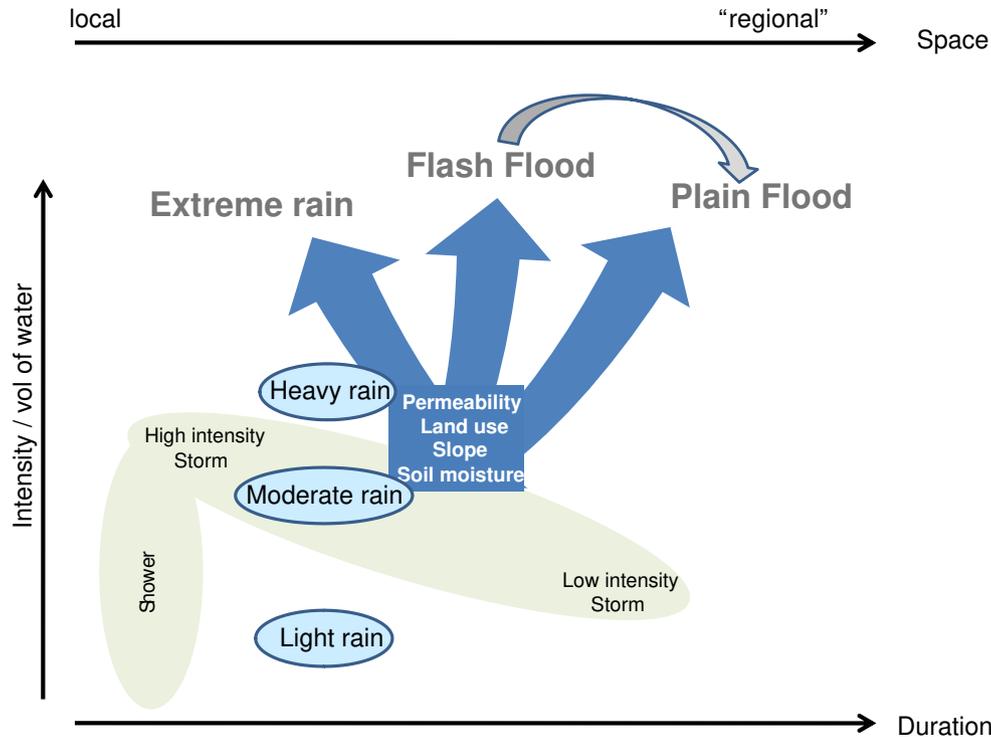


Figure 1. Types of events with regard to intensity and duration of rain. Categories of rain are defined by their intensity. Commonly, heavy, moderate and light rain are characterized respectively by 2.5 mm, 2.5–7.5 mm and >7.5 mm of water/hour. Showers and low-intensity or high-intensity storms can also be distinguished according to the duration of such rainfall. The consequences also depend on several parameters (soil moisture, permeability, land use and field slope) and can result in extreme rain or flooding, respectively, at local or regional scales.

suspended solids, chemical substances (natural and anthropogenic) [7,8] and pathogens [9]. The quality of the drinking water may also be degraded in the event of heavy rainfall or floods because of water-treatment failures (from overloading to flooding) leading to outbreaks of water-borne disease [4,10]. At the very least, an uncontrolled overload of microbial and chemical pollutants can be difficult to handle through the use of conventional drinking-water-treatment (DWT) processes. The diversity of native flora and wildlife generally also decreases, while tolerant species become more abundant [11–13]. As an example, some studies showed a higher presence of enteric pathogens resistant to chlorination (e.g., *Cryptosporidium*) during the rainy season [14,15]. Moreover, the increased load of suspended particles can jeopardize the efficiency of water-filtration and water-treatment systems, increasing the risk of contamination of the drinking-water supply [16].

Short-term, intense rainfall events could lead to a strong increase in dissolved organic carbon (DOC) in surface waters. It was found that most DOC is exported from catchments during storm events [17]; meanwhile, a DOC increase in surface waters has already been observed for the past two decades due to reduction in acidic deposition [18]. Among the constituents influencing the transport and the mobility of pollutants, natural organic matter (NOM) has an indisputable role

in sorption and leaching of hazardous organic chemicals in the environment [19,20]. Refractory organic substances are also found in drinking water, and are important precursors, along with NOM, of the formation of haloforms [also known as trihalomethanes (THMs)] and further disinfection by-products (DBPs) during application of chlorine [21,22].

