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Water quality monitoring strategies — A review and future perspectives

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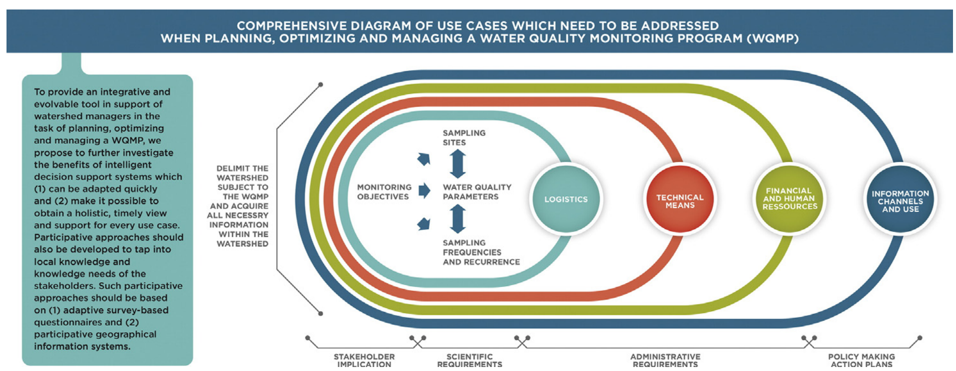
HIGHLIGHTS

- No holistic solution exists to cover all steps of water quality monitoring programs.
- Existing approaches to plan or optimize water quality monitoring programs were reviewed.
- Intelligent decision support systems are needed in support of watershed managers.
- Participative geographical information systems are useful to tap into local knowledge.
- Stakeholder involvement is necessary for successful integrated watershed management.

GRAPHICAL ABSTRACT



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ABSTRACT

The reliable assessment of water quality through water quality monitoring programs (WQMPs) is crucial in order for decision-makers to understand, interpret and use this information in support of their management activities aiming at protecting the resource. The challenge of water quality monitoring has been widely addressed in the literature since the 1940s. However, there is still no generally accepted, holistic and practical strategy to support all phases of WQMPs. The purpose of this paper is to report on the use cases a watershed manager has to address to plan or optimize a WQMP from the challenge of identifying monitoring objectives; selecting sampling sites and water quality parameters; identifying sampling frequencies; considering logistics and resources to the implementation of actions based on information acquired through the WQMP. An inventory and critique of the information, approaches and tools placed at the disposal of watershed managers was proposed to evaluate how the existing information could be integrated in a holistic, user-friendly and evolvable solution. Given the differences in regulatory requirements, water quality standards, geographical and geological differences, land-use variations, and other site specificities, a one-in-all solution is not possible. However, we advance that an intelligent decision support system (IDSS) based on expert knowledge that integrates existing approaches and past research can guide a watershed manager through the process according to his/her site-specific requirements. It is also necessary to tap into local knowledge and to identify the knowledge needs of all the stakeholders through participative approaches based on geographical information systems and adaptive survey-based questionnaires. We believe that future research should focus on developing such participative approaches and further investigate the

Abbreviations: DSS, decision support systems; IDSS, intelligent decision support systems; IWM, integrated watershed management; PCA, principal component analysis; WFD, Water Framework Directive; WQMP, water quality monitoring program; WQP, water quality parameter.

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benefits of IDSS's that can be updated quickly and make it possible for a watershed manager to obtain a timely, holistic view and support for every aspect of planning and optimizing a WQMP.

1. Introduction

Watershed management has a long-standing history and knowledge of the connection between water quality and quantity and watershed preservation that goes back to at least 2880 BCE (Neary et al., 2009). However, this knowledge was partially lost during the Dark Ages and only progressively reintroduced in the mid 19th century due to poor water quality, a consequence of industrialization (Neary et al., 2009; Timmerman et al., 2010). Since then, declining water quality of rivers, lakes and groundwater has progressively become a global issue of concern, and many countries have embarked on reforming water governance towards sustainable development through an integrated approach, as recommended in 1992 Agenda 21 (UNEP, 2012). This approach is generally referred to as integrated watershed management (IWM). IWM implies managing all human activities and natural resource uses in an area known as the watershed, in a coordinated and sustainable manner (Conservation Ontario, 2010). All water stakeholders, defined as policy-makers, city planners, water conservation organizations, industry sectors, universities and the general public, should be part of the process in order to take joint decisions and actions to protect the resource for economic, social, environmental and public health reasons (Bartram and Ballance, 1996; Demard, 2007; Islam et al., 2011). Given the growing pressure on water resources, IWM is increasingly being adopted to achieve targets aimed at preventing and managing water pollution.

One of the main challenges posed by IWM is to obtain a reliable assessment of surface water quality (lakes and rivers) in a given watershed through water quality monitoring programs (WQMPs) so that decision makers can understand, interpret and use this information in support of their management activities (for water destined for consumption, recreational and industrial use, or preservation and restoration of the ecological status).Water quality monitoring is the "long-term, standardized measurement and observation of the aquatic environment in order to define status and trends" (Bartram and Ballance, 1996). Monitoring also implies a long-term, spatially distributed, standardized surveillance and assessment of all monitoring activities based on common protocols, a panoply of knowledge needs (regulatory or not) on water quality, as well as land use of a given watershed (Bartram and Ballance, 1996).

When planning or optimizing a WQMP, the following elements need to be considered: (1) identification of monitoring objectives (e.g., the information that needs to be produced); (2) determination of a sampling site network for lakes and rivers; (3) selection of the water quality parameters (WQP); (4) establishment of sampling frequencies and recurrence; (5) estimation of human, technical and financial resources; (6) preparation of the logistics (e.g., field work, laboratory work, quality control and assessment, data handling, data storing, data analysis); (7) identification of information diffusion channels and (8) an assessment if the information generated has been put to use (Bartram and Ballance, 1996; Gray, 2010; Harmancioglu et al., 1999; Strobl and Robillard, 2008). A WQMP is considered holistic when all these elements have been considered and activities have been standardized. The term "planning a WQMP" refers to designing a WQMP in a watershed where no WQMP has been implemented. The term "optimizing a WQMP" refers to the process of reviewing and improving an existing WQMP. Optimizing does not necessarily imply reducing the number of sampling stations, sampling frequencies or WQPs. Rather, optimizing implies the verification that initial monitoring objectives have been met and whether additional monitoring objectives have been identified which have to be addressed. Optimizing also implies that every element of the existing WQMP is appraised.

As many decisions concerning watershed protection (regulations, land zoning, etc.) depend on the information acquired through water quality assessment, it is essential that water quality data be relevant, precise and reliable in space and time, thus requiring the implementation of WQMPs. This is particularly important in order to avoid the multiplication of data collection from various organizations that represent water quality neither on a spatial nor on a temporal scale in a given watershed (Bartram and Ballance, 1996; Harmancioglu et al., 1999). For instance, it has to be avoided that data is being produced that cannot be easily compared (e.g. because sampling frequencies are based on a monthly basis as opposed to a bi-monthly basis, detection limits for contaminant analysis are not the same or because sampling strategies provide different contaminant concentrations). Thus, data that has not been collected with a common protocol is often of little or no use due to its heterogeneity, incompleteness and inadequateness (Bartram and Ballance, 1996; Harmancioglu et al., 1999).

Monitoring water quality remains a very complex process due to the large number of factors to consider. Indeed, the problem of planning and optimizing WQMPs for surface waters has been addressed by several researchers, particularly since the 1940s, and a great many handbooks, guidelines and papers have been published on the subject (Chen et al., 2012; Ning and Chang, 2002; Park et al., 2006; Quevauviller et al., 2005; Ward et al., 1990). For instance, the selection of representative sampling points, WQPs and sampling frequencies has to be adapted to the constraints of the territory, based on realistic and practical knowledge needs, and planned within the available human, financial and technical resources, as well as legal and political obligations, such as the Water Framework Directive (WFD) of the European Union (Australia, 2009; Harmancioglu et al., 1999; Madrid and Zayas, 2007; Moss, 2008; Mäkelä and Meybeck, 1996; Ouyang, 2005; Strobl and Robillard, 2008).

Strobl and Robillard (2008) have summarized the problem of planning a WQMP as follows "(…) a plethora of considerations as well as issues that need to be addressed (…)". In addition, watershed managers who have to plan or optimize WQMPs face the challenge of integrating new tools for water quality monitoring, such as effect-based tools (e.g., biomarkers and bioassays) (Wernersson et al., 2015), automated monitoring devices (Winkelbauer et al., 2014; Winkler et al., 2008) and remote sensing (Tyler et al., 2009). Also, watershed managers have to adapt their WQMPs to evolving issues of water quality, such as chemical mixtures (Altenburger et al., 2015), as well as new policies and regulations (Fölster et al., 2014; Timmerman et al., 2010). Moreover, many approaches to optimize the number of sampling stations and WQPs are proposed in the literature from which the watershed manager has to choose from. As outlined by Strobl and Robillard (2008), many of these approaches have not been implemented since they are "either too general, too specific (i.e. too case-limited), or simply too difficult for a watershed manager to easily incorporate into a water quality monitoring network design, given time and budget constraints". The authors also agree on the fact that prior to planning a successful WQMP, it is crucial to choose precise and realistic monitoring objectives according to knowledge needs on water quality (Australia, 2009; Bartram and Ballance, 1996; Gray, 2010; Harmancioglu et al., 1999; Timmerman and Langaas, 2005; Ward et al., 1990). However, there is no generally accepted practical strategy to support all phases of WQMP planning and optimizing in a holistic manner (Khalil et al., 2011; Strobl and Robillard, 2008). In addition, knowledge needs on water quality on which WQMPs are based, are often not representative of the real needs (Australia, 2009; Bartram and Ballance, 1996; Harmancioglu et al., 1999; Ning and Chang, 2002; Timmerman et al., 2010).

We argue that these statements are justified and that the reasons for the difficulties are that (1) proposed approaches do not address the issues of planning and optimizing WQMPs in a holistic way, namely that the approaches do not consider every element of WQMP planning or optimizing; (2) every watershed has its own constraints and it is not possible to have a "one- size-fits-all" solution; and (3) an effort has to be made to get the most out of the existing knowledge on the subject in order to propose a holistic approach for water quality monitoring that can evolve over time while having to face site specificities that can originate from natural particularities (e.g., geology and hydrology), human induced circumstances (e.g., land-use, technical, human, financial resources), and previous monitoring activities. In other words, planning or optimizing WQMPs is a suite of common use cases. A use case is defined herein as a sequence of actions to achieve a goal (Balzert, 2005).

Therefore, the general aim of this paper is to present a critical review of the available approaches and tools placed at the disposal of watershed managers tasked with planning and optimizing a WQMP. The specific objectives are to (1) identify the use cases a watershed manager has to consider in the process of planning or optimizing a WQMP of lakes and rivers and list the main elements of these use cases (purpose, actions and interactions); (2) present and analyze examples in the literature that have addressed one or more of the use cases and propose approaches to aid in the process of planning or optimizing a WQMP; (3) identify new challenges in water quality monitoring; and (4) discuss how the use cases and proposed approaches may be integrated in a more holistic and evolvable solution for WQMP planning and optimization.

2. Methodology

The literature review was conducted in the following sequence: First, handbooks, official guidelines and scientific papers were searched in order to identify the use cases related to planning and optimizing WQMPs, their purpose and the basic sequence of underlying actions and interactions leading to their realization. Then, scientific papers were selected and qualitatively analyzed to determine which use cases they address and to what extent. In the following steps, some of the proposed approaches to address use cases (e.g. optimize the number and distribution of sampling points; evaluate the representativeness of a sampling site network for the water quality of a watershed; evaluate the representativeness of the type and number of WQPs, explore relationships between WQPs, assess sampling frequency and recurrence) were selected and submitted to a more in-depth analysis in order to verify their transferability, case specificity and degree of difficulty of application, the main critique points raised by Strobl and Robillard (2008). The final step was to evaluate, according to the review outcome, how future research could contribute to addressing the challenge of planning and optimizing WQMPs.

2.1. Selection criteria for the literature consulted

The selection criteria for the literature were established as follows: handbooks were selected for their reputation of being cited, or of their authors being quoted, in the field of water quality monitoring. The aim was to select at least five comprehensive handbooks. Official guidelines were chosen either for their representativeness (either on a national or global scale) or their degree of bindingness (either on a national or transnational scale). Sources were official websites; the aim was to cover Canada, the United States and Europe, each with an official document. Scientific papers were selected with the help of search machines such as Ariane 2.0, Google Scholar and Scopus. The objective of this search was to determine, as best possible, the use cases and identify at least one paper for each use case proposing an in-depth description of a suite of actions for a watershed manager to take in order to address the use case. In addition, we aimed at identifying five to ten literature reviews on water quality monitoring issues in order to guide our analysis of the proposed approaches.

2.2. Identification of use cases

General use cases have already been identified in the literature and depicted in comprehensive diagrams (Harmancioglu et al., 1999; Ward et al., 1990). However, each of the use cases shown in these diagrams can be described as a black box that does not reveal the purpose and the basic sequence of underlying actions and interactions leading to its realization. Therefore, the purpose was to (1) identify additional essential use cases, (2) delve into the use cases to show the underlying actions and interactions, and (3) search the literature to identify approaches providing important leads to address the use cases. Fig. 1 shows a comprehensive diagram of the use cases on which the search was based.

2.3. Analyze approaches for planning and optimizing water quality monitoring programs

Once the use cases were established, the aim was to find papers that proposed an approach to address one or more of the use cases identified in the previous section. Then, each paper was first submitted to a qualitative analysis: it was identified if a use case was mentioned (yes/no) and if it was addressed, to what degree in-depth information was provided (+ = specific use case mentioned and briefly discussed/++ = specific use case addressed with some additional information/ +++ = specific use case addressed with in depth information, e.g., main subject of the paper).

