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INTELLIGENT DECISION SUPPORT SYSTEM TO OPTIMIZE, MANAGE AND PLAN WATER QUALITY MONITORING PROGRAMS BASED ON A PARTICIPATIVE APPROACH

Thèse

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Résumé

Cette thèse s’intéresse au développement d’un système intelligent d’aide à la décision (SIAD) destiné à la conception, à la gestion et à l’optimisation des programmes de suivi de la qualité de l’eau (PSQE). Toute son originalité repose sur le fait qu’elle aborde la question dans une perspective holistique qui se traduit par le développement d’une approche participative dans le but de déterminer les besoins en connaissances sur la qualité et la quantité de l’eau sur lesquels se base le SIAD pour assister les gestionnaires de PSQE à toutes les étapes de la planification, de la gestion et de l’optimisation d’un PSQE.

Ce système s’adresse aux organisations responsables de PSQE ainsi qu’aux divers utilisateurs qui, au sein de ces organisations, ont besoin d’outils d’aide à la décision adéquats pour les appuyer dans tous les aspects de leur travail. De plus, le SIAD est conçu pour documenter tout type de décision prise durant les étapes de conception, de gestion et d’optimisation du programme afin de découvrir précisément quand, pourquoi et comment des modifications sont apportées. Par ailleurs, cette thèse propose d’élaborer une approche participative afin de cerner les préoccupations de tous les intervenants d’un bassin versant, tant les organisations que les citoyens, par rapport à la qualité de l’eau. L’objectif de l’approche participative consiste à déterminer les besoins en matière de connaissances ainsi que les préoccupations liées à la qualité de l’eau afin d’aider les gestionnaires de PSQE à définir les priorités en ce qui concerne l’acquisition de connaissances. Tant le SIAD que l’approche participative ont été mis à l’épreuve dans le cadre d’études de cas réalisées dans deux bassins versants de la province du Québec, au Canada (le bassin versant de la rivière du Nord et celui de la rivière Saint-Charles).

La première partie de cette thèse porte sur une revue critique de la littérature existante qui traite de tous les aspects du suivi de la qualité de l’eau. Les lignes directrices, les manuels, les politiques et les méthodes proposées dans la littérature scientifique sont ainsi analysés en fonction de leur potentiel à aider les gestionnaires de PSQE et leurs équipes à prendre des décisions éclairées quant à la conception, à la gestion et à l’optimisation des PSQE.

En deuxième partie de thèse sont présentées la méthodologie et la mise en œuvre de l’approche participative, laquelle est conçue pour définir de nouveaux objectifs de suivi et d’optimisation pour les PSQE, ainsi que pour déterminer les moyens de communication à privilégier lorsqu’il est question de l’eau.

La troisième partie de la thèse expose la méthodologie liée à la conception du SIAD, dont le modèle conceptuel, qui est décrit en langage de modélisation unifié, est basé sur une collecte d’informations recueillies au moyen d’une recension des écrits, d’entrevues menées auprès de 44 experts issus de six pays

qui jouissent d'une renommée internationale en matière de qualité de l'eau, de rencontres avec des spécialistes des technologies de l'information, ainsi que d'ateliers avec de potentiels utilisateurs finaux. La séquence des opérations effectuées par le système (cas d'utilisation) ainsi que les livrables qui y sont liés (scénarios, bibliothèques, arbres décisionnels, etc.) sont décrits selon les concepts de méthode agile et de cas d'utilisation 2.0.

En quatrième partie de thèse, les fonctions d'optimisation du SIAD ont été mises à l'épreuve sur des données qui proviennent de deux études de cas (données de lac et données de rivière, respectivement), ainsi que sur un échantillon d'objectifs d'optimisation issus de l'approche participative. Voici certains des éléments du SIAD qui ont été testés : aide à la décision au cours des étapes relatives à (1) la compréhension des raisons qui justifient l'existence des PSQE actuels, à (2) la validation et à l'intégration des données (contrôle de la qualité et stockage), au (3) choix du processus d'optimisation parmi ceux proposés par la littérature, ainsi qu'à (4) la mise en œuvre et au (5) parachèvement du processus d'optimisation.

Abstract

This thesis focuses on the development of an intelligent decision-support system (IDSS) to plan, manage and optimize water quality monitoring programs (WQMPs). The main originality of this thesis is to have approached the question of planning, managing and optimizing WQMPs in a holistic manner. The holistic approach transcends into the developing of a participative approach to identify knowledge needs on water quality and quantity to feed an IDSS which assists WQMP managers in every aspect of planning, managing and optimizing WQMPs.

The system is directed at organizations in charge of WQMPs and a variety of users within these organizations who need adequate decision support for every aspect of their work. In addition, the IDSS is designed to document any type of decision during the planning, management and optimization phases in order to obtain a clear idea of when, why and how changes are made. This thesis also proposes the development of a participative approach to identify all concerns raised by stakeholders in a watershed—both organizations and citizens—regarding water quality. The purpose of the participative approach is to elicit knowledge needs and concerns regarding water quality in order to direct WQMP managers towards priorities in knowledge acquisition. Both the IDSS and the participative approach were tested in two watershed case studies in the province of Quebec, Canada (the Rivière du Nord watershed and the Rivière Saint-Charles watershed).

The first component of the thesis consists of a critical review of the literature regarding all aspects of water quality monitoring. Existing guidelines, handbooks, policies and methods proposed in the scientific literature are analyzed to determine their capacity to provide decision support to managers and their teams to plan, manage and optimize WQMPs.

The second component proposes the methodology and application of the participative approach. The participative approach is designed to yield new monitoring objectives and optimization objectives for WQMPs. It is also designed to determine preferred modes of communication on water-related issues.

The third component of the thesis presents the design methodology of the IDSS. The conceptual model of the IDSS is based on an information collection methodology consisting in a literature review, a series of interviews conducted with 44 international water quality experts from six countries, meetings with information technology specialists and workshops with potential end-users. The conceptual model is described in the Unified Modeling Language. The sequence of operations performed by the system (use cases) and related deliverables (use-case scenarios, libraries, decision-support trees, etc.) are described according to the concepts of agile development and Use Case 2.0.