As stated in a recent WHO report [17], extreme weather events could affect the efficiency of DWT processes, leading to a possible degradation of quality in distributed drinking water. Water suppliers can prepare to minimize the impact of extreme events on the service provided in a number of ways (e.g., implementation of pro-active measures to identify changes in quantity and quality of water resources).

Finally, these concerns are of primary importance for small-scale water suppliers (SSWSs), private, community-based or public, which usually prevail in rural areas. Considering that part of the population living in rural areas does not have access to improved drinking-water sources {e.g., 16 million people in Europe [23]}, SSWSs are facing several challenges, including their regulatory environment, administration, management, operation, and their available technical, human and financial resources [16].

In this context, simple tools are needed in various areas {e.g., for the rapid assessment of the vulnerability

of water utilities to climate change [23] or the improvement of compliance monitoring, validating effectiveness and monitoring performance against water-quality limits, particularly during or after heavy rainfall events}.

This article summarizes the analytical issues and currently available tools required to produce water at a constant quantity and quality in situations of extreme climatic events (e.g., heavy rain). It also aims to provide an overview of suitability, needs, and future developments for drinking-water-safety policy required to meet the special conditions of such events.

2. Needs and available solutions

Within the implementation of the water-safety plan, water-quality monitoring is a key factor for all hazards related to potential deterioration of water bodies, namely surface and karstic waters [3,4]. In this context, drinking-water monitoring during short-term, intense rainfall events involves careful consideration of the whole analytical process, from sampling design to analysis and delivery of results. Indeed, such a climatic event is mainly characterized by strong increase in water flow, leaching, and run-off, all resulting in a change in the transport of contaminants and likely alteration to the quality of raw water (in particular, surface and karstic waters) used for drinking-water production. Moreover, the modification to flows can disrupt the performance of the water-supply plants, particularly if they are small scale. Thus, it is important to implement analytical methods adapted to these changes in order to anticipate any modification or disruption affecting the production of drinking water.

2.1. Sampling

Sampling is a critical step in the monitoring procedure because it could represent the main contribution to error in the whole analytical process [24]. Thus, defining temporally accurate sampling strategies during fast variations in flow is essential for accurate assessment of the degradation in quality of raw water and drinking water. The WFD has set up guidelines for designing monitoring programs that include the objectives of supporting risk-assessment procedures and appraising long-term changes whose causes are both natural and anthropogenic [25]. This involves consideration of fast degradation in water quality during rainfall events. As a consequence, we need appropriate sampling tools and methods, easy to use and reliable, taking into account flow variations and allowing an adequate number of samples to be taken.

Several studies have compared the efficiency of grab and composite samples during fluctuations in water volume. While periodic manual grab-sample collection with

adequate frequency is useful to characterize baseflow water quality, it is not adapted to the context of extreme rainfall events. Guidance has been proposed to assist in designing appropriate sampling strategies; in particular, several general recommendations have been made, including the use of flow-interval or variable time-interval sampling, and also composite sampling to limit the number of samples collected [26,27]. Grab sampling has been judged a relatively inefficient methodology for capturing mean concentrations for water subjected to highly variable loads [28]. Moreover, when comparing grab, integrated, and automated storm-sampling techniques, the frequency and the duration of sampling, on the one hand, and the location of sample collection, on the other, have to be taken into account. In particular, reduction in the uncertainty of measured concentrations can be considered by using automated sampling, multiple integrated samples throughout the duration of the event, or, if integrated or automated sampling cannot be carried out, multiple grab samples from various locations throughout a cross-section [29].

Automatic samplers are designed to obtain a more representative picture of water quality. These devices could be used with peristaltic and vacuum sampling lines. In the event of heavy rainfall events, vacuum samplers seem to be more suitable, considering recommendations of the field investigation section of the US Environmental Protection Agency (EPA) [30]. More representative samples are obtained, particularly when turbidity and particles are present in the water flow, as is the case in rainfall events. Moreover, in these conditions, absence of a pump seems to be an advantage, because it ensures the continuous correct functioning of the sampler.

Furthermore, two different collection regimes, either at regular time intervals (time-controlled) or in response to discharge changes (flow-controlled) can be proposed. Flow-controlled configuration, in rainfall conditions, is more viable for detecting rapid changes in raw-water quality, in particular because it can adapt the sample drawn to the flow rate [24] and then collect flow-connected fractions. More generally, automatic samplers are adaptable to suit the type of collection required for analytical purposes (e.g., glass or polyethylene) and permit sample identification (e.g., sampling time and location of sampling).