From these papers, the plan was to select ten papers proposing mathematical - statistical methods to optimize a WQMP in order to submit them to a more in-depth analysis. The focus here was to test an approach to analyze existing optimizing approaches based on a number of criteria so as to verify the possibility of integrating them into a more holistic and evolvable tool. The aim is to eventually propose the existing approaches to watershed managers with specific optimizing objectives and datasets.

Thus, for each of these papers we (1) identified the statistical technique; (2) identified the statistical tool; (3) defined the data category (e.g., mode matrix); (4) recalled the objectives the authors pursued with their approach; (5) evaluated the relative difficulty of application of the approach; (6) evaluated the transferability and (7) verified whether the authors achieved their objectives.

The relative degree of difficulty of application was evaluated based on the following elements: (1) theoretical knowledge necessary to use the statistical technique; (2) prior knowledge of the conditions of application; (3) technical knowledge needed for application on a computer, and (4) ease in reading and interpreting results. Each value was chosen as a maximum for one of the 4 criteria and the final scale from 01 to 05 was: 01-Uncomplicated to apply, no prior statistical skills needed; 02-Easy to apply, some basic statistical skills required; 03-Solid statistical skills required; 04-Solid statistical skills and theoretical background knowledge required and 05-Very technical and specific technique for which an expert is required for application and interpretation. The transferability of each method was evaluated based on the possibility of use with any set of variables. For instance, principal component analysis (PCA) is used in many domains such as psychology, biology, ecology because PCA works well with various origins or types of variables as long as the application conditions are respected. Any specific element that might affect transferability was also identified.

3. Results

3.1. Identification of the use cases

The first aim of this literature review was to identify the use cases that a watershed manager has to consider in the process of planning or optimizing a WQMP. It is particularly important that WQMPs, once established, remain stable and flexible (Ward et al., 1990). This means

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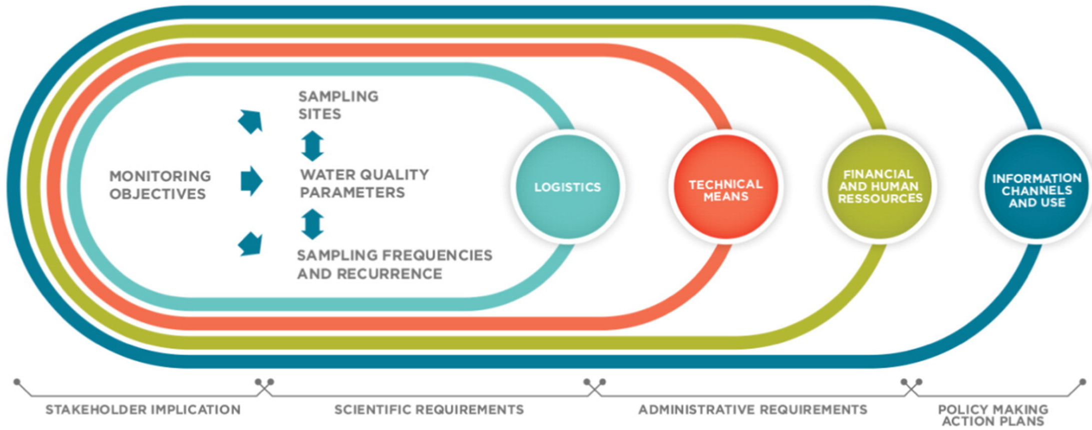

Fig. 1. Comprehensive diagram of use cases which need to be addressed when planning or optimizing a WQMP.

that long-term data on some specific sites is essential to establish long-term trends, while the WQMPs need to be adapted in response to new environmental pressures (e.g., evolving pollution sources and chemicals) and emerging sampling tools (e.g., effect-based tools, automated sampling and continuous on-line sampling) (Altenburger et al., 2015; Brack et al., 2015). Therefore, it is not always feasible, or desirable, to separate the notions of planning and optimizing. Rather, it is a spiral approach where a constant learning process is enabled through feedback, critical reflection and quantitative optimization methods (de Vries et al., 1992). However, in order to facilitate the representation of the underlying actions and interactions of the use cases, planning and optimizing are presented separately. Also, the literature review showed that in general, lakes and rivers are treated separately. Waterbodies should not be treated separately when planning or optimizing a WQMP as rivers feed lakes and vice versa. Especially for lake monitoring it is crucial to integrate monitoring of its tributaries for nutrient load calculation and to evaluate whether the tributaries provide the lake with oxygen-rich and cool waters (Thomas et al., 1996). In addition, it is important to ensure that the same type of probes and laboratories are used in order to be able to compare values and mutual influences. Therefore, the information in Table 1 provides the overview of the thirteen (13) use cases to plan and optimize WQMPs for lakes and rivers within a given watershed. They were identified through the literature review as was their purpose and the main sequence of underlying actions and interactions leading to their realization.

In addition to the use cases identified in Fig. 1 and discussed in the introduction, the literature review allowed the addition of three additional use cases. The first use case added was to “delimit the watershed subject to the WQMP”. This use case was of particular interest in papers discussing integrative watershed management issues, such as implementation of policies and actions (Raadgever et al., 2008). The second use case was “classify waterbodies”. This use case has gained an important status due to the WFD (Directive, 2000/60/EC; Moss et al., 2003), meaning that waterbodies need to be classified according to regions based on criteria such as geology, climatology, size, altitude, etc. (Directive, 2000/60/EC). Also, the use case “classify WQPs” was added. Although the selection of WQPs was already considered a major use case at the outset of this review, the classification of WQPs has been complicated due to changes in paradigms, partly also due to the WFD. For instance, the objective is no longer to mainly measure concentrations of chemicals; more and more, the objective is shifting towards the evaluation of ecological integrity and the effects of chemical mixtures (Fölster et al., 2014; Hatton-Ellis, 2008; Moss et al., 2003; Timmerman et al., 2010). The latter is due in part to the fact that is particularly difficult to establish criteria for each known chemical, as the list is expanding rapidly (Altenburger et al., 2015; Brack et al., 2015). Therefore, watershed managers are faced with an even broader scope of WQPs to choose from in order to assess water quality and ecological integrity.

When delving into the use cases, the observation was made that it is difficult, if not impossible, to find one paper, handbook or guideline that addresses every necessary step for a given use case. Although some of the handbooks and guidelines consulted are very comprehensive, the information is not always up to date. Constant emerging new challenges, related in particular to new sampling tools, such as in line monitoring (monitoring devices providing continuous data which is automatically transferred), effect based tools (in order to assess the effect of chemical mixtures on the ecological integrity for instance), as well as WQPs such as chemical mixtures make it impossible for authors of handbooks and guidelines to provide quickly updated and accessible information. Also, the review revealed that one of the main challenges is related to the use case “identify communication channels”, wherein the challenge is to produce information that is relevant, easy to understand, timely, trustworthy and conveyed efficiently to policy and decision makers (Raadgever et al., 2008; Timmerman et al., 2010). Therefore, it is also indispensable that the rationale behind a given WQMP, as well as the produced data, is well documented and easily accessible and that continuity of data sets is considered in order to ensure comparability of long-term data trends even if short-term decisions have to be made on some aspects (Davies-Colley et al., 2011; Fölster et al., 2014).

3.2. Approaches addressing the planning or optimizing of a WQMP

As the literature on planning and especially optimizing WQMPs is very prolific, some limitations were set for this part of the review. From the literature, one to seven papers were selected for each of the thirteen use cases for planning and optimizing WQMPs, for a total of 34 papers. The limit of the number of papers was set from one to seven since the previous section has revealed that some use cases do not seem to be very much documented in scientific papers (e.g. methods to identify monitoring objectives; approaches to assess the attainment of monitoring objectives; assessing quality control of field work procedures and the importance of defining sampling routes and sampling calendars) while other use cases have been extensively discussed (e.g. optimizing the number of sampling sites and WQPs).The purpose of this part of the review is to cover each use case identified in Table 1 rather than provide an in-depth review of papers for each.

According to the proposed methodology, these papers were submitted to the qualitative analysis criteria. In order to facilitate the visualization to which degree use cases were addressed, we summarized the categories “yes”, “+”, “++” and “+++” into the category “considered use case” as opposed to the category “use case not considered”. In order to do justice to some papers that specified some sub-use cases, we split up the use cases “delimit the watershed”, “determine and assess monitoring objectives”, “establish a sampling site network”, “delimit the watershed”, “plan quality control and assessment” and “identify communication channels”. The results of this analysis are illustrated in

Table 1
Use cases, their purpose and main sequence of actions and interactions to plan and optimize WQMPs for lakes and rivers.

Use case	Planning Purpose and main sequence of actions and interactions	Optimizing Purpose and main sequence of actions and interactions
Delimit the watershed subject to the WQMP (Directive, 2000/60/EC; Raadgever et al., 2008; WMO, 2013)	Choose the watershed(s) subject to the WQMP in order to • assess scalability • coordinate river basin management plans (Directive, 2000/60/EC) • coordinate monitoring activities Acquire information on: • other sampling activities (local, regional or transnational) • information on land use • number of weather stations • number of hydrological measurement stations • previous studies • stakeholders (information users) • geology • climatic region • hydrology • topography (Chapman, 1996; Timmerman et al., 2000; Ward et al., 1990)	Verify if the watershed was covered adequately by the WQMP in order to ensure that the: • WQMP was able to provide the required information in a timely and adequate manner • the spatial coverage was adequate • the acquired data could be kept comparable Assess whether: • the chosen area was covered and required information was produced • other sampling activities could be coordinated • information on land use has been updated • number of weather and hydrological stations has varied • additional studies have been conducted • stakeholders have evolved • verify whether the WQMP should be scaled down to sub-watersheds or scaled up in order to cover larger areas (Davies-Colley et al., 2011; Fölster et al., 2014; Timmerman et al., 2000)
Determine and assess monitoring objectives (Bartram and Ballance, 1996; CCME, 2015; Chapman, 1996; Smeltzer et al., 1989; Timmerman and Langaas, 2005; Ward et al., 1990; Wilkinson et al., 2007)	Specify realistic and representative knowledge (information) needs on water quality in order to be able to • determine monitoring objectives • produce information that is needed to support policy making and implement action plans Set up baselines for participative approaches and communication channels: • perform a stakeholder analysis (Schmeer, 2000) • establish a dialogue "between information users and information producers to develop the connecting questions – questions that are clearly articulated and understood by both information producers and users" (Timmerman et al., 2000) • "Determine how the answer should be presented and the level of detail and precision to be included in the answer" (Timmerman et al., 2000) • divide the information needs into information categories (Ward et al., 1990) • quantify the information needs in terms of identifying objectives of improvement in water quality (Timmerman et al., 2000) • identify what will be done with the information • identify indicators that are able to convey the information more easily • use indexes (aggregation of indicators) describing a more complex situation • define the type of monitoring (e.g., as requested in the WFD). • include any monitoring objectives that are part of legal or policy requirements • tap into local knowledge in order to obtain a better overview of concerns in the watershed and activities which may impact water quality (Timmerman et al., 2010; Wernersson et al., 2015)	Determine whether the set monitoring objectives have been attained and verify if new knowledge needs have emerged in order to be able to • determine new monitoring objectives • adapt the WQMP in order to attain past and new monitoring objectives Validate whether any of the sequences of the planning process need to be repeated and • verify if the legislative information demands have evolved (Timmerman et al., 2010) • new problems have emerged and need to be addressed • tap again into local knowledge • follow the optimizing steps of use case "Delimit the watershed subject to the WQMP" (Davies-Colley et al., 2011; Fölster et al., 2014; Timmerman et al., 2000)
Classify waterbodies (CCME, 2015; Keum and Kaluarachchi, 2015; Wetzel, 2001)	Classify waterbodies in order to • prioritize waterbodies to be monitored • be able to select the number of sampling stations and water quality parameters • be able to better interpret data The classification can include documenting the: • type, size, morphometry, origin, geology, climatic region, stream order, use, anthropogenic modifications of the watershed and hydrology of a waterbody	Verify whether waterbody classification and available information was sufficient to aid in • prioritizing waterbodies • set up an adequate network of sampling stations (see following use case) • analyzing water quality data
Establish a sampling site network (Anttila et al., 2008; Anttila et al., 2012; Chapman, 1996; Madrid and Zayas, 2007; Ward et al., 1990)	Select a network of sampling sites on a macro and micro level in order to obtain: • an adequate spatial coverage according to monitoring objectives • representative monitoring sites In order to set up an initial sampling site network, every element	Optimizing a sampling site network may be necessary to • downscale the network for financial reasons or redundancy in information • upscale the network if financial means allow it and if a finer network is needed

(continued on next page)

Table 1 (*continued*)