The fourth component of the thesis tests the optimization features of the IDSS based on the data from the two case studies (respectively lake data and river data) and a selection of optimization objectives resulting from the participative approach. Some of the tested elements of the IDSS are: decision support in the steps of (1) understanding the underlying rationale of the existing WQMPs; (2) data validation and integration (quality assessment and storage); (3) selecting optimization procedures proposed in the literature; 4) applying the optimization procedures and (5) finalizing the optimization procedure.

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Behmel, S., M. Damour, Ludwig, R. Rodriguez, M..J

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Behmel, S., M. Damour, Ludwig, R. Rodriguez, M..J

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Abbreviations

Abrinord *– Organisme de bassin versant de la rivière du Nord;*

APEL *– Association pour la protection de l'environnement du lac Saint-Charles et des Marais du Nord;*

DSS – *Decision support systems;*

FC – *Fecal coliforms;*

IDSS *– Intelligent decision support system;*

IT – *Information technology;*

IWM *– Integrated watershed management;*

IWRM – *Integrated Water Resources Management;*

PCA – *Principal component analysis;*

PPGIS *– Public participation geographical information system;*

ROS *– Representatives of organized stakeholders;*

TP – *Total phosporus;*

TSS – *Total suspended solids;*

UML – *Unified Modeling language;*

W1 *– Watershed 1 = Watershed of the Saint-Charles river;*

W2 *– Watershed 2 = Watershed of the rivière du Nord;*

WFD – *Water Framework Directive;*

WQMP *– Water quality monitoring program***;**

WQP – *water quality parameter.*

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GENERAL INTRODUCTION

The general introduction of this thesis begins with a brief history of water resource management and knowledge acquisition related to water resources in order to place the research in a historical context (Section I). Section II provides an overview of modern integrated water resource management (IWRM) and modern means to acquire knowledge on water resources. The lessons learned from this review contextualize the need for improved water quality monitoring strategies and programs. They also support the thesis hypothesis and objectives presented in Section III. Section IV provides a summary of the methodology used to achieve the proposed specific objectives of the thesis. Finally, section V provides a short overview of the authors' contributions to the papers. The references mentioned in this general introduction are presented at page 176 at the end of the thesis.

This thesis is divided into four main chapters (Chapters 1 to 4), each written in the form of a scientific paper. Each chapter presents a detailed section for the introduction, methodology, results, discussion and conclusions.

The last section is the general conclusion of the thesis. In the general conclusion, elements such as the originality of this thesis and its strengths and limitations are discussed. Finally, an outline is provided for future research.

I. Brief history of water resource management and knowledge acquisition processes and methods

To comprehend water resource management in the 21st century, it is necessary to position modern understanding on water resource management as well as knowledge acquisition methods and processes on water resources in their historical context. To grasp a science or a concept, it is necessary to place historic facts in their cultural and historic background (Steleanu, 1986). Therefore, following is a brief overview of the historical development of water resource management and knowledge acquisition methods and processes on water resources. The main eras which are going to be presented are: Antiquity (1100 B.C. ~ 500 A.D.), the Roman Empire (27 B.C. – 476 A.D.), the Dark Ages (5th ~ 15th century A.D.), the Renaissance (14th ~ 15th century A.D.), the Age of Discovery (15th ~18th century A.D.), and Industrialisation (18th century A.D. to today) (Hotz, 2004a, b, c).

Several examples of watershed management and water resource management during the pre-Antiquity, Antiquity and Roman Empire periods show that authorities were aware of the human impacts on water quality and quantity. For instance, the Greek, Chinese and Romans would protect the watersheds upstream of their drinking water sources through regulations and protective measures. The Chinese implemented laws to protect their forests by 300 B.C. The importance of forests to regulate the local hydrologic cycle and ensure water quality was well known. In terms of water resource management – water supply, wastewater evacuation, drainage of wetlands and irrigation – the civilizations during the pre-Antiquity and Antiquity periods demonstrated remarkable engineering skills (Neary et al., 2009). However, the functioning of the local, regional or global hydrologic cycle was not really known or understood, nor was it known how human-induced changes would impact the hydrologic cycle. In some civilizations that had flourished through water resource management favouring agriculture, this led to the overharvesting of water through over-irrigation and over-deforestation. This unsustainable management of water resources even contributed to the decline of civilizations such as the Sumerians (4000 – 2300 B.C.) and the Mayas (250 A.D.) (Hermon, 2008).

The lack of knowledge of the local, regional and global water cycle was addressed by scientists such as Aristotle. Aristotle contributed to the understanding of the water cycle, as well as to how human activities (wastewater in particular) could affect water quality (Neary et al., 2009; Steleanu, 1986). Before Aristotle, the water cycle was described vaguely: water rising from the ground by evaporation caused by the sun is precipitated and collected underground in a huge underground cavity of which the outlets were rivers. Aristotle nuanced this picture and came very close to what is known today as the natural hydrologic cycle (Steleanu, 1986).

During the Dark Ages, most of this knowledge was refuted and lost because the Bible was considered to be the standard of knowledge against which all new knowledge and ideas were measured. The water cycle was described in Ecclesiasts 1 as follows: "All the rivers go down to the sea, but the sea is not full; to the place where the rivers go, there they go again." Based on this description, the theory was established that ocean water seeped into the ground and would soar upwards into the mountains from where the water would return to the rivers. The ground was viewed as a gigantic filter. This theory is also known as the sponge theory (Steleanu, 1986). Only during later periods of the Dark Ages was knowledge from the Greek philosophers accepted once again (Steleanu, 1986). Notwithstanding the sponge theory which precludes water resource protection, there are some known examples of forest protection during this era. For instance, King Louis the VI recognized the importance of forests for the conservation of water quality and promulgated "The Decree of Waters and Forests" in 1215 (Chang, 2013).

The Renaissance was marked by a change in the concept of having the Bible and Antiquity as a standard for scientific knowledge. For instance, Bernard Palissy (1510 – 1590) questioned the sponge theory and the theories from Antiquity on the hydrologic cycle. He presented the first modern water cycle in his book:

Discours admirable: De la nature des eaux et fontaines 1580 (Palissy and France, 1969). An example for this period to protect water resources is the initiative of forest preservation by the Swiss to protect water quality and reduce the risk of avalanches. The Swiss designated 322 forests for protection between 1535 and 1777 (Neary et al., 2009).