2.2. Analysis

Conventional laboratory methods are often too time consuming for adequate in situ operational response in the case of fast degradation of raw-water quality, and do not make it possible to protect human health in real time [31]. Other rapid tools can optimize the time necessary for parameter determination and reduce sample alteration due to transport and storage. These techniques are required by water utilities, in particular SWSs, which are more vulnerable to any changes in influent quality.

Three main field methods are commonly differentiated: in situ; on-line; and, off-line [32]:

- (1) in situ techniques require the use of sensors placed in the water body with no sampling step.
- (2) on-line methods involve a sampling step, followed generally by pre-treatment and measurement based on optical techniques; all these steps could be automated.
- (3) off-line methods generally require a conventional spot-sampling step, followed by an analytical method that is faster and/or less expensive than commonly-used laboratory methods.

These tools, which were developed for surface waters and wastewaters [33], allow fast diagnosis of water-quality degradation, so they present a clear potential for implementation in SWSs during fast variations in flow. It should be noted that these alternative monitoring tools are not fit for purpose in terms of complying with regulations (e.g., WFD), but they can be used as to complement standardized laboratory methods. However, field and on-line methods used for chemical monitoring programs should, for example, have to comply with the requirements of Directive 2009/90/EC, which set minimum performance criteria (uncertainty of measurement and limit of quantification). Directive 2009/90/EC also requires that methods are validated and documented in accordance with the EN ISO/IEC-17025 standard or other equivalent standards accepted at the international level [34].

2.3. Physico-chemical parameters

Water utilities already use sensors for process control and regulatory compliance {e.g., contaminant detection [32] throughout the DWT process and the distribution system}. In drinking-water plants, sensors can be used for in situ measurement of temperature, pH, redox potential, conductivity, dissolved oxygen, free chlorine, total chlorine, total organic carbon, nitrates, nitrites, ammonia, turbidity and particle counts [34]. These sensors are mainly based on electrochemical [35] or spectroscopic techniques [32]. Acquisition of ultraviolet (UV)-visible spectra is on-line or off-line for measuring turbidity and nitrates/nitrites, and assessing chemical oxygen demand, biological oxygen demand, total organic carbon, total suspended solids, and aromatic compounds [31,36].

Laboratory-derived techniques (e.g., on-line DOC analyzers) could also represent an efficient method, already implemented in a DWT plant [37], even if this technique is not commonly used at present.

Finally, colorimetric test kits could also be useful to determine quickly nutrient concentrations (nitrates, nitrites, ammonium and phosphates) in raw water, despite their low sensitivity [37].

However, whatever the techniques, the increase in water-pollution charge during rainfall events, in partic-

ular, the high amount of suspended solids and organic matter, can lead to clogging or high interference with sensors, and consequently decrease their performance. To prevent clogging, some techniques already exist (e.g., implementation of ultrasonic cleaning and the development of inductive probes to reduce interference). To prevent interference, optical techniques (e.g., UV-visible absorptiometry) could require a dilution stage to ensure a quantifiable measurement.

Generally, one common solution for on-line systems is to add a dilution loop to prevent interference [38] although this could limit sensitivity.

2.4. Chemical micropollutants

Micropollutants are not systematically monitored in raw and treated waters. Chromatographic techniques coupled with mass spectrometry have already been used on-line to measure micropollutants {e.g., THM [38–40] and pesticides [41]}, and can provide quasi-real-time information [31]. However, in order to prevent device clogging by heavily loaded waters, these systems could be equipped with a filtering unit [42] or other pre-treatment [32].

Immunoassay-based tests have been widely used in detection of micropollutants, in particular in environmental waters. They could make fast analysis possible, and comparison with reference methods shows similar results. As an example, the on-line RIANA system was able to measure on-line the presence of atrazine and isoproturon in a DWT plant [43]. Enzyme-linked immune sorbent assay (ELISA) tests have proved suitable for measuring atrazine, glyphosate, alachlor and phenylureas in raw waters during precipitations/run-off events [44]. Nevertheless, it was found that these tests have a significant bias towards finished (drinking) waters [44] and could also cross-react with other molecules with similar structures [37].