Use case	Planning Purpose and main sequence of actions and interactions	Optimizing Purpose and main sequence of actions and interactions
	from the previous planning use cases needs to be followed. The sampling site network can then be established based on approaches, such as the risk based approach, the stream order hierarchical approach (CCME, 2015; Sharp, 1971), based on previous extensive studies, on the classification of the size of the waterbodies and their watershed or on expert opinion (Ward et al., 1990). In any case, it is always necessary to validate the sites according to • monitoring objectives • land use • point and non point sources • water uses • size of the water body (one or more stations) • priority waterbodies • hydrometric stations available (might be necessary depending on the monitoring objectives) • representativeness • mixing • local influences, dependency of waterbodies and accessibility • number of samples for each transect or depth which need to be taken. • justifications for each site (Gray, 2010; Mäkelä and Meybeck, 1996; Tchobanoglous and Schroeder, 1985; Thomas et al., 1996; Ward et al., 1990)	• redesign the initial network if the initial one has not yielded the sought-after information or if the information needs have shifted to other areas of the watershed The literature proposes many different optimizing approaches. In any case, the main sequence of actions is to follow the sequence of action of the previous optimizing use cases as well as the following use case (select and classify WQPs) and to • understand the design and design objectives of the existing network • determine evaluation objectives (e.g., has the network produced the information it was designed for? Is there a need to reduce the number of WQPs due to budget restrictions, etc.) • select sampling sites to be included in the optimizing scheme (e.g., river monitoring vs. lake monitoring) • select a time frame • verify if changes in the existing WQMP may have affected the comparability of the data • select variables (e.g., WQPs, sampling site justification) • determine evaluation method • generate and present the results from the evaluation • validate the new network design with the information users • verify if a site has yielded historical and time series need to be continued for long-term trends (Fölster et al., 2014; Horowitz, 2013; Olsen et al., 2012; Strobl and Robillard, 2008; Timmerman et al., 2010)
Select and classify water quality parameters (WQP) (Altenburger et al., 2015; Bartram and Ballance, 1996; Chapman, 1996; Fölster et al., 2014; Timmerman et al., 2010; Ward et al., 1990; Yang et al., 2008)	Select and classify WQP in order to be able to • attain the knowledge needs established in an earlier step, such as the identification of pollution sources or the impacts on water quality and ecosystems The essential sequence of action is to • include the reflection on possible WQPs while establishing the monitoring objectives and the monitoring network (Chen et al., 2012) During this process it is necessary to reflect upon • local regulations • recognized water quality indices and indicators (biological, chemical, physical and hydrological) (CCME, 2015; Directive, 2000/60/EC) • parameter dependence and significance (Harmancioglu et al., 1999) • matrix (Chapman, 1996; Wernersson et al., 2015) • technical means to measure them (e.g., probes; laboratories) • establishing common methods (Davies-Colley et al., 2011) considering effect-based tools (Wernersson et al., 2015) • including intelligent monitoring networks (Winkelbauer et al., 2014) • ensure that the knowledge to interpret the data can be made available	Optimizing a WQMP as to WQP may be one of the most frequent challenges a watershed manager has to face, especially when considering the evolving knowledge on chemicals, the effect-based tools, evolving technology of laboratories and in situ measurement facilities, as well as the inclusion of biological indicators such as macro-invertebrates, aquatic plants, etc. Some of these new elements may be mandatory, others may be optional. In any case, it is necessary to include in the reflection previous optimization use cases as "… different parameter sets may lead to different networks." (Chen et al., 2012) Thus, the essential sequence of action is to validate whether • the collected data has yielded the sought-after information • new regulations and indicators have been issued • new WQPs need to be taken into consideration as new issues arise • correlation between WPPs could permit the elimination of some of them • the technical means to measure WQPs have proven satisfactory (e.g., satisfying detection limits from laboratories; probe data has proven to be reliant) • new tools could prove to be more efficient • historical data has been collected and time series need to be continued for long-term trends • ensure that the knowledge to interpret the results is available Several statistical methods exist to optimize WQMPs, see the essential sequence of actions in the use case to optimize a sampling site network
Establish sampling frequency and recurrence (CCME, 2015; Mäkelä and Meybeck, 1996; Smeltzer et al., 1989; Von Der Ohe et al., 2009)	Establishing sampling frequencies, as well as recurrence, is necessary in order to • yield the information that will induce policy making and action plan implementation The essential sequence of action is to verify • statistical requirements dependent on monitoring objectives, indices, indicators, WQPs and waterbodies (Ward et al., 1990) • scientific consensus • accepted frequencies based on agreements as to what is considered acceptable • the need for continuous, punctual or grab sampling	Assessing sampling frequencies is necessary in order to ensure that • sampling frequency, recurrence and type have yielded the sought for information • statistical needs have been met • lacks and gaps in data quality or quantity have not been an obstacle to information production • the WQMP is cost effective Sampling frequency and recurrence can be assessed through various statistical methods generally closely linked to the optimizing use cases for sampling site and WQPs selection. Therefore, the main sequence of action to be followed can be consulted in these sections
Evaluate human resources Note: Some authors argue that the involvement of volunteers in monitoring activities is not only a means of reducing costs, but also a	Evaluating human resources needs is essential in order to ensure that the necessary skills for each task are available, either fulltime, part-time or by way of outsourcing (Fölster et al., 2014) The essential steps are to choose staff according to	Assessment of human resources is necessary in order to verify whether the human resources • were adequate to fulfill the tasks • needed more training

Table 1 (*continued*)

Use case	Planning Purpose and main sequence of actions and interactions	Optimizing Purpose and main sequence of actions and interactions
means of enhancing stakeholder involvement and awareness, in addition to offering wider screening possibilities of the watershed and taking advantage of the local knowledge (Jalbert and Kinchy, 2015)	• the needed skills (depending on each task from WQMP management, field work, data analysis and reporting – it is necessary to describe the skills that are expected) • the need to receive additional training • long-term availability (in order to ensure continuity) • availability of (skilled) volunteers It can also be useful to establish partnerships with research centres and universities in order to remain up to date on new developments or to add studies to support the WQMP	• had to be outsourced • were the reason for changes in quality (Thoma et al., 2012) The sequence of action is to verify whether • some of the actual resources should receive more training or should be replaced • if outsourced resources have been efficient or if it is necessary to integrate these resources in the WQMP staff (or to outsource more) • reduced financial means imply that volunteer monitoring should be implemented, extended or reduced (see note) • if training program were adequate
Identify technical resource needs (Bartram and Ballance, 1996; Capella, 2013; Chapman, 1996; Davies-Colley et al., 2011)	The identification of technical resource needs is necessary for • budgeting • a cost-effectiveness analysis to choose monitoring tools and laboratories. The essential steps are to assess technical resource needs for: • transportation (e.g., car; boats; helicopters (Li and Migliaccio, 2011) • available and necessary sampling material (probes, samplers, clothing, security, GPS, refrigeration, etc.) • continuous monitoring sampling (energy sources; data transmission, data validation, remote access) (Winkler et al., 2008) • screening and monitoring emerging tools (SMETS) (Graveline et al., 2010) A cost-effectiveness analysis must then offset the cost of: • laboratory analysis as opposed to using probes • cost of one laboratory as opposed to another (verify travelling distances, accreditations, detection limits & quantification limits); long-term contracts; efficiency of data transmission • costs and acceptability of SMETS as opposed to laboratory analysis (Graveline et al., 2010) • cost of material maintenance	Assessment of technical resource needs is necessary to ensure that the chosen means of transportation, assessment tools and laboratories were adequate to attain the set objectives and whether technical means have evolved and can be used to optimize the WQMP The essential steps are to: • assess that transportation means were adequate and did not have a negative influence on the sampling • verify that the equipment was appropriate to ensure safety, navigation, and sample transportation • assess whether sampling tools or laboratories should or need to be changed • ensure the continuity of data sets, an essential consideration before taking any decision as to changing a probe, a SMET or a laboratory A cost-effectiveness analysis can help in these steps. However, considerations on continuity of data sets in a WQMP is crucial in order to ensure comparability of long-term data trends (Davies-Colley et al., 2011; Fölster et al., 2014)
Estimate financial resources (Davies-Colley et al., 2011; Timmerman et al., 2010)	Estimation of financial resources required is essential in order to be able • to scale the WQMP • prioritize sampling objectives Financial resources must be evaluated based on the following cost elements for time (salaries) & material: • coordination of WQMP on a daily basis • sampling and field work expenditure • laboratory analysis • data quality assessment & plausibility, data entry, data analysis, reporting & revision • dissemination of the information • supervision • equipment maintenance	Assessment of financial resources is necessary to verify whether they were used adequately and whether funding has evolved (augmented or reduced) and can be used to optimize the WQMP The essential assessment steps are to: • verify if monitoring objectives were attained (see corresponding use case) • whether quality control & assessment were adequate • coordination was efficient • data analysis and reporting need to be adapted to information needs (may reduce reporting time – see corresponding use case) • dissemination of the information was efficient • supervision was adequate • equipment maintenance was efficient and if equipment needs to be replaced The assessment of financial resources should be done with the team involved in the WQMP in order to obtain feedback to increase efficiency and identify problems
Plan quality control and quality assessment (Bartram and Ballance, 1996; CCME, 2015; Davies-Colley et al., 2011; USEPA, 2001)	Planning quality control and assessment is essential to ensure that the margin of error at every step from the planning, to the sampling, transportation, data validation, data treatment, data analysis and reporting is reduced in order to avoid critiques and loss of data (Ward et al., 1990). To achieve this, it is necessary to define protocols and ensure periodic training of the staff (Davies-Colley et al., 2011; Madrid and Zayas, 2007; Thoma et al., 2012) Protocols must include (also see corresponding use cases): • sampling routes • handling and calibration (if applicable) of sampling tools • description of how and where to take samples and fill the bottles in order to avoid contamination • adequate refrigeration procedures	Assessing quality control and assessment procedures is necessary to ensure that the WQMP yields high quality results Necessary steps are to: • identify the number of rejected data • do controls on field work • verify variations in probe data according to calibration results • verify whether any changes in laboratory methods were introduced without having been communicated • verify if field sheets were appropriately filled out • list all critiques made by the revisers of the reports • hold a meeting with the staff in order to identify gaps in the procedures and in the understanding of the protocols • revise the existing protocols and quality assessment and control procedures accordingly

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Table 1 (*continued*)

Use case	Planning Purpose and main sequence of actions and interactions	Optimizing Purpose and main sequence of actions and interactions
	• maximum transportation times to laboratories • field protocols with in-build quality assessment procedures • field sheets that ensure that any additional information is being collected on-site • procedures to verify data plausibility before data storing • data storing procedures • data analysis & reporting procedures • data use and dissemination procedures • communication channels with laboratories	• propose field outings in order to compare sampling procedures and corresponding results (LFU, 2016)
Define sampling routes and sampling calendar	Sampling routes and calendars must be defined to ensure that data at a given station is collected in order to • "minimize variations due to diurnal patterns" (Davies-Colley et al., 2011) • ensure timely transport to the laboratories • to respond to sampling objectives (e.g., assess up- to down-stream variations within a sub-watershed Necessary steps are to identify: • the sub watershed and waterbodies that are to be sampled in a day and in which order • the time it takes for each sampling station • the time it takes between sampling stations • coordination if more than one team is needed (e.g., synchronization) • laboratory availability and receiving hours • monitoring objectives that call for specific timing and flexibility in the calendar (e.g., dispersion, transport time, nutrient load calculation, river flow) (Horowitz, 2013) (also see corresponding use case)	Sampling routes and calendars must be assessed in order to ensure that • timing could be respected • sampling objectives were attained The main steps are to: • analyze the data according to monitoring objectives • identify the shortcomings of the data (e.g., not enough samples taken at high-flow conditions for nutrient load calculations) (Groupe de travail sur la réduction du phosphore dans la baie Missisquoi, 2005) • identify the constraints that were limiting (e.g., lack of flexibility of human resources, laboratories or lack of knowledge response-times to be able to get the high-flow conditions) • verify whether sampling routes and timings were realistic • validate with the team if the amount of sampling stations should be increased or reduced to avoid errors due to fatigue
Prepare data handling, storage, analysis and reporting (Quevauviller et al., 2005; Ward et al., 1990)	Preparing for data handling, storage, analysis and reporting needs to be considered at every step of planning a WQMP in order to • avoid loss of data, errors in data concatenation (e.g., bringing together information on field observations, probe data and laboratory data) • ensure data analysis in accordance with monitoring objectives • produce the type of information in accordance with specific needs identified in the outset (also see corresponding use-cases) The essential steps are to: • identify data storage needs and choose software accordingly • select necessary tools for data analysis and select software accordingly • look up examples of reporting types and decide which are appropriate for the information needs and the target audience of the information Also see use case on quality control and assessment	Optimizing data handling, storage, analysis and reporting is essential in order to verify whether the information could be produced efficiently and was produced according to the initial needs The essential steps are to assess whether: • any issues on data handling and storage had arisen (e.g., loss of data due to deficient data storing means, errors in data) • data analysis and information production were a problem due to a lack of technical or human resources • the information was produced in accordance with the audience • the information users appreciated the produced information • data accessibility of data and information was satisfactory • the information is sufficiently known to be existent and circulated • resources were planned appropriately Also see use case on quality control and assessment
Identify communication channels Note: Two levels of communication channels have to be established: (1) communication channel between the instances of the WQMP and (2) between the producers of the information and the users of the information (Madrid and Zayas, 2007; Quevauviller et al., 2005; Raadgever et al., 2008; Timmerman, 2005; Timmerman et al., 2010; Timmerman and Langaas, 2005; Timmerman et al., 2000)	It is necessary to ensure communication channels between the instances of the WQMP in order to ensure effectiveness and mutual understanding of what is expected (e.g., communication between those who choose WQPs to be analyzed in a laboratory and the laboratory chemists and biologists) The necessary steps are to: • include every instance, department or partners (depending on the size of the organization) in the planning process • plan regular meetings to exchange between the different instances of the WQMP • establish communication channels and procedures The establishment of communication channels between the producers and users is necessary in order to avoid that "the lack of communication and of clear coordination mechanism leads to research outputs not being used or simply known by policy-makers, and to policy research needs not being communicated to the scientific communities in a timely fashion" (Quevauviller et al., 2005) The necessary steps are to: • assess the management regime, namely formal and informal governance (Raadgever et al., 2008)	It is necessary to update the communication channels in order to avoid the production of a lot of information that is not used or not useful The following steps are necessary: • communication channels have functioned and are being kept open between the different persons working on the WQMP • validate if all the initially identified information channels are still in place • information on water quality has been channelled properly • information users were able to use the information for policy--making and action taking • additional information needs to be produced • the format of information was satisfactory • new knowledge needs have emerged (see corresponding use case) • follow up on information use, e.g., inclusion in action plans • follow up on the implementation of actions (short-, medium- and long-term actions)

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Table 1 (*continued*)

Use case	Planning Purpose and main sequence of actions and interactions	Optimizing Purpose and main sequence of actions and interactions
	• identify information users • establish communication channels and hierarchy according to the type and urgency of the information (Ward et al., 1990) • identify stakeholders who need information in order to ensure action plan preparation and implementation	

General note: Within the scope of this paper, the integration of components necessary to ensure coordination of surface water monitoring with groundwater monitoring, air quality monitoring, and precipitation and hydrological monitoring was not considered. However, these elements should be kept in mind if the analysis of the data and the monitoring objectives require this information.