The Age of Discovery, in particular the 17th century, was marked by a convergence of independent (no communication between the scientists) discoveries and theories concerning the hydrologic cycle as we understand it today. Varenius (Varen) Bernard (1622 – 1651) in particular contributed significantly to the categorization and understanding of waterbodies (Chapter XV) and the hydrologic cycle (Chapter XVI) (Varenius and Newton, 1672). However, there was scant understanding of the quantification of global water cycle compartments (e.g., how much water is in the oceans, the ice cover, the atmosphere). The Age of Discovery was also marked by the coexistence of old and modern theories. For instance, the Jesuit Kirchner continued to defend the pre-Aristotle theory of having a huge cavity of water in the ground from which all rivers are fed (Steleanu, 1986).

At the end of the 19th century with industrialization well underway, there was still no consensus on the natural hydrologic water cycle. Volger, an engineer and hydrologist, stated in 1877: “No water in the ground originates from rainwater.” This sparked a discussion on the source and formation on groundwater which lasted several decades. Only with Otozky and Mezger was some consensus on the hydrological cycle, the formation of groundwater and a certain quantification of the compartments of water achieved in 1922 (Steleanu, 1986).

This is remarkable, since humans had been modifying the hydrologic cycle at the local, regional and global levels during all these eras. Industrialization was a culmination of the modification of the hydrologic cycle through the building of dams, deforestation, irrigation, urbanization, river channelization, cloud seeding, etc. (Turner, 1990). Indeed, Industrialization was marked by heavy impacts of human activities on the hydrologic cycle and on water quality, yet neither the impact of these activities on the hydrologic cycle or on water quality was well known. In addition, knowledge acquisition processes and concepts of water resource protection did not evolve (or receive general acceptance) as quickly as industrialization and engineering solutions (e.g., river regulation, dams and drinking water treatment). In the United States alone, there are more than 87 000 known dams (Townsend, 2014). As a consequence of this fast evolution, water quality and availability declined rapidly in many areas.

In addition, it is significant that knowledge acquisition processes on water quality and quantity were only formalized as a science by François Alphonse Forel (1841-1912). Forel is considered to be the founder of limnology, the science of lakes and rivers (Steleanu, 1986). Limnology is an encompassing science that includes geography, hydrography, geology, climatology, hydrology, hydraulics, thermals, optics, acoustics, chemistry and biology (Forel and Forel, 2012). Each science has evolved and advanced at a different rhythm. Several monographies on lakes were written in Switzerland in the 17th and 18th centuries and are considered as the precursors of limnology. The authors described lake biology, size and depth and their surrounding areas. Some of the instrumentation and tools to measure optics, nutrient concentrations and oxygen concentrations were also developed in the 18th and 19th centuries. For instance, Angelo Secchi developed the Secchi disk in 1865 to measure water transparency and turbidity. The Secchi disk is still one of the instruments most used in limnology (Wetzel, 2001). For further reading on the development of these sciences, please consult Steleanu (1986).

Forel is considered to be the first to have pooled and formalized the existing knowledge of these sciences through his studies of lake Leman (starting in the late 1860ties) and to have adapted and implemented the first limnological studies program of Lake Constance in 1886. The program involved developing methods to understand the waterbody and providing methods for the characterization of water quality. Between 1886 and 1906, most European lakes (and others) were studied according to their morphology, physiography and biology (Steleanu 1986).

A groundbreaking element of modern limnology was the foundation of the International Society of Limnology (SIL) in Kiel, Germany in 1922. The founders sought to eradicate the borders erected during World War I between the scientists and science, since international collaboration was deemed essential for science and human wellbeing (Steleanu, 1986). Ever since, scientists working on water quality and quantity assessment processes have tried to keep abreast of the ever changing and additions of human-induced agents of degradation and transformation of water quality and quantity (Altenburger et al., 2015; Brack, 2015; Chapman, 1996; Islam et al., 2011; Ludwig et al., 2003; Steleanu, 1986; Von Der Ohe et al., 2009; Ward et al., 1990).

Hence, as declining water quality and changes in the hydrologic cycle have become local, regional and global issues of concern due to industrialization and globalization – with additional challenges such as climate change, human population growth and the expansion of industrial and agricultural activities – many countries have begun to reform water governance and focus on sustainable development through an integrated approach, as recommended in the 1992 Agenda 21 (UNEP, 2012). Agenda 21 is the basis of modern IWRM, providing a program of actions for sustainable development on how states must apply “Integrated approaches to the development, management and use of water resources” (UNEP, 2012). Key elements of Agenda 21 include: instauration of restorative and protective measures based on knowledge acquisition and stakeholder involvement.

II. What is Modern Integrated Water Resource Management?

Agenda 21 set the standard for modern IWRM, yet does not provide a definition of the concept (Hermon, 2008). However, Agenda 21 has provided a series of key activities to improve and implement water resource management and knowledge acquisition processes. The knowledge acquisition processes include general recommendations regarding water quality and quantity monitoring, tapping into local knowledge (including specific traditional knowledge and women's knowledge), citizen involvement and citizens' groups and organizations of all types and at all levels (industry, government, non-government organizations, etc.) (UNEP, 2012).

On the local, regional, national and international levels, IWRM has been defined and redefined constantly. Therefore, it is still not possible to provide an universal definition of IWRM. For the subsequent discussion, a definition inspired by Conservation Ontario is proposed: IWRM implies managing all human activities and natural resource uses in an area, the watershed (i.e. the territory on which surface water converges toward a single point at a lower elevation, where it joins another water body), in a coordinated and sustainable manner (Conservation Ontario, 2010).

According to this definition, all water stakeholders – policymakers, city planners, water conservation organizations, industry sector, universities and the general public – should be part of the process in order to take joint decisions and actions to protect the resource for social, economic and environmental reasons (Bartram and Ballance, 1996; Demard, 2007; Islam et al., 2011). Also, as strongly recommended by the Rio Agenda 21, this implies that participative approaches should be developed and implemented in decision making, and that decision making must be based on sound scientific knowledge of the issues. Thus, it is necessary to develop and improve participatory practices and formalize knowledge acquisition processes such as water quality monitoring programs (WQMPs).