The effect of the presence of micropollutants can also be assessed by in situ biological systems (e.g., *Daphnia* taximeter, ToxControl Musselmonitor and Truitosem). These early warning systems (EWSs) are integrated monitoring systems that can analyze and interpret results in real time [31]. EWSs are based on living organisms and monitor overall water quality by measuring changes in species behavior. These systems were initially developed to protect water supplies against accidental contamination, but they could also be used to monitor short-term degradation of raw-water quality after rainfall events and to prevent delivery of water unsuitable for drinking purposes. Such EWSs could constitute a viable option for remote monitoring and control of small drinking-water facilities. However, in spite of their high sensitivity, such devices find their limit in treated waters through their poor selectivity and the sensitivity to chlorine of the living organisms chosen [31].

Finally, micropollutant analysis needs to face new challenges, including the presence of emerging contaminants (e.g., human and veterinary pharmaceuticals, steroids and hormones, prescription and non-prescription drugs, and personal-care products). It is well known that they are present in the different environmental compartments (soil, water, sediments) and their behavior can depend on environmental parameters [45]. In particular, intense rainfalls and associated run-off modify their transport and mobility from soil to water [46–48], increasing the contamination levels of surface waters and, potentially, drinking water. As they are suspected to have an impact on both the environment and human health [49], mainly through chronic exposure to low concentrations (ng/L– μ g/L), there is a clear need for quick detection of these substances as well as detection of by-products generated by disinfection processes. Indeed, it has been shown that chlorinated by-products could lead to higher genotoxicity or carcinogenicity than their mother molecules [38,50].

2.5. Biological contaminants

As for sewage, fertilizers and other organic wastes and chemicals, heavy rainfall and associated floods, if occurring, can flush microorganisms into waterways and aquifers. Greater water flow contributes to increasing the pathogen load and the penetration speed of pathogens into resource waters and the drinking-water supply [51]. Levels of biological contaminants tend to increase during such events. As an example, a significant number of outbreaks of waterborne disease have involved the transport of bacteria, viruses, or small parasites into water systems or well-heads [52] and references therein; [53] and references therein}. Monitoring the increase of this biological charge is very important to ensure maximum efficiency of the treatment and protection of the population.

The main laboratory technique currently used to detect the presence of pathogenic strains in drinking-water and/or water resources is based on microbiological culture. Although reliable under normal conditions, it is not suited to times of crisis (e.g., periods of intense rainfall). Indeed, the tedious, time-consuming process of culture represents a huge drawback with regard to rapid quality control (QC). Moreover, only cultivable bacteria (in appropriate culture media) can be detected, while there is a need for wider bacterial screening. As for viruses, most species of fecal origin cannot be detected with conventional cell-culture methods [54].

Molecular techniques have been developed in the laboratory for more sensitive, rapid characterization of biological contamination. These techniques are used for the rapid detection of specific species (bacteria and viruses) as indicators of human fecal contamination. Traditional fecal indicator bacteria (e.g., fecal coliforms, *Escherichia coli* and enterococci) have been used for a

long time. But, because there are questions about their ability to predict the likely presence of pathogens, other indicators have been proposed (e.g., bacteroides, RNA phage and host-specific viruses) [55]. However, they remain difficult to implement directly in the field because they require DNA amplification as a principal step of the analytical process. Moreover, one additional difficulty is the preconcentration of microorganisms, in particular viruses, as there is no universal method for good recovery of the majority of these [54].

Here, therefore, is a very important challenge: to develop new methods for the rapid characterization of biological contamination. Currently, characterization of the global bacteria charge is often rapidly assessed by ATP measurement [56,57] but without any selectivity. Rapid tests are commercially available [e.g., QGA from Luminultra (www.luminultra.com) or Dendridiag SW from GLBiocontrol (www.gl-biocontrol.com)]. With regard to viruses, rapid methods are scarce, particularly because of the difficulty of quantitatively concentrating them from water. Nevertheless, methods [e.g., reverse-transcription polymerase chain reaction (RT-PCR)] have shown satisfactory efficiency in detecting viruses (e.g., hepatitis A) in tap water in the laboratory [58], but, so far, the PCR stage has been difficult to implement in the field.

3. Trends

As previously shown, short-term, intense rainfall events are characterized by high volumes of water, high loads of suspended particulate matter, increases in organic matter transported by run-off and increased concentration of microorganisms (some of them being pathogens).