Fig. 2. The use cases split up for this figure are grouped in the corresponding boxes.

For each of the 34 papers, we identified the main use cases treated ("+++"). The main contributions of these papers and some comments are summarized in Table 2. We included information if the approach was a planning or optimization approach, if the authors addressed lake and/or river monitoring and what were the main use cases addressed. The observations that may be drawn from the qualitative analysis (illustrated in Fig. 1 and Table 2) are that while some use cases are considered important, they are not discussed with any in-depth information, while other use cases are discussed and addressed extensively.

One of the use cases considered as the most important in nearly all the papers, is the determination of monitoring objectives. However, none of the papers actually propose a method of determining monitoring objectives. Only a few papers address the use case of designing a monitoring network according to specific monitoring objectives or to assess the attainment of monitoring objectives. In general, the establishment of monitoring objectives and the assessment of the latter are either drawn from the literature, regulations, or based on expert opinion. Thus, there seems to be a lack of stakeholder involvement (including the public) in spite of the fact that there is "a growing need to involve the public in a deliberative participatory way (…)" (Timmerman et al., 2010). Approaches to establish a sampling site network are nearly all optimizing approaches based on existing networks. The main focus is on the selection of macro-location without considering site selection and assessment on the micro-level, but for generalities such as accessibility (e.g., thus, not considering mixing and local influences). The selection and classification of WQPs is discussed extensively, but also seems to be one of the fields that evolves very quickly, as much on the side of contaminants of emergent interest and chemical mixtures, as well as on tools to assess them (e.g., in-situ measurement tools; new methods of analysis in the laboratory and effect-based tools). Establishing sampling frequency and recurrence is also widely discussed, especially for the optimization of a WQMP, while it remains difficult to establish sampling frequencies and recurrence adequately at the outset. The evaluation of technical, human and financial resources for the planning and optimizing of WQMPs is mentioned and discussed in terms of technical resource needs for new monitoring tools such as in-situ probes, and automated data transfer. Some of the optimizing approaches for sampling site networks propose formulas where financial

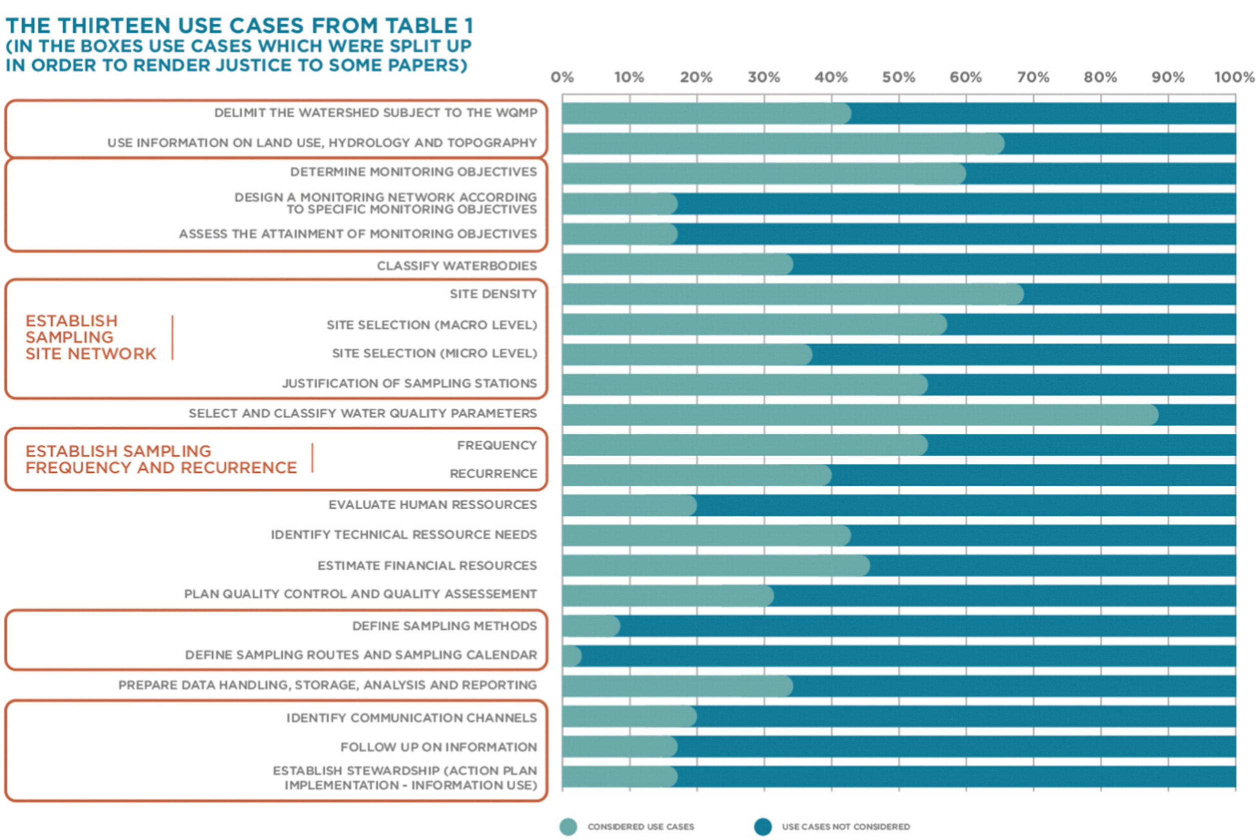

Fig. 2. Percentage of papers that considered the use case, as opposed to the percentage of papers that did not. To facilitate the presentation, we summarized the categories "yes", "+", "++" and "+++" into the category "considered use case", as opposed to the category "use case not". The boxes that group together some of the use cases are use cases split apart from those considered in Table 1 in order to do justice to some of the authors.

Table 2
Summary of the main contributions of the approaches addressing planning or optimizing use-cases of a WQMP (chronological order).

Author/year	Main contributions – Comments
(Hilton et al., 1989)	*Planning and optimizing – Lakes – Main use cases: Establish a sampling site network; select and classify water quality parameters; identify technical resource needs* Five sampling techniques (e.g., dip sampling vs. integrative tube sampling) in different types of lakes (e.g., shallow vs. deep lakes) are tested for a variety of sites (e.g., open water vs. shore sampling) to verify representativeness. The authors conclude that (1) patchiness might have more of an influence on results than sampling sites; (2) any site is probably only representative during its maximum mixing period and (3) final decisions must be based on the information needs (e.g., integrative tube sampling provides a good estimate of the algal population while overestimating nutrient concentrations)
(Smeltzer et al., 1989)	*Optimizing – Lakes – Main use cases: Assess attainment of monitoring objectives, select and classify water quality parameters, establish sampling frequency and recurrence* The authors apply various statistical methods in order to assess the attainment of monitoring objectives within the Vermont lake monitoring program (e.g.,trend analysis, model development, state-wide portray of lakes, etc.). They conclude that sampling frequencies and recurrence must be adapted (or planned) according to the WQPs and monitoring objectives and that watershed management for lakes should not await changes in the lake before being implemented due to high inter-annual variations.
(Timmerman et al., 2000)	*Planning and optimizing – Lakes and rivers – Main use cases: Determine monitoring objectives; prepare data handling, storage, analysis and reporting; identify information channels.* The authors present a framework that "assists information producers in developing tailor-made information that is sized to fit the needs of information users". The authors propose steps to identify the information needs, the information network, the type of information and an information strategy. The proposed framework can be used as a decision support for the identified use-cases.
(Ning and Chang, 2002)	*Optimizing-Rivers – Main use cases: Establish and assess a sampling site network;* assess the attainment of monitoring objectives Approach focuses on the optimizing of a WQMP through the verification of whether initial monitoring objectives were attained. This verification was obtained through questionnaires submitted to an expert committee that had to assess the attainment of the initial monitoring objectives and how well the sampling sites were located. A final priority list for each sub-catchment was submitted to goal-programming. The results were subsequently submitted to a multi-objective optimization approach including considerations such as budget and sensitivity of WQPs. Land use and hydrology were also considered.
(Ouyang, 2005)	*Optimizing-Rivers – Main use cases: Establish and assess a sampling site network; select and classify water quality parameters* Approach based on principal component analysis and principal factor analysis to identify sampling sites and WQPs important to assess annual variations. The authors enumerate the six monitoring objectives (e.g., determining mass loads) on which the monitoring program was constructed; however, the method does not seem to allow assessing whether these objectives were attained and focuses on the annual variations to suggest the main WQPs and sampling sites.
(Quevauviller et al., 2005)	*Planning and optimizing – Lakes and rivers – Main use case: Identify communication channels* The authors focus on "science policy integration" in the context of the WFD. Channelling information in a timely manner from scientists to policy-makers and vice-versa is considered a major issue. Policy-makers must receive the information in a form they can understand and policy-makers must convey their information needs and time limits to the scientists. The authors propose three steps to develop a "science-policy integration framework" in order to streamline information: (1) Information for the general public and local authorities; (2) information for operational managers and research and technological development (RTD) providers and (3) information for RTD program managers and policy implementation. The ideal information exchange platform needs to be adapted to the political level of local, regional, national and international governance.
(Park et al., 2006)	*Planning and optimizing-Rivers – Main use cases: Establish and assess a sampling site network, design a network according to specific monitoring objectives* Approach using a genetic algorithm and a geographic information system. The focus is on planning and optimizing a WQMP according to specific monitoring objectives and land use and hydrology. No preference weights are proposed for the land use criteria (but can be integrated). Fitness functions are proposed to select sampling sites according to monitoring objectives, e.g., for the objective "surveillance of pollution sources" in the fitness function the distance to a pollution source and the number of pollution sources in the upstream zone are considered. Micro-location assessment and WQPs are not considered.
(Strobl et al., 2006a) & (Strobl et al., 2006b)	*Optimizing – Rivers – Main use cases: Use information on land use, hydrology and topography,* The authors propose to "Develop with minimal data and by using analytical tools such as GIS, fuzzy logic, and the simulation model GWLF v.2.0, a practical and scientifically based design methodology for designating critical water quality monitoring network sampling points within small agricultural-forested watersheds with respect to total phosphorus". The methodology proposed includes detailed information on land use (buffering zones, pollution sources; topography, hydrology, even soil permeability and evapotransporation processes. The authors use total phosphorus as an indicator variable, but affirm that their method could be extended to other parameters. They also provide a formula (and its limits) to estimate costs for the ensemble of the costs per station, such as administrative overhead, sampling trip cost, laboratory analysis, replica cost, data interpretation cost, data reporting cost and aggregated costs.
(Madrid and Zayas, 2007)	*Planning and Optimizing – Lakes and Rivers: Main use case: Plan quality control and quality assessment* Focus is on quality control at the field stage and communication between planners, field technicians and laboratories. The authors emphasize the fact that the sampling stage needs improved quality control: assessment of site representativeness; specification of precise sampling location (micro-level) and sampling time; ensuring correct sampling containers and sample preservation; use of field blanks; establishment of a field-data sheet and a chain of custody; following ISOguides for sampling. The use of alternative sampling methods is discussed briefly with respect to their advantages and limitations.
(Anttila et al., 2008)	*Optimizing – Lakes – Main use cases: Assess sampling site density; select and classify water quality parameters* Methodology to assess representativeness of sampling sites in lakes for a given WQP. Lake monitoring is often concentrated at the deepest spot, thus does not consider heterogeneity due to mixing on the vertical and horizontal layers.
(Raadgever et al., 2008)	*Planning and optimizing – Lakes and rivers – Main use cases: Delimit the watershed subject to the WQMP, identify communication channels* The authors address the question as to whether transboundary river basins can support adaptive management. In order to assess this, they provide a framework in which they suggest identifying actor networks, legal frameworks, policy, information management and financing. After having identified and assessed the management regime, it is possible to work on elements that may need improvement, such as information transfer, public participation, identifying knowledge needs, trust building, implementation of actions and policies, identifying additional financial resources, allocating tasks and including experts from various organizations.
(Telci et al., 2009)	*Optimizing – Rivers – Main use case: Establish and assess a sampling site network* The authors propose a method to determine sampling sites for the specific objective of early detection of contaminants within a watershed according to potential spill sites. For this method, they propose to determine the dynamic behaviour of a contamination event and the optimum monitoring stations. For the first step, they use the EPA Storm Water Management Model. Potential monitoring sites are attributed to the confluences, upstream locations and equally distributed river sections. In the following steps, scenarios are tested based on the detection threshold of the contaminant, reliability and average detection time.
(Khalil et al., 2010)	*Optimizing – Rivers – Main use case: Select and classify water quality parameters* Methodology to reduce the number of WQPs through a modified correlation-regression approach and a record extension technique to

Table 2 (*continued*)