The term "area" in the definition of IWRM pinpoints another difficulty, namely distinguishing the watershed or territory to be subject to knowledge acquisition, participative approaches and, ultimately, the implementation of the restorative and protective measures. For instance, the watershed of the St. Lawrence River comprises parts of Canada and the United States with an area of 1.6 million km^2 that drains more than 25% of the world's freshwater (Environment Canada, 2013). A population of 30 million in the United States and 15 million in Canada (Environment Canada, 2013) lives within this watershed. Hence, the IWRM of this watershed requires a transnational approach, yet must cover sub-watersheds managed along more local political boundaries, such as provinces or states and municipalities. Also, jurisdictions that have embraced IWRM impose watershed boundaries that generally encompass watersheds from large rivers. The size of these watersheds is very variable and can range from less than 1000 km^2 to more than 170 000 km^2 (Choquette and Létourneau, 2008; Directive, 2000/60/EC). The question may be then asked as to whether the proposed watershed boundaries lend themselves to effective IWRM since they may be very heterogeneous in terms of their political boundaries, land use, geology and population dynamics. The proposed watershed boundaries do not take "human" catchment areas into account. Human catchment areas are defined in human geography as the area to which a city, institution or, in this case, water resources in a watershed, attracts a population that uses its services. Therefore, the people living in the human catchment area may not be considered by the IWRM of these watersheds. Yet, they may be the principal users or population benefitting from the water of a watershed where they do not live and from which they are excluded from management decisions.

Knowledge on water quality and quantity monitoring has evolved rapidly since the 17^{th} to the 19^{th} century monographies on Swiss lakes and Secchi and Forel in the 19^{th} century. WQMPs have been implemented in many countries and at different scales (Davies-Colley et al., 2011; Fölster et al., 2014; Timmerman et al., 2011). A definition of monitoring is provided by the International Organization for Standardization: "Monitoring is the programmed process of sampling, measurement, and subsequent recording or signalling, or both, of various water characteristics, often with the aim of assessing conformity to specific objectives." Several sub-divisions are possible. Here the aspect of monitoring considered as the "long term, standardized measurement and observation of the aquatic environment in order to define status and trends" is addressed (Bartram and Ballance, 1996). The challenges common to all WQMPs are: select the territory subject to the WQMP; set precise monitoring objectives (knowledge needs); identify a sampling site network; select water quality parameters; set sampling frequency and recurrence; ensure quality control, assessment and data storage; produce timely, understandable and robust information; and embed the knowledge needs, scientific considerations, logistics and administrative considerations into the available human, technical and financial resources (Behmel et al., 2016; Harmancioglu et al., 1999; Loftis and Ward, 1980; Timmerman et al., 2000; Ward et al., 1990).

Several methods exist to optimize or implement a WQMP: empirical, conventional statistical and "emerging methods" (Chen et al., 2012). The empirical method may be defined as planning, managing and optimizing WQMPs based on handbooks, guidelines and subject matter expert knowledge. The conventional statistical methods include identification and optimization of the amount of monitoring stations and water quality parameters based on techniques like principal component analysis (Olsen et al., 2012; Ouyang, 2005)); factor and correlations analysis (Pinto and Maheshwari, 2011); and correlation and cluster analysis (Khalil et al., 2010). “Emerging methods” include techniques available because of increased modern-era computing capacities: genetic algorithms (Khalil et al., 2011; Park et al., 2006); entropy analysis (Mahjouri and Kerachian, 2011); matter-element analysis (Chen et al., 2012) that may be combined with geographic information systems (GIS) (Park et al., 2006); artificial neural networks and maintenance of variance extension techniques (Khalil et al., 2011), self organizing maps (Tobiszewski et al., 2010), etc.; for example, to determine sampling locations based on the hydrological network and contamination fate (Telci et al., 2009).

However, all these methods are rather compartmentalized: they do not address the process of planning, managing and optimizing WQMPs in a holistic and, to some extent, standardized manner. For example, a network based on the empirical method may be biased by arbitrary decisions regarding the amount of stations, sampling frequencies and number of parameters to sample (Strobl and Robillard, 2008). The statistical methods do not necessarily take micro-location, accessibility, mixing and local influences into account, nor do they consider all the administrative elements of planning a WQMP (financial, human, technical resources). At some point of their application, all these methods require decision making by experts (Beveridge et al., 2012; Gray, 2010; Olsen et al., 2012; Strobl and Robillard, 2008). Some of the emerging methods do not consider the fact that the problem domain is not stable and is subject to constant changes in land use and knowledge needs (Van Leeuwen, 2012). All the methods have one thing in common: subject matter expert knowledge is required at some point and decisions must be taken that will influence the results and the recommendations of the WQMPs. Therefore, it is essential to capture these decisions in order to understand their impact and render them transferable and transparent.

In addition, WQMPs are often based on imprecise objectives. This may be due to a failure to make allowances for participative approaches to identify the knowledge needs of citizens, organizations and decision makers (Government of Australia, 2009; Bartram and Ballance, 1996; De Stefano, 2010; Harmancioglu et al., 1999; Quevauviller et al., 2005). This shortcoming is real, despite the fact that it is a major premise of IWRM. This situation is probably associated with the fact that public participation can take many forms depending on the goals pursued, the scope, participants to be involved and complex local, regional and national structures (European Commission, 2003). A critical review of the methods used to implement WQMPs and further analysis of the potential contribution of participative approaches in this area are presented in Chapter 2 of this thesis. The result of this critical review strongly motivates the specific objectives and methodological choices made for the various components of this thesis.

III. Hypothesis and objectives

Both the historic context and the review of modern IWRM show that there is a need to develop and integrate knowledge acquisition processes into water-related questions. It has also been shown that it is necessary to encourage the participation of all parties involved in water resource protection and restoration. Two main issues for modern IWRM were identified: the need to obtain a reliable assessment of water quality and quantity through WQMPs; the need to encourage stakeholder involvement and identify the scale of the territories to be targeted. Combining WQMPs and stakeholder involvement will contribute to understanding the stakes of water resource management and prove instrumental in joint decision making to protect and restore water resources.