Large drinking-water units can absorb this kind of variation and are not really disrupted by such events, except in particularly extreme conditions. Conversely, SSWs, fed by surface water, are not well adapted to deal with such events and will face severe difficulties. This is confirmed by a very recent decision of the Committee of the European Drinking Water Directive (DWD), which concluded that increased implementation and enforcement efforts are required to ensure safe drinking water, particularly in smaller supplies, and that no revision of legislation is required for the DWD [59]. As an example, increased pH and turbidity (high load of organic matter) can modify the efficiency of coagulation-sedimentation treatment [60]. Higher TOC and turbidity can also interfere in chlorination processes by reducing the free-chlorine residual and creating chlorine demand [61]. Consequently, processes need to be adapted to consider such variation, and there is an important need to help water managers to take the appropriate decisions; monitoring is a key element. These efforts will also help to improve the treatment efficiency of smaller supplies even outside rainy periods.

Rapid tools for water-quality monitoring are required in this case, not only systems giving a quantitative response (e.g., concentration of contaminant), but also systems providing information on changes in water quality (e.g., indicator and index). In the case of an unusual event, a follow-up procedure using comparisons with regular conditions, based on EWSs, could often be sufficient to manage and to anticipate a potential crisis. Thus, implementation of indicators of the global physico-chemical, chemical and biological quality should be promoted. The first of these (e.g., probes and sensors) are already available, even if in some cases their sensitivity can be questionable, as explained previously.

Concerning chemical (micropollutant) and biological (pathogen) indicators, there are very few adequate solutions, and here there is a major challenge. Indeed, the strategy used so far, involving development of one system for each substance, is limited because of the number of substances to monitor, the cost, and the time required to perform a total analysis. A strategy for each family or group of compounds must be favored. Sensors should be developed to give access to quantitative information (concentration or representative parameter) and, at the same time, qualitative information (effect or representative parameter). This can be achieved by molecular biodiagnostic tools, which couple a molecular recognition element (e.g., enzyme, antibody, peptide, receptor, nucleic acid) with a physico-chemical transducer (e.g., optical, electrochemical, and physical) [62]. These transducer technologies can be miniaturized and allow compact, portable devices to be made available.

Furthermore, these tools require improvements in rapid sampling and on-site extraction procedures in order to achieve increased sensitivity and purity of samples. (Micro)extraction using solid phases in association with portable devices needs to be developed. Indeed, this technique has been successfully developed as a pre-treatment for chromatography (liquid and/or gas) but now needs to be adapted to on-line or on-site devices. Very few models are currently available.

The Hocer Aquapod SPE50 (<http://hocer.images-creations.fr/content.cfm?id=129>) couples a solid-phase extraction (SPE) module with a UV detector and is used to detect pesticides, hydrocarbons and other industrial substances. Improvements are planned for this system, with remote sensing and assistance, and better sensitivity. Note that passive samplers, which are one of the main sampling methods of the future for micropollutants in water [32], could also be suggested for use in heavy rainfall events, but they would need to be adapted to an on-line sampling belt or connected directly to a sensor. Unfortunately, there has been no such development to date.

The rapid assessment of pathogenic contamination is even more challenging. Indeed, the culture method still remains the method principally used in all circumstances in spite of its drawbacks. For several years, molecular

biological methods [e.g., PCR, quantitative PCR (QPCR) and microarray] have been developed in some drinking-water monitoring applications [63–65]. They are based on the detection of specific gene(s) after amplification. However, these methods are currently difficult to implement on-site because of the lack of miniaturized PCR devices. A recent study tested the efficiency of a new portable real-time RT-PCR (rRT-PCR) unit (RAPID, Idaho Technologies, Salt Lake City, UT, USA) for in-field detection of avian influenza virus in wild birds, and compared it with virus isolation combined with rRT-PCR conducted in a laboratory. Results indicated that the portable rRT-PCR unit had equivalent specificity to virus isolation with no false positives, but sensitivity was compromised at low viral titers [66]. Another portable PCR is available {[67], Ahram biosystem <http://www.ahrambio.com/product.html>}, but still needs some validation for its application in the context of climate change and water quality.

Detection of viral particles also suffers, due to their relatively low density in aquatic environments that makes representative, reliable measurement particularly difficult to perform without preliminary concentration. Different solutions are available for concentrating viruses from water, but their recovery rate does not exceed 60% [68], except in particular cases [54]. Polymers using biomaterial (e.g., chitosane and lysine) can be used due to their affinity [e.g., weak interaction (e.g., electrostatic, hydrogen bond)] with viral particles (containing electrostatic charges and hydrophobic groups expressed variably as a function of pH, chemical and organic components of the water). To be compatible with rapid, on-site applications, they must be packaged in an appropriate form (i.e. powder, magnetic beads, hollow fibers, or foam). This application has already been developed for medical diagnostics [e.g., Ademtech (<http://www.ademtech.com/>) and ApoH technologies (<http://www.apohtech.com/en/home.html>)], and is to be extended to environmental applications.