Author/year	Main contributions – Comments
	reconstitute discontinued variables. An equal weight for each parameter is proposed, as well as thresholds that can guide the decision if a parameter should be discontinued. The method allows experts to express a preference weight for a given parameter. The method can be made site-specific through the input of experts and cost analysis, thus providing a justification for continuing or stopping the measurement of parameters at one or more sites.
(Noori et al., 2010)	*Optimizing-Rivers – Main use cases: Establish and assess a sampling site network; select and classify water quality parameters* Multivariate statistical analysis to identify the most "informative" monitoring sites and to evaluate correlations between WQPs. The approach provides leads on which WQP or station to eliminate, but more decision support elements are necessary to make final choices.
(Pobel et al., 2010)	*Planning and optimizing – Lakes – Main use cases: Establish and assess a sampling site network, establish sampling frequency and recurrence* The authors focus on the optimum sampling site identification and sampling frequency for cyanobacteria monitoring in shallow lakes. The authors tested several sampling sites and considered temporal variations, different species, wind-direction and spatial variations in the water column. The authors conclude that for small shallow lakes, biweekly sampling at strategic sites may be sufficient, but that visual observations must be carried out on a weekly basis. They also conclude that sampling strategies must be adapted to every lake, as there are even different optimal sampling stations according to the present bloom-forming species.
(Khalil et al., 2011)	*Optimizing – Rivers – Main use cases: Use information on land use, hydrology and topography; establish and assess a sampling site network; select and classify water quality parameters* Approach that allows increasing the number of sampling stations, while taking land use (point and non-point sources) and stream specificities into account. The authors use a record extension technique to reconstitute discontinued variables. The authors stress the fact that "the assessment and redesign of the water-quality-monitoring locations are more reliable when they are based on several water quality indicators" (see also Khalil et al., 2010).
(Lim and Surbeck, 2011)	*Optimizing – Lakes – Main use case: Prepare data handling, storage, analysis and reporting* Approach to make further use of data collected on a set of lakes for regulatory reasons. The aim is to obtain information on spatial and temporal water quality variations. Lake hydrology is taken into account in order to interpret the results of the statistical analysis. Since WQMPs can be based on imprecise monitoring objectives and old data sets need to be used to yield new information, this approach provides interesting leads to data valorization and WQMP optimization.
(Mahjouri and Kerachian, 2011)	*Optimizing-Rivers – Main use cases: Establish and assess a sampling site network; select and classify water quality parameters* Entropy-based approach using spatial, temporal and spatial-temporal analysis to (1) increase, reduce or relocate sampling stations; (2) improve sample frequency for specific WQPs and (3) reduce the number of WQPs. The approach is based on long-term data and river discharge and requires expert opinions to prioritize WQPs.
(Pinto and Maheshwari, 2011)	*Optimizing-Rivers – Main use case: Select and classify water quality parameters* Factor analysis is used to reduce the number of WQPs to be measured in a given watershed. The parameters to be kept are those for river health assessment. In order to provide such an analysis, it is necessary to work with quite a large number of WQPs. The authors themselves state that there remains "uncertainty associated with the ecological relationship between chosen WQPs and biotic communities". However, this approach can yield information on WQPs having the main impact on ecological health. This information can contribute to focusing on specific pollution reductions in a watershed.
(Anttila et al., 2012)	*Optimizing – Lakes – Main use cases: Establish sampling frequency and recurrence; identify technical resource needs; plan quality control and quality assessment* Methodology assessing representative sampling frequency for a given lake with a focus on chlorophyll *a* content. Discrete as opposed to continuous sampling, as well as quality control and assessment of data generated through continuous sampling is discussed.
(Beveridge et al., 2012)	*Optimizing – Lakes - Main use case: Assess sampling site density* Geostatistical approach to reduce sampling sites in big lakes (e.g., lake Winnipeg) with high site density. Methodology is applicable for one WQP at a time and shows that site representativeness varies with the WQP. Final selection of sampling sites to be retained must therefore be based on sampling objectives.
(Chen et al., 2012)	*Optimizing – Rivers - Main use cases: Assess a sampling site network* Optimizing approach for what is qualified as a "sub-optimal monitoring network". The approach is based on (1) an extension of water quality data through flow and water quality modelling and (2) identifying homogenous (in terms of water quality data) river reaches. Stations with redundant information can be reduced and others can be added. Approach requires an extensive network of flow gauges.
(Thoma et al., 2012)	*Planning and optimizing – Lakes and rivers – Main use case: Plan quality control and quality assessment* The authors propose a methodology (alternative measurement sensitivity technique) to assess the accuracy of WQPs measured in the field by probes in order to provide information on measurement certainty. The method is an alternative to the method detection level used in laboratories. This paper is particularly pertinent, as more and more data are being collected through probes. Calibration, handling and stabilization times are discussed as very important factors to ensure that the probe data is reliable. More often than not, the values of probes are taken at face value, as the sensitivity of probes is underestimated.
(Thompson et al. 2012)	*Planning and optimizing – Rivers – Main use case: select and classify water quality parameters* The authors test the hypothesis that electric conductivity (EC) can be used as an indicator for stream health, given that previous studies have shown a relationship between aquatic life and conductivity. The focus is on distinguishing anthropogenic sources that impact EC as opposed to background levels of EC. The advantage of using a single indicator is its simplicity, cost efficiency and integrative character of showing degradation within a watershed with similar geological background.
(Capella et al., 2013)	*Planning and Optimizing - Rivers - Main use case: Identify technical resource needs* Description of technical considerations to implement an in-line river monitoring system (wireless sensor network), such as energy supply, sensor selection, data transmission, data validation, calibration and data management system. No description of site selection, which can be challenging for deployment of permanent in-situ devices, is provided.
(Memarzadeh et al., 2013)	*Optimizing-Rivers – Main use cases: Assess a sampling site network; select and classify water quality parameters* Entropy based approach with a previous application of dynamic factor analysis (DFA) to reduce time consuming entropy-based analysis aimed at reducing the number of WQPs. The approach is similar to the one proposed by Mahjouri and Kerachian, 2011.
(Chang and Lin, 2014)	*Planning and Optimizing – Rivers-Main use cases: Establish and assess a sampling site network* Multiple criteria analysis and fuzzy theory based on six types of land use and the existing network to optimize the WQMP in place. Land use type values were provided through a geographical information system. Weights of the criteria were determined through a questionnaire submitted to professionals of each of the sub-watersheds. Inclusion of experts in the weighting process is useful as they provide knowledge needs on WQ and priorities.
(Fölster et al., 2014)	*Optimizing – Lakes and rivers – Main use case: Determine monitoring objectives* Comprehensive paper of the need for adaptive monitoring based on: new knowledge needs, evolving science and new requirements (e.g., WFD) while continuing long-term data series to document the benefits of action (e.g., sewage sanitation measures). One of the few documents to discuss lake and river monitoring as an ensemble.
(Levine et al., 2014)	*Optimizing – Lakes and rivers – Main use case: Establish sampling frequency and recurrence (Two approaches)* (1) Approach to simulate if the sampling frequency for NO_3 and SO_4 could be reduced from weekly to bimonthly sampling in a stream.

(continued on next page)

Table 2 (*continued*)

Author/year	Main contributions – Comments
	Results differ for each parameter: uncertainty increases for NO_3 on bimonthly sampling due to seasonal variations, but not for SO_4. Optimum sampling frequency differs for each parameter and should be based on knowledge needs. (2) Approach to simulate reduction in sampling frequency and the number of lakes to be monitored (same two parameters). Results show that monitoring frequency could be reduced from monthly to once a year. Reducing the number of lakes would increase uncertainty. Approach can contribute to reduce sampling frequency and recurrence without reducing the number of stations.
(Winkelbauer et al., 2014)	*Planning and optimizing – Rivers – Main use cases: Establish sampling frequency and recurrence, identify technical resource needs, plan quality control and assessment* The authors discuss the implementation of automated monitoring stations. The authors illustrate future challenges of planners of WQMPs to choose automated in situ tools, implement a data control system, propose a platform where the data can converge and produce (convey) information based on this data. Also, challenges such as site selection and maintenance must be considered.
(Altenburger et al., 2015)	*Planning and optimizing - Lakes and rivers- Main use case: Select and classify water quality parameters* Insight and future perspectives on solution-oriented monitoring. Considers chemical mixtures in environmental assessment rather than individual chemicals. Perspectives on various bio-analytical tools are provided in order to improve impact assessment and, therefore, eventually improve watershed management so as to attain better ecological status in waterbodies. Sampling techniques and laboratory needs for these tools are also discussed.
(Keum and Kaluarachchi, 2015)	*Optimizing – Rivers - Main use cases: Establish and assess a sampling site network* Optimizing a network of stations based on land-use variables and estimations on water quality load expressed in total dissolved solids (TDS) for sub-catchments using the SPARROW water quality model and a station ratio based on the TDS loads and the total stations of the network. Approach requires a network of stream flow gauging stations and TDS data series, and is based on the assumption that watersheds with high TDS loads need higher site density than watersheds with low loads.
(Ross et al., 2015)	*Optimizing – Rivers – Main use cases: Establish sampling frequency and recurrence, identify technical resource needs* Approach to establish the best possible sampling frequency according to sampling objectives, WQPs and resources. Using a 24/7 automated sampler, a fair amount of data was collected in order to be able to (1) apply a statistical analysis and (2) submit the results to a multi-criteria comparison and decision matrix to take an informed decision on optimum sampling. The decision matrix includes elements such as cost, execution difficulty, ability to capture short-term fluctuations and extremes.
(Wernersson et al., 2015)	*Planning and optimizing – Lakes and rivers- Main use case: select and classify water quality parameters* One of the main challenges of the WFD is probably the requirement to assess ecological status. Thus, the aim of the report on which this paper is based was "to identify potential effect-based tools (e.g., bioassays, biomarkers and ecological indicators) that could be used in the context of the different monitoring programs (surveillance, operational and investigative) linking the chemical and ecological status assessment". Effect-based monitoring tools need to be implemented in order to avoid the necessity of developing assessment criteria for each of the very large number of chemicals. Criterion per chemical does not take potential cumulative effects into account. Actually, the emphasis is not on WQPs as such, but rather on tools that will make it possible to assess cumulative effects of various pollutants on the ecosystem, thus avoiding the necessity of developing standards for each chemical and ensuring that cumulative effects can be monitored. In other words, this approach steers away from the traditional approach of measuring concentrations towards a more integrative and ecosystemic approach.

resources can be integrated into the final decision making on the number of sampling stations. Planning quality control and quality assessment is mentioned in several papers, while few actually discuss approaches to assess errors in field measurements, due to inadequate (or inadequately applied) sampling methods, probe calibration, sampling routes and sampling calendars. While several papers discuss the importance of data handling, storage, analysis and reporting, little information is provided on the information needed to support the data to be stored and how to select a data base accordingly. The papers that discuss the identification of communication channels, the follow up on information and the establishment of stewardship illustrate that more research is needed to connect this use case with the use case of determining monitoring objectives and assessing them – and that this is linked to the importance of delimiting the watershed subject to a WQMP and its capacity for adaptive management (as discussed by (Raadgever et al., 2008)). Finally, it is important to note that river and lake monitoring are almost always treated separately, just as the connection between groundwater monitoring and surface water monitoring is rarely made. Given the fact that all these waterbodies are connected and influence each other in terms of water quality and quantity, WQMPs should be planned considering these connections. This would probably facilitate understanding of water quality and quantity issues and lead to more integrated actions to protect the resource (Fleckenstein et al., 2013). In order to achieve such a coordinated WQMP, it is necessary to consider the time and cost of integrating experts from these fields during the planning or optimizing process.

In summary, the main observations from Part 2 of the review are that (1) the approaches addressing WQMP planning and optimizing are rather compartmentalized (e.g., addressing only a few of the use cases at a time and missing out on necessary sequences of actions); (2) none of the approaches propose an approach to elicit knowledge needs on WQ; (3) monitoring objectives are considered important, but are usually assumed or retrieved from the literature, experts or regulations; (4) criteria to optimize WQMPs are based on inadequately identified assumptions (for instance they do not take initial monitoring objectives into account); (5) river and lake monitoring is generally treated separately.

3.3. Degree of transferability of existing approaches

From the papers presented in Tables 2, 10 were selected to submit them to a further analysis, mainly to assess whether the critique of Strobl and Robillard (2008) is justified, meaning that the proposed approaches are too site specific, complicated or too general to be applied by watershed managers, thus not transferable or used. The papers were selected so as to cover with at least one paper each, use cases for which statistical - mathematical approaches were proposed for each lake and river: optimization of sampling site networks; assessment of the number of WQPs; assessment of sampling frequency and recurrence; identification of key variables and optimizing approaches not only reductive with respect to the number of sampling sites. Also, the objective was to find at least two approaches where more than one use case was addressed (e.g., more holistic approaches such as the one proposed by Park et al., 2006). The goal was not to provide a literature review of each type of approach since this kind of analysis is already proposed by other authors (e.g. Olsen et al., 2012; Khalil and Ouarda, 2009). The goal was rather to evaluate if existing approaches could be eventually integrated into a more holistic and evolvable tool to optimize WQMPs.

The results of this analysis are presented in Table 3. As for the critique that optimizing approaches are too difficult to apply, too case specific or too general (Strobl and Robillard, 2008), the results show that

Table 3
Analysis of statistical methodologies used in various optimization approaches (* Data category: refers to the six modes proposed by Cattell (1966) on how data can be read on three-dimensional data sets (objects; variables and time). The two modes identified in the papers are Q mode: relationships between objects (e.g., sampling sites) and variables (e.g., WQPs) and O mode: relationships between time and variables (e.g., WQPs).)