In line with this reflection, the following research hypotheses are proposed for this thesis:

(1) Existing approaches to develop WQMPs are inadequate for the real-world contexts of IWRM and do not sufficiently address all the issues related to planning, managing and optimizing WQMPs.

(2) Using an IDSS to plan and optimize a WQMP combined with the participative approach facilitates the planning and optimization of WQMPs in line with local or regional needs, resources and WQMP planning issues.

(3) Using a participative approach to prompt stakeholders to voice their knowledge needs on water quality and quantity within a watershed is useful in identifying monitoring objectives more representative of these issues within a given watershed than those proposed in the literature and obtained through the collaboration of experts alone.

(4) Using an IDSS combined with a participative approach to optimize a WQMP results in a WQMP which is more representative of local or regional needs, resources and WQMP optimizing issues than a standard optimizing method.

(5) Using an IDSS that considers expert knowledge, as well as information from the literature, yields WQMPs for which the decision-making processes are more transparent and for which knowledge (from both the literature and from subject matter experts) and decisions are transferable over time and space.

The principal objective of this thesis is to develop an Intelligent Decision-Support System (IDSS) to plan, manage and optimize water quality monitoring strategies integrating participative approaches. More specifically, the objectives are to:

(1) Design the conceptual model of the IDSS based on a literature review and subject matter expert knowledge;

(2) Develop a participative approach to determine knowledge needs on quality and tap into local knowledge required for water quality monitoring programs;
(3) Test both the IDSS and the participative approach in real watershed case studies.

The chapters of this thesis are written in the form of scientific papers (published, submitted, or to be submitted, to scientific journals). The first paper, Chapter 1, presents a critical literature review of WQMP planning and optimization methods. The second paper, Chapter 2, explains the work carried out to develop and test a participative approach to determine knowledge regarding water quality and quantity issues. The third paper, Chapter 3, details the development of the IDSS. Finally, the fourth paper, Chapter 4, demonstrates how the results from the participative approach to determine knowledge needs drive the IDSS and how the IDSS can be used to optimize WQMPs.

The titles of the chapters read as follows:

1. Chapter 1: WATER QUALITY MONITORING STRATEGIES - A REVIEW AND FUTURE PERSPECTIVES (PUBLISHED)

2. Chapter 2: PARTICIPATIVE APPROACH TO RETRIEVE WATER QUALITY MONITORING NEEDS FROM STAKEHOLDER GROUPS – AN APPLICATION OF INTEGRATED WATERSHED MANAGEMENT (SUBMITTED – UNDER REVIEW)

3. Chapter 3: INTELLIGENT DECISION-SUPPORT SYSTEM TO PLAN, MANAGE AND OPTIMIZE WATER QUALITY MONITORING PROGRAMS: DESIGN OF A CONCEPTUAL FRAMEWORK (SUBMITTED – UNDER REVIEW)

4. Chapter 4: OPTIMIZATION OF SURFACE WATER MONITORING PROGRAMS USING A PARTICIPATIVE APPROACH AND AN INTELLIGENT DECISION SUPPORT SYSTEM (SUBMITTED-UNDER REVIEW).

IV. Thesis methodology in brief

For each of the four papers, a detailed methodology is provided. Here, only an overview of the methodological aspects of the thesis components is provided.

To develop the conceptual model of an IDSS to assist watershed managers in the planning, management and optimization of WQMPs, an iterative design method inspired by the Agile development concepts was chosen. Agile development concepts are used to build software systems through constant interaction with end users and by implementing components of the system progressively rather than designing a system based on a large and detailed requirement analysis at the outset of the project and then implementing the system in its globality (Schön et al., 2016). The advantage of the Agile method is that it keeps the risks scalable and provides users with a set of implemented elements of the system that they can understand, test and provide feedback on during the entire process (Beck et al., 2001).

The aim was to integrate knowledge from the literature and subject matter experts into the IDSS. Therefore, first a literature review of more than 100 papers, handbooks and guidelines was conducted (Chapter 1). Thirty-four papers of this literature review were analyzed in depth based on the information and decision support they would provide to the main use cases identified during this literature review: *Delimit a watershed (territory) subject to the WQMP*; *Define monitoring objectives*; *Classify waterbodies*; *Establish a sampling site network*; *Select water quality parameters*; *Establish sampling frequency and recurrence*; *Plan field work*; *Plan quality control and assessment*; *Establish communication channels within the WQMP*; *Establish communication channels for the information produced by the WQMP*; *Prepare data handling, storage and reporting*; and *Evaluate resource needs*.

In order to close the gaps in information and decision support identified through the literature review, a series of interviews with 44 water quality experts from Canada, the United States, Germany, France, Switzerland and Spain were conducted. To ensure that the IDSS would ultimately respond to the end users' needs, the potential end users from the two watershed case studies were consulted throughout the process and provided with implemented elements of the IDSS to be tested. The collaboration culminated with a lengthy workshop to identify the end users' needs, including all type of users within these organizations (e.g., administrator, field technician, WQMP manager). The conceptual model is described mainly in the Unified Modeling Language (UML). The sequence of operations performed by the system (use cases) and related deliverables (use-case scenarios, libraries, decision-support trees, etc.) are described according to the concepts of agile development and Use Case 2.0. (Jacobson et al., 2016) (Chapter 3 and Appendix A).

The participative approach that was developed to identify all concerns and knowledge needs in the territory subject to a WQMP first proposes two steps in the preparation of the participative approach which can be adapted to local and regional needs. These steps include a stakeholder analysis through workshops, as well as the preparation, testing and communication of an on-line survey featuring an interactive map. The participative approach was tested on two watershed case studies of the province of Quebec, the Saint-Charles river watershed north of Quebec City (W1) and the Rivière du Nord river watershed northeast from the city of Montreal (W2). The target groups of the participative approach included citizens and representatives of organized stakeholders (ROS) identified through the stakeholder analysis. Subsequently, the results of the participative approach were submitted to a statistical analysis of the results based on specific goals (e.g., eliciting knowledge needs and concerns, as well as preferred communication means). The results were then presented to ROS and citizens who evinced interest in participation through the survey. Members of the organizations in charge of the WQMPs of the two case studies were also present at these workshops. The aim of these workshops was to assess the achievement of past monitoring objectives and identify future objectives and needs of the local WQMPs, taking into account the results of the survey. Finally, the results of this process led to a list of optimization objectives and new monitoring objectives for which priorities were established with the respective WQMP managers of the two case studies (Chapter 2).