Finally, as for resource and water management, the development of decision-support systems (DSSs) could be particularly advantageous in cases of extreme rainfall events. According to Power et al. [69], any system supporting decision-making (e.g., executive information systems, executive support systems, geographic information systems, and on-line analytical processing and software agents) may be called a DSS. Generally, DSSs involve the development of models to support decision making for water (and wastewater) preventive management systems. Different criteria can be used (e.g., health, environment, economy, social, or technology), each requiring a set of indicators {i.e. quantitative or qualitative data, including satellite imaging [70–72]}, to assess comparatively the different options in the decision-making process, taking into account the different criteria [73].

As a recent example, GESCAL, a DSS for water-quality issues, simulates conductivity, phosphorous, carbonaceous organic matter, dissolved oxygen, organic nitrogen, ammonia, and nitrates to provide an integrated model of water quality for whole water-resource systems, including reservoirs and rivers [74]. The practice of modeling is not recent, as shown by the modeling support systems (WODA) developed to register biological oxygen demand (BOD) and dissolved oxygen (DO) concentrations in a stretch of river under different hydrological and thermal conditions [75] or the generic DSS (Aquatool) designed for the planning and operational stages of decision making associated with complex river basins [76]. But advances in computer technology, availability of real-time hydroclimatic data, and improvements in the ability to develop user-friendly graphical model interfaces have made possible development and application of DSS for drinking-water-resource systems. EPA's National Homeland Security Research Center (NHSRC) has developed the Water Systems Materials Disposal Decision Support Tool (DST), a Web-based platform, to assist and to help incident responders in emergency response to biological or chemical contamination of water systems (DWT or wastewater treatment plant) [77]. A real-time DSS for adaptive daily and weekly management of a reservoir system that provides drinking-water has also been described [78]. By integrating watershed models, reservoir hydraulic models, and a reservoir water-quality model, it offers the ability to optimize reservoir operations. As shown in these examples, DSS represents an interesting way of controlling water quality, in particular during strong and rapid modifications of water-system conditions. It should allow improved reactivity during a period of crisis, with the selection of the best scenario(s) from the rapid assessment of the degradation of the water system. Although currently limited to a Web interface, the concept is intended to be developed through the development of real-time data transmission (e.g., phone and Wi-Fi). Finally, DSS should be implemented by both drinking-water managers and producers and sanitary authorities. This is of primary importance for SSWs, with regard to efforts planned for the improvement of drinking-water quality compliance in one-third of SSWs in Europe and the implementation of a risk-based approach for more effective QC [59].

4. Conclusion

Heavy rainfall events are characterized by high volumes of water, increased flow rates, and, consequently, more significant run-off transportation of suspended solids and possibly chemical and biological substances. The quality of water resources (surface water and karstic groundwater) can be severely impacted, and the

quality of the associated drinking water may also be degraded because of a lack of adaptability or failures in water treatment, in particular in small-scale supply services.

While Water Safety Plans are increasingly being integrated into water regulations with the implementation of hazard assessment for risk management, drinking-water quality compliance in small-scale water treatment should be improved. These actions do not necessarily fit in with the need for better understanding of the impact of short-term, heavy rainfall events, based on more frequent, relevant measurements in order to monitor short-term variations in water quality. But forgetting the impacts of climate change will cancel out these efforts, so, at least for the next decade, development and implementation of suitable monitoring tools and procedures must be planned with a view to a better knowledge of water-quality variation for a complete risk assessment and management program. In particular, field systems (on-line, on-site) need to be employed.

Sampling procedures should be adapted to meet the special nature of such events and the associated water quality. Concerning analytical issues, global parameters could be measured in real time with available tools. However, these are lacking for chemical and biological micropollutants, as such analytical developments are very challenging. Some methods are described, but are not widely used.

Finally, to respond and to react adequately to the crisis, analytical data need to be transferred to, and translated for, water managers for relevant, accurate decision making. DSSs represent the solution of the future, and are beginning to be employed in the drinking-water supply sector.

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