Author /year	Statistical technique	Statistical software	Data category*	Objective	Relative difficulty of application /5	Transferability	Attainment of objectives and *Comments*
(Ouyang, 2005)	Principal Component Analysis (PCA) Principal Factor Analysis (PFA)	SAS	Q mode matrix: sites vs. WQPs	Optimize: identify monitoring sites and WQPs which are relevant to assess annual variations	04	Easily transferable to identify relevant sampling stations and WQPs	3 stations out of 22 are less important in explaining the annual variance Some WQPs are more important than others to the dataset *The PFA can be affected if the dataset contains missing values, and if relations between parameters are not linear*
(Park et al., 2006)	Spatial analysis Genetic algorithm	ArcView 3.2 Visual C++ and Galib	Q mode matrix: sites vs.WQPs	Optimize: Propose an effective network according to 5 criteria: representativeness of a river system, compliance with water quality standards, supervision of water use, surveillance of pollution sources and examination of water quality changes. The sampling site network is then analyzed by an association of a genetic algorithm and spatial analysis	05 05	A very good knowledge of the watershed is necessary and it takes an expert to apply the proposed methodology. The methodology provides a decision support free of subjectivity.	From the original network the methodology validated only 35 of 110 stations. The authors concluded that the current network should be carefully re-examined (e.g., reduce the number of stations) *Special attention should be paid to the construction of the initial chromosomes of the genetic algorithm, as the information it contains can deeply impact the final network.*
(Khalil et al., 2010)	Correlation analysis Clustering analysis Maintenance of Variance (MOVE) record-extension	Not reported	Q mode matrix: sites vs. WQPs	Optimize: Identify WQPs to be sampled continuously and other where the sampling frequency could be reduced or discontinued Reconstitution of discontinued variables	03 05	Transferable to WQMPs with a large amount of variables and data sets	Authors indicate that their approach provides a useful decision support tool for the optimized selection of water quality variables. *Import of data* (e.g., *selection of data used for the analysis) can be subject of subjectivity.*
(Noori et al., 2010)	Principal Component Analysis (PCA) Canonical Correlation Analysis (CCA)	Not reported	Q mode matrix: sites vs. WQPs	Optimize: determine important monitoring sites and WQPs Optimize: explore relationship between physical and chemical parameters	04 04	Multivariate analysis such as PCA or CCA are especially indicated for this type of dataset (several WQPs collected on several stations over a period of several years)	The authors indicate that 4 stations on 19 are non-principal, and all measured WQPs are important. The authors estimate that 4 physical and chemical variables are particularly important according to CCA. *Expert opinion is still necessary for final decisions on retaining or abandoning sites or WQPs*
(Pinto and Maheshwari, 2011)	Correlation analysis Factor Analysis (PCA based)	Excel, Minitab, SPSS	Q mode matrix: sites vs. WQPs	Optimize: Identify key WQPs which impact river health	03 04	Easily transferable to other datasets, other WQPs if the conditions of application are respected	The authors succeeded in identifying 9 key variables that could be responsible for impacting river health
(Khalil et al., 2011)	Regression Analysis Artificial Neural Network Maintenance of Variance (MOVE) record-extension	Not reported	Q mode matrix: site vs. WQPs	Reconstitute information about water quality variables at discontinued locations	03 05 05	These different tools provide a way to reconstruct datasets that have been discontinued	In this case study, MOVE 3 technique shows better performance in preserving the statistical characteristics of the water quality records. *According to the techniques, estimations of mean and variance could be underestimated or overestimated*
(Beveridge et al., 2012)	Multivariate analysis (NMDS /PCA)	Not reported	Water isotope samples	Optimize: Quantify redundancy of information of neighbouring	04	Easily transferable to other datasets and other WQPs	The authors succeeded in removing up to four stations within each cluster without

(continued on next page)

Table 3 (*continued*)

Author /year	Statistical technique	Statistical software	Data category*	Objective	Relative difficulty of application /5	Transferability	Attainment of objectives and *Comments*
	Kriging Moran's Indice			sampling sites in a Lake in order to reduce the number of sampling sites	04 04		significant loss of information *According to the authors, it is important to include expert opinion as to the removal of any station, as the redundancy of WQPs varies from station to station.*
(Chen et al., 2012)	Matter-element analysis Numerical model	Delft3D-WAQ package from delwaq library	Q mode matrix: samples vs. WQPs	Optimize: Reduce the number of stations by sub-dividing the watershed into homogenous units according to simulated water quality information created with a numerical model	05	Transferable only if a substantial dataset is available for a large river system	Some river reaches were identified that should be monitored while others could be moved (according to the criterion of avoiding redundancy of information in homogenous river reaches) *Additional stations had to be simulated in order to support the model*
(Levine et al., 2014)	General Linear Model regression	R	O mode matrix: time vs. chemical WQPs from a single site	Optimize: Assess the increase of uncertainty in case of the decrease of the sampling frequency and evaluate statistical confidence in trend detection	03	Easily transferable if sufficient data are available	Sampling frequency cannot be reduced without the risk of losing confidence in the trend detection. *This approach requires a sufficient number of samples to detect trends and differences*
	Repeated-measures mixed-effect model	SAS	Q mode matrix: sites vs. WQPs	Optimize: assess the impact of sub-sampling on the mean and standard-error	04	Easily transferable to assess the impact of changes in sampling frequency	Monthly sampling can be reduced to annual sampling without affecting the long-term trend. *Decreasing the sampling effort may increase the incertitude for the estimator of concentrations*

the least degree of difficulty is 03 and most of the approaches are situated in degrees of difficulty ranging from 04 to 05. This means that in general an expert is required in the application of these statistical tools. Generally, the approaches are transferable if a given amount of data is available. An interesting result of this analysis is that all these approaches require the input of the watershed manager of the specific WQMP. This input may be necessary to attribute weights and select preferences for some of the approaches (e.g., the approach proposed by (Park et al., 2006). Other approaches require final decisions from the watershed manager, based on the outcome of the statistical analysis in order to choose a sampling site network, a set of WQPs, sampling frequency and recurrence. These decisions must be based on the initial and future sampling objectives and available resources. In summary, the proposed approaches are generally transferable if an expert in the application of statistical tools is available, if sufficient data exists, if some conditions of application are met and if the local watershed manager is empowered to take final decisions based on knowledge needs and available resources.

4. Discussion and future perspectives

4.1. Discussion

The literature review shows that there is always a use case or an important sequence of action that is missing in the handbooks, guidelines and papers that address the challenge of planning and optimizing a WQMP. This is probably due to several factors:

1) Although there are very comprehensive handbooks and guidelines on the subject, they are not able to keep up with the speed at which the field of WQMPs is evolving. This is particularly true for WQPs and tools to measure them, and approaches that propose the optimization of sampling station networks.
2) Besides scientific considerations, there are considerations to manage a WQMP which fall into the spheres of business intelligence, communication, politics and governance.
3) Watershed managers face very different challenges from watershed to watershed, including governance, political and regulatory requirements, hydrological network, land use, climate, available resources and knowledge needs.

Therefore, it is more than understandable why such an amount of handbooks, guidelines and papers exist to support watershed managers in their task. Indeed, the amount of information on the subject is so vast that it may appear scanty and the task may seem overwhelming or totally underestimated. If the task seems too overwhelming and expert resources are not available, WQMPs may not be implemented at all. If the task is underestimated, it may lead to badly planned and executed WQMPs that do not yield any usable information.

The review also reveals that research focuses mainly on optimizing WQMPs in terms of site density, macro-location of sampling sites, WQPs to be measured and sampling frequency and recurrence. This is probably due to the fact that most watersheds already have some sort of WQMP and that planning is still very much based on subject matter expert knowledge. In addition, evolving knowledge needs, regulatory and political requirements, changes in available resources, new types of WQPs and tools to measure them call for adaptive management of WQMPs, thus tools to optimize them. It is also crucial to maintain historical data series. Therefore, there is a huge need for integrating historical sampling schemes into updated versions, while being able to continue working on these time-series, as well as being able to generate data according to evolving knowledge needs and scientific knowledge.

A growing focus on three issues were detected through this review: (1) integration of continuous monitoring devices with automated data-transfer options in a WQMP, (2) development and integration of effect-based tools (e.g., bioassays and biomarkers) and (3) proposing schemes of integrating science, policy and implementation of protective and restorative measures. Indeed, while (Ward et al.) were concerned in 1986 about a "data-rich – information poor syndrome" (Ward et al., 1986), there now seems to be growing concern directed at reaching an information-rich, but communication and action poor syndrome (in spite of the fact of well-documented successes in regenerating lakes and rivers).

As to the particulars revealed in this review, they are in some aspects in line with statements from other authors. For instance, the question remains as to whether some of the optimizing approaches are based on data from existing networks that may not have been structured properly in the first place, implying that optimizing approaches are biased from the start (Chen et al., 2012; Olsen et al., 2012). Also, methods such as statistical analyses to optimize WQ monitoring networks are not submitted to standard procedures (Olsen et al., 2012). As to Strobl and Robillard (2008) stating that methods are too case specific, too general and too complicated for a watershed manager to implement easily, our analysis of the degree of difficulty of some of the approaches confirms this statement. However, we believe that these "weaknesses" do not imply that the methods are not valid or useful, but rather that guidance is needed to valorize them according to the specific optimizing objective, existing data sets and available technical and expert resources.

In addition to these particulars, we identified some issues for some of the use-case categories. With respect to the delimitation of the watershed subject to the WQMP, almost no author addresses the question regarding the necessity to examine the size of the watersheds in order to improve WQMPs and the management issues that arise from watersheds monitored or managed on too large or too small a scale. For instance, the watershed of the St. Laurence River covers an area of 1.6 million km^2. Hence, monitoring and managing such a huge area amounts to a degree of complexity that may lead to failure in adequately protecting the resource. This may even be true for catchments of a smaller scale, especially when political boundaries and conflicting interests are a hindrance to the implementation of WQMPs and action plans. Therefore, when planning a WQMP, the reflection should also focus on the area chosen for a WQMP, since not only does the implementation of the WQMP need to be considered, but also the subsequent implementation of actions to protect the resource. Monitoring objectives are considered important and mentioned in every document, but they are usually assumed and retrieved from the literature. In the optimizing approaches, their attainment is rarely ever discussed. The classification of waterbodies is not widely discussed and, for some reason, lakes and rivers are almost always treated separately. The question that arises is how lake and river monitoring agencies collaborate with each other to coordinate sampling efforts. As to the approaches proposed to optimize sampling site networks, it seems that criteria to optimize WQMPs are made on inadequately justified assumptions. This may stem from the fact that initial design criteria are not sufficiently considered. In addition, hardly any micro-level assessment of sampling stations, especially in rivers, is considered. WQPs are a major issue in planning and optimizing WQMPs due to their large amount, the tools to measure them and the difficulty of obtaining adequate sampling frequency and recurrence. In general, too few WQPs are taken into account in the optimizing approaches. This may be one of the main limitations of the optimizing approaches in addition to the lack of considering monitoring objectives and initial design considerations.

The review also showed that in the planning process, subject matter expert opinion is crucial. Even optimizing approaches always require an instance of decision making by a subject matter expert, either regarding the method (e.g., provide weights) or to take final decisions. Indeed, no fully automated approach is available and subject matter expert opinion is always required.

Thus, future research should focus on providing watershed managers with tools that can guide them through the decision-making process of every specific use case, while being rapidly adaptable to continuous and arising challenges: adaptation of the WQMP to additional knowledge needs, new regulations, newly developed tools to measure WQPs parameters, statistical approaches that provide assistance in optimizing a WQMP, changes in human, technical and financial resources, continuous quality control and assessment, data storage, adequate and timely information production for the stakeholders and changes in governance. In other words, a tool that can rapidly assist the watershed manager in every aspect of a WQMP: stakeholder implication, scientific requirements, administrative requirements, and governance. In addition, monitoring objectives have been identified as being crucial to planning and optimizing WQMPs. However, due to a lack of stakeholder inclusion in defining knowledge needs and validation if the produced information is adequate, WQMPs produce information that does not encourage stakeholders to actively participate in IWM and protective measures. Therefore, a participative approach should be developed in order to encourage stakeholder involvement.

4.2. Future perspectives

This being said, two important questions need to be addressed: (1) what type of decision support tool could live up to the challenge of guiding watershed managers through the process of planning and optimizing a WQMP? (2) what type of participative approach could contribute to a better understanding of the knowledge needs and improvement of stakeholder involvement?

We believe that a computerized decision support system (DSS) is necessary to provide the support watershed managers' needs in the process of planning and optimizing WQMPs. Several levels and types of DSS have been identified in the literature according to the decision support they provide. First, a differentiation between a passive, active and cooperative DSS can be made. A passive DSS only assists the decision-making process, but does not provide explicit decision suggestions or solutions while an active DSS does. A cooperative DSS allows the decision maker to interact, as it offers the possibility of modifying and refining decision suggestions (Kautish and Thapliyal, 2012). The types of DSS comprise communication driven DSS (e.g., chats and instant messaging software), data driven DSS (e.g., databases having a query system, geographical information systems, etc.), document driven DSS (e.g., library and web site searching machines), model-driven DSS (e.g., accounting models to forecast budgets) and knowledge-driven DSS which are "computer systems with specialised problem-solving expertise" (Power, 2001) where knowledge is "stored as fact, rules and procedures" (Kautish and Thapliyal, 2012). Knowledge driven DSS are also called intelligent DSS (IDSS) (Power, 2001). In other words, IDSS are computer-based active and corporative tools which, by emulating human capabilities in gathering and analyzing data, identifying and diagnosing problems, proposing possible actions and evaluating their effects, can contribute significantly to complex multicriteria decision processes (Amir, 2014; Power, 2001; Van Leeuwen, 2012). IDSS are probably the most appropriate type of DSS to address the challenge of proposing evolvable decision support for planning and optimizing WQMPs.

Given the fact that the literature review has shown that planning and optimizing a WQMP is complex and involves multiple variables, rules and perspectives, as well as expert knowledge in the process, we believe that an IDSS could support watershed managers in the decision-making process of planning and optimizing a WQMP in a holistic manner. This is particularly the case, since the challenge of planning and optimizing WQMPs is specific to each watershed. Competing objectives may be pursued and trade-offs will be necessary. Also, we wish to underline that the users of an IDSS may not always be familiar with

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every aspect of WQMPs. Therefore, we advance the argument that there is a need for a user-friendly IDSS that allows a user to plan and optimize a WQMP, built and adaptable upon a literature review input and input from experts. Indeed, such a tool would not, as such, propose new optimizing methods, but rather guide the watershed manager through the process of deciding which method would be appropriate for his optimizing challenge, as well as providing him/her with the necessary initial reflections.