Finally, the IDSS was tested on the two case studies, W1 and W2. Some of the optimization objectives determined through the participative approach were selected to test the IDSS. Then, some of the features of the IDSS were tested. These features included some that had been implemented and some not yet implemented. The testing included verifying the decision support provided by the IDSS to: understand the existing WQMP; onboard the data and information related to these WQMPs into the data base Enki™ connected to the IDSS (Enki™ was developed in earlier work (Behmel, 2010)); use the IDSS to select optimization methods provided in the literature; use the IDSS to provide decision support during the application of these optimization methods; and finally, to provide decision support to analyze the results of these optimization methods and final expert (IDSS) decision support to come to a final, and transparent, decision for the optimized WQMPs (Chapter 4).

V. Authors' contribution to the papers

The content of this thesis is an original idea of the author, Sonja BEHMEL. All four papers in this thesis were written by the same four authors in the following order: BEHMEL, Sonja; DAMOUR, Mathieu; LUDWIG, Ralf and Manuel RODRIGUEZ. The idea to develop and test both the IDSS and the participative approach is issued from the earlier work and experience of Sonja BEHMEL in the field of water quality monitoring and IWRM. Thus, the work presented in all four papers in this thesis is essentially proposed, executed and written by Sonja BEHMEL. Manuel Rodriguez, being the director of the thesis, contributed significantly to the work through discussions, critical review, editing and providing the necessary resources to the completion of the papers and the thesis. Ralf Ludwig, co-director of the thesis, also contributed through critical review, editing and discussions. He also provided the opportunity of an internship in Germany where he introduced Sonja Behmel to several subject matter experts on WQMPs for the interviews (third paper). Mathieu Damour contributed significantly to each of the papers through his expertise on statistical methods and on their application. Every section of the four papers relating to statistics was realized in many hours of joint discussions as to the specific needs relating to the papers. The execution of the statistical analysis in the second and fourth paper is attributed to Mathieu Damour. He was also key to explaining the rationale of the statistical methods and contributed markedly to the analysis of the results and to the thesis author's learning curve on statistics.

1. CHAPTER 1: Water quality monitoring strategies - a review and future perspectives

Stratégies de suivi de la qualité de l'eau – revue de la littérature et perspectives d'avenir

Résumé. Il est primordial d'obtenir une évaluation fiable de la qualité de l'eau au moyen d'un programme de suivi de la qualité de l'eau (PSQE) afin de permettre aux décideurs de comprendre, d'interpréter et d'utiliser cette information comme fondement de leurs actions qui visent à protéger la ressource. Depuis les années 1940, le défi que pose le suivi de la qualité de l'eau a été amplement abordé dans la littérature. Toutefois, il n'existe à ce jour aucune stratégie pratique, holistique et généralement reconnue sur laquelle fonder chacune des étapes d'un PSQE. L'objectif de cet article est de faire un compte rendu des cas d'utilisation que doit aborder le gestionnaire d'un bassin versant en vue de concevoir ou d'optimiser un PSQE, et ce, du défi que posent la définition des objectifs de suivi, le choix des sites d'échantillonnage et des paramètres de qualité d'eau ainsi que la définition de la fréquence d'échantillonnage, à la prise en compte de la logistique et des ressources, en passant par la mise en œuvre d'actions basées sur l'information recueillie au moyen du PSQE. Une recension des écrits et une critique de l'information, des approches et des outils à la disposition des gestionnaires de bassins versants ont été proposées afin d'évaluer la manière dont l'information existante peut être intégrée à une solution holistique, évolutive et facile à utiliser. En raison des différences entre les exigences réglementaires, les normes relatives à la qualité de l'eau, les contextes géographiques et géologiques, l'occupation des sols et les autres particularités de chaque site, il est impossible de fournir une solution universelle. Cependant, nous soumettons l'hypothèse qu'un système intelligent d'aide à la décision (SIAD) basé sur les connaissances d'experts qui intégrerait les approches existantes et les études antérieures pourrait, en fonction des exigences particulières du site, guider le gestionnaire d'un bassin versant tout au long du processus. Par ailleurs, il est essentiel de puiser dans les connaissances locales pour déterminer les besoins en connaissances de tous les intervenants au moyen d'une approche participative fondée sur des systèmes d'information géographique et des questionnaires de sondage adaptables. Nous croyons que de futures études devraient se pencher sur le développement de telles approches participatives ainsi que sur l'examen plus approfondi des avantages qu'offre un SIAD pouvant être rapidement mis à jour et permettant au gestionnaire d'un bassin versant d'obtenir, en temps opportun, un point de vue global ainsi que de l'aide concernant tous les aspects de la conception et de l'optimisation d'un PSQE.

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 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.

Keywords: *Water quality monitoring programs; intelligent decision support system; participative approaches*

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.*

1.1. 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 B.C (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 (Government of 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 (Government of 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 (Government of 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

1.2. 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.

1.2.1. 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 and GOOGLE 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.

1.2.2. 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. Figure 1.1 shows a comprehensive diagram of the use cases on which the search was based.

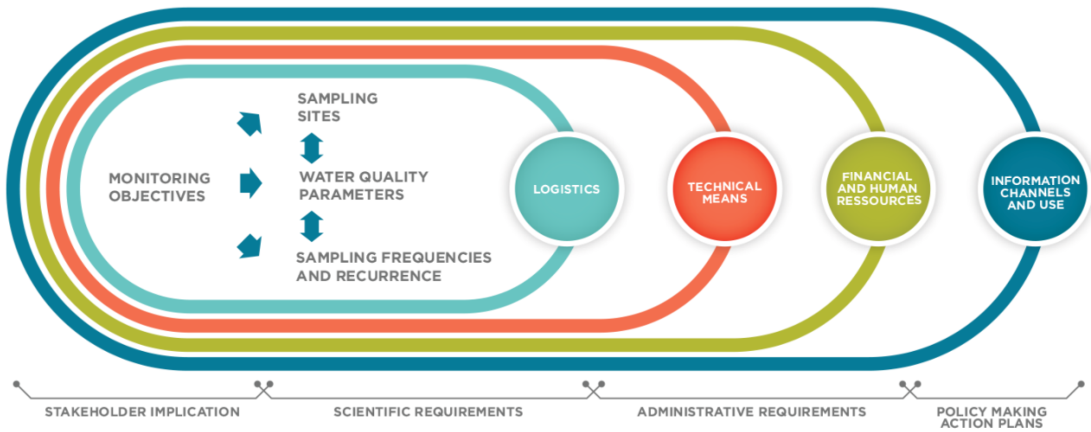

Figure 1. 1*: Comprehensive diagram of use cases which need to be addressed when planning or optimizing a WQMP.*

1.2.3. 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.

1.3. Results

1.3.1. 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 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 1.1 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 Figure 1.1 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).

Table 1. 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 J. and R. 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"	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

Use case	Planning Purpose and main sequence of actions and interactions	Optimizing Purpose and main sequence of actions and interactions
	(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)	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;**	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 from	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

Use case	Planning Purpose and main sequence of actions and interactions	Optimizing Purpose and main sequence of actions and interactions
Madrid and Zayas, 2007; Ward et al., 1990)	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 J. and R. Ballance, 1996; Chapman, 1996;**	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)	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

Use case	Planning Purpose and main sequence of actions and interactions	Optimizing Purpose and main sequence of actions and interactions
Fölster et al., 2014; Timmerman et al., 2010; Ward et al., 1990; Yang et al., 2008)	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	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	Evaluating human resources needs is essential in order to ensure that	Assessment of human resources is necessary in order to verify

Use case	Planning Purpose and main sequence of actions and interactions	Optimizing Purpose and main sequence of actions and interactions
resources **Note: Some authors argue that the involvement of volunteers in monitoring activities is not only a means of reducing costs, but also a 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 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 • 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	whether the human resources • were adequate to fulfill the tasks • needed more training • 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 J. and R. 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)	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

Use case	Planning Purpose and main sequence of actions and interactions	Optimizing Purpose and main sequence of actions and interactions
	• 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	• 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 J. and R.**	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	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

Use case	Planning Purpose and main sequence of actions and interactions	Optimizing Purpose and main sequence of actions and interactions
Ballance, 1996; CCME, 2015; Davies-Colley et al., 2011; USEPA, 2001)	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 • 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	• 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 • 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 downstream 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	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

Use case	Planning Purpose and main sequence of actions and interactions	Optimizing Purpose and main sequence of actions and interactions
	flexibility in the calendar (e.g., dispersion, transport time, nutrient load calculation, river flow) (Horowitz, 2013) (also see correspondent use case)	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)**	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	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

Use case	Planning Purpose and main sequence of actions and interactions	Optimizing Purpose and main sequence of actions and interactions
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)**	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) • 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	• 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)

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.

1.3.2. 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 1.1 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 Figure 1.2. The use cases split up for this figure are grouped in the corresponding boxes.

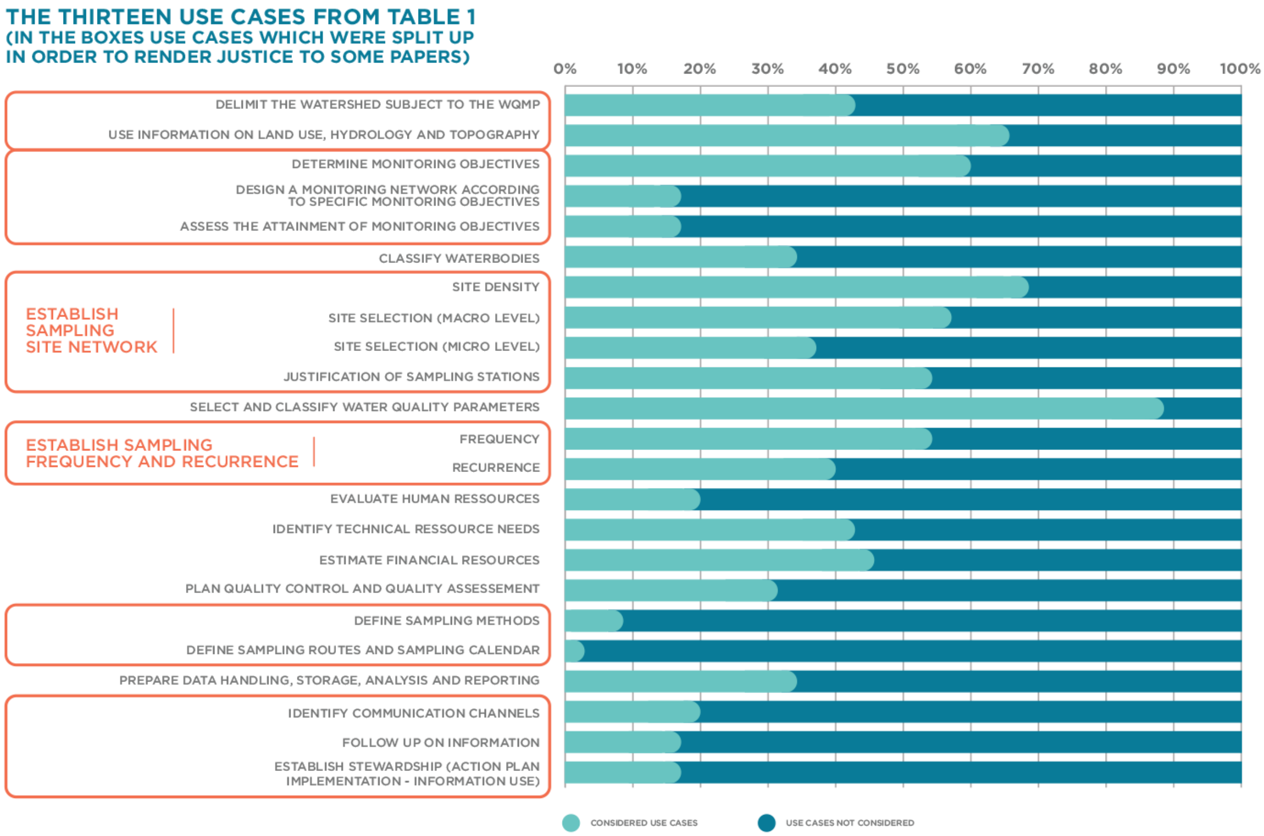

Figure 1. 2: Percentage of papers that considered the use case, as opposed to the percentage of papers that did not. To facilitate the presentation, we summarized the categories “yes”, “+”, “++” and “+++” into the category “considered use case”, as opposed to the category “use case not”. The boxes that group together some of the use cases are use cases split apart from those considered in Table 1.1 in order to do justice to some of the authors.