However, before a computer code can be written for such an IDSS, it is essential to design the system's conceptual model, depicted by a diagram. Such a diagram represents processes, scenarios of decision problems, cause-effect relationships and various indicators to be considered for decision-making. In order to make sure that the proposed IDSS corresponds to the end-users' needs (e.g. watershed managers), careful designing is essential (Hahn et al., 2009; Kautish and Thapliyal, 2012). Therefore, it would be necessary to pursue the literature review, delve on existing approaches and interview experts in the domain of water quality monitoring. This step is indeed essential to attain the goal of developing an IDSS (del Águila et al., 2014, Rhem, 2006). Designing the structure of an IDSS is also termed as knowledge modelling (Rhem, 2006). Knowledge models are a way of representing knowledge in a structured way through symbols which represent pieces of knowledge and their relationships. They are constructed from "knowledge objects such as concepts, instances, processes (tasks, activities), attributes and values, rules and relations" (Abdullah et al., 2005; Rhem, 2006). DSS were developed since the early 1960s, especially for organizational management. If most were a failure and did not achieve the goal they were constructed for, this was apparently attributable to the fact that information technology (IT) professionals "misunderstood the nature of managerial work" (Kautish and Thapliyal, 2012) due to top down decisions of the IT professionals and managers as well as a linear development approach. Since these early failures, DSSs' planning, design and development for every application domain has evolved towards significant user participation and adaptive development (Kautish and Thapliyal, 2012). The development method of an IDSS to support watershed managers in planning, optimizing and even managing a WQMP should thus be iterative and progressive to sort out optimal rules in order to increase the probability to receive a satisfying solution to a posed problem (Geertman and Stillwell, 2009).

An IDSS could also contribute to making the decision-making process more transparent for watershed managers and users of the information. As underlined by Fölster et al. (2014), WQMPs face critique and need to be regularly updated. Without documenting the underlying decision-making processes it is difficult to update WQMPs and respond to critique. In addition, it would be possible to integrate existing software modules specifically developed for business intelligence, as well as a previously developed spatio-temporal database for water quality data management (Behmel, 2010).

As we underlined earlier, integrated watershed management (IWM) is based on stakeholder involvement. In fact, the generally expected benefits of involvement are to raise public awareness, gain better acceptance of projects or actions and learn from local and expert knowledge (Behmel, 2006; BMVI, 2014; Reed, 2008).

In the preamble of the European Water Framework Directive (WFD) it is stated that "The success of this Directive relies on close cooperation and coherent action at (European) Community, Member State and local level as well as on information, consultation and involvement of the public, including users" (Preamble 14, EC, 2000). In assessing stakeholder participation in several EU countries, De Stefano (2010) came to the conclusion that "already in 2003 there were positive examples of stakeholder participation, but [...] the WFD implementation will require significant efforts to improve on participatory practices throughout Europe". The fundamental need for participatory practices as such, as well as the call for developing, improving and encouraging participation in the context of IWM has been underlined by several authors (De Stefano, 2010; Moss, 2008; Reed, 2008; ROBVQ, 2015).

It is precisely the lack of use of participatory practices that include policy makers, decision makers, representatives of organized stakeholders and the general public that was identified in planning and optimizing WQMPs, especially when referring to addressing knowledge needs on water quality within a watershed (Fölster et al., 2014; Timmerman, 2005; Timmerman et al., 2010). The general lack of use of participatory practices may be due to the fact that they are complex and differ according to the research needs, scope and participants involved (Reed, 2008). Therefore, we believe that an adaptable participative approach must be developed, comprising a public participation geographic information system in order to be able to tap into local knowledge, as well as to identify knowledge and information needs.

5. Conclusions

The main purpose of this literature review was to report the use cases that a watershed manager has to address when planning or optimizing a WQMP. Thus, an inventory of the information, approaches and tools placed at the disposal of watershed managers tasked with this was proposed in order to initiate a discussion on how the available information, approaches and tools could be integrated in a more holistic and evolvable solution compared to those currently available.

Within this literature review, thirteen use cases were identified, along with a considerable amount of underlying actions and interactions. The detailed review of 34 relevant papers addressing one or more of these use cases to offer leads and approaches to watershed managers has shown that it is virtually impossible to propose a one-size-fits-all approach, handbook or directive. However, it was possible to identify the leading challenges and gaps in the literature. The challenges consist of being able to rapidly update a WQMP according to new tools and requirements, while continuing valuable historical data series and introducing spheres of business intelligence communication, politics and governance, as well as improving stakeholder involvement.

Past critiques of WQMPs have led to an effort to standardize WQMPs in every step, thus providing regulatory and other standards for their implementation. Examples are the WFD (Directive, 2000/60/EC and updates), the Canadian Environmental Guidelines (CCME, 2015), the United States Environmental Protection Agencies' *Guidelines for Preparation of the Comprehensive State Water Quality Assessments* (USEPA, 2001 and updates), and the World Meteorological Organizations' guidelines *Planning of water quality monitoring programs* (WMO, 2013). However, one of the main challenges is, and will be, to comply with regulatory standards such as the WFD, in harmony with specific local challenges such as specific water quality issues, land use, and human and technical resources. In addition, it is necessary to integrate past monitoring activities into new directives and regulations.

Given the difference in regulatory requirements, water quality standards, geographical and geological differences, land use variations, etc., it is difficult, if not impossible, to suggest a one-in-all solution for the decision processes of planning and optimizing a WQMP. However, it is possible to suggest that an intelligent decision support system can guide a watershed manager through the process for his/her site-specific requirements, be they natural, regulatory or land use specific (or any other constraint). In addition, it is necessary to develop 1) participative approaches based on geographical information systems which represent spatially the territory and 2) adaptive questionnaire-based surveys to tap into local knowledge and the knowledge needs of the stakeholders. Therefore, we believe that future research should focus on 1) developing participative approaches involving all stakeholders in a given watershed in order to identify knowledge needs and 2) further investigating the benefits of intelligent decision support systems that can be updated quickly and would make it possible for a watershed manager to obtain a timely, holistic view and support for every aspect of planning and optimizing a WQMP. Such an IDSS as well as a participative approach should be tested on one or several case studies.

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References

Abdullah, M.S., Kimble, C., Paige, R., Benest, I., Evans, A., 2005. Developing a UML profile for modelling knowledge - based systems. In: Assmann, U., Aksit, M., Rensink, A. (Eds.), MDAFA 2003/2004. Springer-Verlag, Berlin-Heidelberg, pp. 220–233.

Altenburger, R., Ait-Aissa, S., Antczak, P., Backhaus, T., Barceló, D., Seiler, T.-B., Brion, F., Busch, W., Chipman, K., de Alda, M.L., de Aragão Umbuzeiro, G., Escher, B.I., Falciani, F., Faust, M., Focks, A., Hilscherova, K., Hollender, J., Hollert, H., Jäger, F., Jahnke, A., Kortenkamp, A., Krauss, M., Lemkine, G.F., Munthe, J., Neumann, S., Schymanski, E.L., Scrimshaw, M., Segner, H., Slobodnik, J., Smedes, F., Kughathas, S., Teodorovic, I., Tindall, A.J., Tollefsen, K.E., Walz, K.-H., Williams, T.D., Van den Brink, P.J., van Gils, J., Vrana, B., Zhang, X., Brack, W., 2015. Future water quality monitoring — adapting tools to deal with mixtures of pollutants in water resource management. Sci. Total Environ. 512–513, 540–551.

Amir, E., 2014. Reasoning and decision making. In: Frankish, K., Ramsay, W.M. (Eds.), The Cambrige handbook of artificial intelligence. Cambridge University Press, Cambridge.

Anttila, S., Kairesalo, T., Pellikka, P., 2008. A feasible method to assess inaccuracy caused by patchiness in water quality monitoring. Environ. Monit. Assess. 142, 11–22.

Anttila, S., Ketola, M., Vakkilainen, K., Kairesalo, T., 2012. Assessing temporal representativeness of water quality monitoring data. J. Environ. Monit. 14, 589–595.

Australia, G.O.W., 2009. In: Water, D.O. (Ed.), Water Quality Program Design: A Guideline to the Development of Surface Water Quality Programs. Government of Western Australia, Perth, Western Australia, p. 35.

Balzert, H., 2005. Lehrbuch der Objektmodellierung - analyse und Entwurf mit der UML 2. Spektrum 2004. Akademischer Verlag Heidelberg (572 pp.).

Bartram, J., Ballance, R. (Eds.), 1996. Water Quality Monitoring: A Practical Guide to the Design and Implementation of Freshwater Quality Studies and Monitoring Programmes. Taylor & Francis, London and New York (383 pp.).

Behmel, F., 2006. International Development Assistance Work Focused on Tropical Smallholder Families: Learning Through Trial and Error. Department of Geography, University of Waterloo.

Behmel, S., 2010. Proposition d'un programme de suivi de la qualité de l'eau à l'échelle du bassin versant de la rivière Saint-Charles. Université Laval, Québec, p. 519.

Beveridge, D., St-Hilaire, A., Ouarda, T., Khalil, B., Conly, F.M., Wassenaar, L.I., Ritson-Bennett, E., 2012. A geostatistical approach to optimize water quality monitoring networks in large lakes: application to Lake Winnipeg. J. Great Lakes Res. 38, 174–182.

BMVI, 2014, Handbuch für eine gute Bürgerbeteiligung, *in* Bundesministerium für Verkehr und digitale Infrastruktur, ed., Berlin, Bundesministerium für Verkehr und digitale Infrastruktur.

Brack, W., Altenburger, R., Schüürmann, G., Krauss, M., López Herráez, D., van Gils, J., Slobodnik, J., Munthe, J., Gawlik, B.M., van Wezel, A., Schriks, M., Hollender, J., Tollefsen, K.E., Mekenyan, O., Dimitrov, S., Bunke, D., Cousins, I., Posthuma, L., van den Brink, P.J., López de Alda, M., Barceló, D., Faust, M., Kortenkamp, A., Scrimshaw, M., Ignatova, S., Engelen, G., Massmann, G., Lemkine, G., Teodorovic, I., Walz, K.-H., Dulio, V., Jonker, M.T.O., Jäger, F., Chipman, K., Falciani, F., Liska, I., Rooke, D., Zhang, X., Hollert, H., Vrana, B., Hilscherova, K., Kramer, K., Neumann, S., Hammerbacher, R., Backhaus, T., Mack, J., Segner, H., Escher, B., de Aragão Umbuzeiro, G., 2015. The SOLUTIONS project: challenges and responses for present and future emerging pollutants in land and water resources management. Sci. Total Environ. 503-504, 22–31.

Capella, J.V., Bonastre, A., Ors, R., Peris, M., 2013. In line river monitoring of nitrate concentrations by means of a wireless sensor network with energy harvesting. Sensors Actuators B 177, 419–427.

Cattell, R.B., 1966. The scree test for the number of factors. Multivar. Behav. Res. 1, 245–276.

CCME, 2015, Guidance Manual for Optimizing Water Quality Monitoring Program Design, *in* C. C. O. M. O. T Environment, ed., p. 88.

Chang, C.-L., Lin, Y.-T., 2014. A water quality monitoring network design using fuzzy theory and multiple criteria analysis. Environ. Monit. Assess. 186, 6459–6469.

Chapman, D., 1996. Water Quality Assessement - a Guide to the Use of Biota, Sediments and Water in Environmental Monitoring. E & FN SPON, London.

Chen, Q., Wu, W., Blanckaert, K., Ma, J., Huang, G., 2012. Optimization of water quality monitoring network in a large river by combining measurements, a numerical model and matter-element analyses. J. Environ. Manag. 110, 116–124.

Conservation Ontario, 2010. Overview of Integrated Watershed Management in Ontario.

Davies-Colley, R.J., Smith, D.G., Ward, R.C., Bryers, G.G., McBride, G.B., Quinn, J.M., Scarsbrook, M.R., 2011. Twenty years of New Zealand's National Rivers Water Quality Network: benefits of careful design and consistent operation. JAWRA J. Am. Water Resour. Assoc. 47, 750–771.

del Águila, I.M., Palma, J., Túnez, S., 2014. Milestones in Software Engineering and Knowledge Engineering History: A Comparative Review v. 2014.

Stefano, L., 2010. Facing the water framework directive challenges: a baseline of stakeholder participation in the European Union. J. Environ. Manag. 91, 1332–1340.

de Vries, H., Weijts, W., Dijkstra, M., Kok, G., 1992. The utilization of qualitative and quantitative data for health education program planning, implementation, and evaluation: a spiral approach. Health Educ. Q. 19, 101.

Demard, H., 2007. L'application du RQEP aux sources de surface protègées d'approvisionnement en eau potable. MDDEP, Québec.

Directive, 2000/60/EC, Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 Establishing a Framework for Community Action in the Field of Water Policy.

Fleckenstein, J., Luo, J., Miegel, K., Nützmann, G., Schöniger, M., Theis, H., Wald, J., Wittenberg, H., 2013. Wechselwirkungen zwischen Grund- und Oberflächenwasser. DWA Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V., Hennef, p. 157.

Fölster, J., Johnson, R., Futter, M., Wilander, A., 2014. The Swedish monitoring of surface waters: 50 years of adaptive monitoring. Ambio 43, 3–18.

Geertman, S., Stillwell, J., 2009. Planning support systems: Content, issues and trends. In: Geertman, S., Stillwell, J. (Eds.), Planning Support Systems Best Practice and New Methods. Springer Science and Business Media, Utrecht, pp. 1–26.

Graveline, N., Maton, L., Lückge, H., Rouillard, J., Strosser, P., Palkaniete, K., Rinaudo, J.-D., Taverne, D., Interwies, E., 2010. An operational perspective on potential uses and constraints of emerging tools for monitoring water quality. Trends Anal. Chem. 29, 378–384.

Gray, N.F., 2010. Water Technology: An Introduction for Environmental Scientists and Engineers. Elsevier Butterworth-Heinemann, Oxford.

Groupe de travail sur la réduction du phosphore dans la baie Missisquoi, 2005i. Programme de suivi des charges du bassin versant de la baie Missisquoi. Vermont Agency of Natural Resources Ministère du Développement durable, de l'Environnement et des Parcs, Québec.

Hahn, B.M., Kofalk, S., De Kok, J.-L., Berlekamp, J., Evers, M., 2009. Elbe DSS: A planning support system for Strategic River basin planning. In: Geertman, S., Stillwell, J. (Eds.), Planning Support Systems Best Practices and New Methods. Springer Science + Business Media B.V.

Harmancioglu, N.B., Fistikoglu, O., Ozkul, S.D., Singh, V., Alpaslan, M.N., 1999. Water Quality Monitoring Network Design. Kluwer Academic Publisher, Dordrecht, the Netherlands (290 pp.).

Hatton-Ellis, T., 2008. The Hitchhiker's guide to the water framework directive. Aquat. Conserv. Mar. Freshwat. Ecosyst. 18, 111–116.

Hilton, J., Carrick, T., Rigg, E., Lishman, J.P., 1989. Sampling strategies for water quality monitoring in lakes: the effect of sampling method. Environ. Pollut. 57, 223–234.

Horowitz, A., 2013. A review of selected inorganic surface water quality-monitoring practices: are We really measuring what We think, and if so, are We doing it right? Environ. Sci. Technol. 47, 2471–2486.

Islam, N., Sadiq, R., Rodriguez, M.J., Francisque, A., 2011. Reviewing source water protection strategies: a conceptual model for water quality assessment. Environ. Rev. 19, 68–105.

Jalbert, K., Kinchy, A.J., 2015. Sense and influence: environmental monitoring tools and the power of citizen science. J. Environ. Policy Plan. 1–19.

Kautish, S., Thapliyal, M.P., 2012. Concept of decision support systems in relation with knowledge management - fundamentals, theories, frameworks and practices. Int. J. Appl. Innov. Eng. Manag. 1, 9.

Keum, J., Kaluarachchi, J., 2015. Development of a decision-making methodology to design a water quality monitoring network. Environ. Monit. Assess. 187, 1–14.

Khalil, B., Ouarda, T.B.M.J., 2009. Statistical approaches used to assess and redesign surface water-quality-monitoring networks. J. Environ. Monit.

Khalil, B., Ouarda, T.B.M.J., St-Hilaire, A., Chebana, F., 2010. A statistical approach for the rationalization of water quality indicators in surface water quality monitoring networks. J. Hydrol. 386, 173–185.

Khalil, B., Ouarda, T.B.M.J., St-Hilaire, A., 2011. A statistical approach for the assessment and redign of the Nile Delta drainage system water-quality-monitoring locations. J. Environ. Monit. 13, 2190–2205.

Levine, C.R., Yanai, R.D., Lampman, G.G., Burns, D.A., Driscoll, C.T., Lawrence, G.B., Lynch, J.A., Schoch, N., 2014. Evaluating the efficiency of environmental monitoring programs. Ecol. Indic. 39, 94–101.

LFU, 2016. Qualitätsicherung Qualität der seen - Qualitätsicherung bei der biologischen Gewässeruntersuchung. Bayerisches Landesamt für Umwelt.

Li, Y., Migliaccio, K.W., 2011. Water Quality Concepts, Sampling, and Analyses. Taylor & Francis, Boca Raton, FL (x, 333 pp.).

Lim, K.-Y., Surbeck, C.Q., 2011. A multi-variate methodolgy for analyzing pre-existing lake water qualiity data. J. Environ. Monit. 2477–2487.

Madrid, Y., Zayas, Z.P., 2007. Water sampling: traditional methods and new approaches in water sampling strategy. Trends Anal. Chem. 26, 293–299.

Mahjouri, N., Kerachian, R., 2011. Revising river water quality monitoring networks using discrete entropy theory: the Jajrood River experience. Environ. Monit. Assess. 175, 291–302.

Mäkelä, A., Meybeck, M., 1996. Designing a monitoring program. In: J., B., Ballance, R. (Eds.), Water Quality Monitoring: A Practical Guide to the Design and Implementation of Freshwater Quality Studies and Monitoring Programmes. Taylor & Francis, London and New York, pp. 35–70.

Memarzadeh, M., Mahjouri, N., Kerachian, R., 2013. Evaluating sampling locations in river water quality monitoring networks: application of dynamic factor analysis and discrete entropy theory. Environ. Earth Sci. 70, 2577–2585.

Moss, B., 2008. The water framework directive: Total environment or political compromise? Sci. Total Environ. 400, 32–41.

Moss, B., Stephen, D., Alvarez, C., Becares, E., Van de Bund, W., Collings, S., Van Donk, E., De Eyto, E., Feldmann, T., Fernandez-Alaez, C., Fernandez-Alaez, M., Franken, R., Garcia-Criado, F., Gross, E., Gyllstrom, M., Hansson, L., Irvine, K., Jarvalt, A., Jensen, J.P., Jeppesen, E., Kairesalo, T., Kornijow, R., Krause, T., Kunnap, H., Laas, A., Lille, E., Lorens, B., Luup, H., Miracle, M., Noges, P., Noges, T., Nykanen, M., Ott, I., Peczula, W., Peeters, E., Phillips, G., Romo, S., Russell, V., Salujoe, J., Scheffer, M., Siewertsen, K., Smal, H., Tesch, C., Timm, H., Tuvikene, L., Tonno, I., Virro, T., Vicente, E., Wilson, D., 2003. The determination of ecological status in shallow lakes - a tested system (ECOFRAME) for implementation of the European water framework directive. Aquat. Conserv. Mar. Freshwat. Ecosyst. 13, 507–549.

Neary, D.G., Ice, G., Jackson, C.R., 2009. Linkages between forest soils and water quality and quantity. For. Ecol. Manag. 258, 2269–2281.
Ning, S.K., Chang, N.-b., 2002. Multi-objective, decision-based assessment of a water quality monitoring network in a river system. J. Environ. Monit. 4, 121–126.
Noori, R., Sabahi, M.S., Karbassi, A.R., Baghvand, A., Taati Zadeh, H., 2010. Multivariate statistical analysis of surface water quality based on correlations and variations in the data set. Desalination 260, 129–136.
Olsen, R.L., Chappell, R.W., Loftis, J.C., 2012. Water quality sample collection, data treatment and results presentation for principal components analysis – literature review and Illinois River watershed case study. Water Res. 46, 3110–3122.
Ouyang, Y., 2005. Evaluation of river water quality monitoring stations by principal compenent analysis. Water Res. 39.
Park, S.-Y., Choi, J.H., Wang, S., Park, S.S., 2006. Design of a water quality monitoring network in a large river system using the genetic algorithm. Ecol. Model. 199, 289–297.
Pinto, U., Maheshwari, B., 2011. River health assessment in pen-urban landscapes: An application of multivariate analysis to identify the key variables. Water Res. 45, 3915–3924.
Pobel, D., Robin, J., Humbert, J.F., 2010. Influence of sampling strategies on the monitoring of cyanobacteria in shallow lakes: Lessons from a case study in France. Water Res. 45, 1005–1014.
Power, D.J., 2001. Supporting Decision-Makers: An Expanded Framework. Decision Support System Resources.
Quevauviller, P., Balabanis, P., Fragakis, C., Weydert, M., Oliver, M., Kaschl, A., Arnold, G., Kroll, A., Galbiati, L., Zaldivar, J.M., Bidoglio, G., 2005. Science-policy integration needs in support of the implementation of the EU water framework directive. Environ. Sci. Pol. 8, 203–211.
Raadgever, G.T., Mostert, E., Kranz, N., Interwies, E., Timmerman, J.G., 2008. Assessing management regimes in Transboundary River basins: do they support adaptive management? Ecol. Soc. 13.
Reed, M.S., 2008. Stakeholder participation for environmental management: a literature review. Biol. Conserv. 141, 2417–2431.
Rhem, A.J., 2006. UML for Developing Knowledge Management Systems. Fla, Auerbach, Boca Raton.
ROBVQ, 2015. Boîte à outils Sur la participation citoyenne. ROBVQ.
Ross, C., Petzold, H., Penner, A., Ali, G., 2015. Comparison of sampling strategies for monitoring water quality in mesoscale Canadian Prairie watershed. Environ. Monit. Assess. 395.
Schmeer, K., 2000. Stakeholder Analysis Guidelines, Washington DC, Partners for Health Reform. World Health Organisation.
Sharp, W.E., 1971. A topologically optimum water-sampling plan for rivers and streams. Water Resour. Res. 7, 1641–1646.
Smeltzer, E., Walker, W.W.J., Garrison, V., 1989. Eleven years of Lake eutrophication monitoring in Vermont: A Crititical review, enhancing States' Lake management programs, Chicago, IL. Proc. National Conference, pp. 53–62.
Strobl, R.O., Robillard, P.D., Day, R.L., Shannon, R.D., McDonnell, A.J., 2006a. A water quality monitoring network design methodology for the selection of critical sampling points: Part II. Environ. Monit. Assess. 122, 319–334.
Strobl, R.O., Robillard, P.D., Shannon, R.D., Day, R.L., McDonnell, A.J., 2006b. A water quality monitoring network design methodology for the selection of critical sampling points: Part I. Environ. Monit. Assess. 112, 137–158.
Strobl, R.O., Robillard, P.D., 2008. Network design for water quality monitoring of surface freshwaters: a review. J. Environ. Manag. 87, 639–648.
Tchobanoglous, G., Schroeder, E.D., 1985. Water Quality : Characteristics, Modeling, Modification. Reading, Addison-Wesley (xxix, 768 pp.).
Telci, I.T., Nam, K., Guan, J.B., Aral, M.M., 2009. Optimal water quality monitoring network design for river systems. J. Environ. Manag. 90, 2987–2998.
Thoma, D., Irwin, R., Penoyer, P., 2012. Documenting measurement sensitivity and bias of field-measured parameters in water quality monitoring programs. Environ. Monit. Assess. 184, 5387–5398.
Thomas, R., Meybeck, M., Beim, A., 1996. Lakes. In: Chapman, D. (Ed.), Water Quality Assessements - a Guide to the Use of Biota, Sediments and Water in Environmental Monitoring. E & FN Spon, London.
Thompson, M.Y., Brandes, D., Kney, A.D., 2012. Using electronic conductivity and hardness data for rapid assessment of stream water quality. J. Environ. Manag. 104, 152–157.
Timmerman, J., 2005. The need for participatory processes and its implications for water management information. Reg. Environ. Chang. 5, 162–163.
Timmerman, J., Langaas, S., 2005. Water information: what is it good for? The use of information in transboundary water management. Reg. Environ. Chang. 5, 177–187.
Timmerman, J.G., Ottens, J.J., Ward, R.C., 2000. The information cycle as a framework for defining information goals for water-quality monitoring. Environ. Manag. 25, 229–239.
Timmerman, J., Beinat, E., Termeer, K., Cofino, W., 2010. Analyzing the data-rich-but-information-poor syndrome in Dutch water Management in Historical Perspective. Environ. Manag. 45, 1231–1242.
Tyler, N.A., Hunter, D.P., Carvalho, L., Codd, A.G., Elliott, J.A., Ferguson, A.C., Hanley, D.N., Hopkins, W.D., Maberly, C.S., Mearns, J.K., Scott, E.M., 2009. Strategies for monitoring and managing mass populations of toxic cyanobacteria in recreational waters: a multi-interdisciplinary approach. Environ. Health 8.
UNEP, 2012. Status Report on the Application of Integrated Approaches to Water Resources Management. United Nations Environment Programme.
USEPA, 2001. Guidelines for Preparation of the Comprehensive State Water Quality Assessments (305b reports) and Electronic Updates, Washington, D.C.
Van Leeuwen, B., 2012. Artificial Neural Networks and Geographical Information Systems for Inland Excess Water Classification. Faculty of Science and Informatics, Szeged.
Von Der Ohe, P.C., De Deckere, E., Prüß, A., Muñoz, I., Wolfram, G., Villagrasa, M., Ginebreda, A., Hein, M., Brack, W., 2009. Toward an integrated assessment of the ecological and chemical status of european river basins. Integr. Environ. Assess. Manag. 5, 50–61.
Ward, R., Loftis, J., McBride, G., 1986. The "data-rich but information-poor" syndrome in water quality monitoring. Environ. Manag. 10, 291–297.
Ward, R.C., Loftis, J.C., McBride, G.B., 1990. Design of Water Quality Monitoring Systems. Van Nostrand Reinhold, New York.
Wernersson, A.-S., Carere, M., Maggi, C., Tusil, P., Soldan, P., James, A., Sanchez, W., Dulio, V., Broeg, K., Reifferscheid, G., Buchinger, S., Maas, H., Van Der Grinten, E., O'Toole, S., Ausili, A., Manfra, L., Marziali, L., Polesello, S., Lacchetti, I., Mancini, L., Lilja, K., Linderoth, M., Lundeberg, T., Fjällborg, B., Porsbring, T., Larsson, D.G., Bengtsson-Palme, J., Förlin, L., Kienle, C., Kunz, P., Vermeirssen, E., Werner, I., Robinson, C., Lyons, B., Katsiadaki, I., Whalley, C., den Haan, K., Messiaen, M., Clayton, H., Lettieri, T., Carvalho, R., Gawlik, B., Hollert, H., Di Paolo, C., Brack, W., Kammann, U., Kase, R., 2015. The European technical report on aquatic effect-based monitoring tools under the water framework directive. Environ. Sci. Eur. 27, 1–11.
Wetzel, R.G., 2001. Limnology: Lake and River Ecosystems. Academic Press, San Diego (xvi, 1006 pp.).
Wilkinson, J., Souter, N., Fairweather, P., 2007. Best practice Framwork for the monitoring and evaluation of water-dependent ecosystems 1: Framework. Department of Water, Land and Biodiversity Conservation, Adelaide.
Winkelbauer, A., Fuiko, R., Krampe, J., Winkler, S., 2014. Crucial elements and technical implementation of intelligent monitoring networks. Water Sci. Technol. J. Int. Assoc. Water Pollut. Res. 70, 1926.
Winkler, S., Zessner, M., Saracevic, E., Fleischmann, N., 2008. Intelligent monitoring networks–transformation of data into information for water management. Water Sci. Technol. J. Int. Assoc. Water Pollut. Res. 58, 317.
WMO, 2013. In: W. M. Organization (Ed.), Planning of water quality monitoring systems. World Meteorological Organization, Geneva, Switzerland, p. 128.
Yang, X.-E., Wu, X., Hao, H.-L., He, Z.-L., 2008. Mechanisms and assessement of water eutrophication. J. Zhejiang Univ. Sci. B 9, 197–209.

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