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 1.2. 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 Figure 1.2 and Table 1.2) 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.

Table 1. 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.

Author /year	Main contributions – Comments
(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 ISO-guides 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 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

Author /year	Main contributions – Comments
	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

Author /year	Main contributions – Comments
	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. 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

Author /year	Main contributions – Comments
	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 Kaluarachch, 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.

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 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.

1.3.3. Degree of Transferability of Existing Approaches

From the papers presented in Table 1.2, 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 and 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 1.3. 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 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.

Table 1. 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)	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
	Principal Factor Analysis (PFA)						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	ArcView 3.2	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	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.*
	Genetic algorithm	Visual C++ and Galib			05		
(Khalil et al., 2010)	Correlation analysis	Not reported	Q mode matrix: sites *vs.* WQPs	Optimize: Identify WQPs to be sampled continuously and other where the	03	Transferable to WQMPs with a large amount of variables and	Authors indicate that their approach provides a useful decision support tool for the optimized selection of water quality variables.
	Clustering analysis						

Author /year	Statistical technique	Statistical software	Data category*	Objective	Relative difficulty of application /5	Transferability	Attainment of objectives and *Comments*
				sampling frequency could be reduced or discontinued		data sets	*Import of data (e.g., selection of data used for the analysis) can be subject of subjectivity.*
	Maintenance of Variance (MOVE) record-extension			Reconstitution of discontinued variables	05		
(Noori et al., 2010)	Principal Component Analysis (PCA)	Not reported	Q mode matrix: sites *vs.* WQPs	Optimize: determine important monitoring sites and WQPs	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.
	Canonical Correlation Analysis (CCA)			Optimize: explore relationship between physical and chemical parameters	04		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 et al., 2011)	Correlation analysis	Excel, Minitab, SPSS	Q mode matrix: sites *vs.* WQPs	Optimize: Identify key WQPs which impact river health	03	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
	Factor Analysis (PCA based)				04		
(Khalil, et al., 2011)	Regression Analysis	Not reported	Q mode matrix: site *vs.* WQPs	Reconstitute information about water quality variables at discontinued locations	03	These different tools provide a way to reconstruct datasets that	In this case study, MOVE 3 technique shows better performance in preserving the statistical characteristics of the water quality records.
	Artificial Neural Network				05		

Author /year	Statistical technique	Statistical software	Data category*	Objective	Relative difficulty of application /5	Transferability	Attainment of objectives and *Comments*
	Maintenance of Variance (MOVE) record-extension				05	have been discontinued	*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 sampling sites in a Lake in order to reduce the number of sampling sites	04	Easily transferable to other datasets and other WQPs	The authors succeeded in removing up to four stations within each cluster without 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.*
	Kriging				04		
	Moran's Indice				04		
(Chen et al., 2012)	Matter-element analysis	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*
	Numerical 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	SAS	Q mode matrix: sites *vs.*	Optimize: assess the impact of sub-sampling on the	04	Easily transferable to assess the	Monthly sampling can be reduced to annual sampling without affecting the long-term trend.

Author /year	Statistical technique	Statistical software	Data category*	Objective	Relative difficulty of application /5	Transferability	Attainment of objectives and *Comments*
	model		WQPs	mean and standard-error		impact of changes in sampling frequency	*Decreasing the sampling effort may increase the incertitude for the estimator of concentrations*

1.4. Discussion and future perspectives

1.4.1. 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.(1986) were concerned 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.

1.4.2. 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 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 (Aquila 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.

1.5. 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, 2000 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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Transition between chapter 1 and chapter 2

The results of the literature review showed that precise monitoring objectives are crucial to planning and optimizing WQMPs. However, due to a lack of stakeholder inclusion in identifying monitoring objectives, WQMPs produce information on water quality that does not encourage stakeholders to participate actively in IWRM and source water protection. Some authors propose participative approaches to obtain monitoring objectives and assess the attainment of monitoring objectives. However, to our knowledge, these approaches are only destined for water “players”, namely persons already involved in the water sector. Therefore, the knowledge needs are not representative of citizens and of a variety of ROS needs (e.g., industry, agriculture, lake associations, and government entities). Therefore, it was proposed to develop a participative approach to prompt knowledge needs at a broader level and include citizens and ROS. In addition, a user-friendly public participative geographical information system (PPGIS) connected to the IDSS/Enki™ was developed and implemented in order to be able to tap into local knowledge The next chapter describes the specific objectives pursued during the development of this participative approach. The proposed participative approach was tested on the two case studies in the province of Quebec, Canada: the watershed of the Saint-Charles river north of the city of Quebec (W1) and the watershed of Rivière du Nord, north-east of the city of Montreal (W2). The results of these tests are also provided in the following chapter.

2. CHAPTER 2: Participative approach to elicit water quality monitoring needs from stakeholder groups – an Application of Integrated Watershed Management

Approche participative visant à connaître les besoins de groupes d'intervenants en matière de suivi de la qualité de l'eau – une application de la gestion par bassin versant

Résumé. Les programmes de suivi de la qualité de l'eau (PSQE) doivent être basés sur des objectifs de suivi qui découlent des besoins réels en matière de connaissances de tous les intervenants d'un bassin versant ainsi que de tous les utilisateurs de la ressource. Cet article propose une approche participative qui consiste à déterminer les besoins en matière de connaissances des citoyens et des représentants d'organismes, ainsi que les modes de communications qu'ils privilégient lorsqu'il est question de qualité et de quantité d'eau. L'approche participative compte six étapes qui peuvent être adaptées et transposées à différents types de bassins versants. Les étapes sont les suivantes : (1) réaliser une analyse des intervenants; (2) mener un sondage adaptable associé à un système d'information géographique pour la participation publique (SIGPP); (3) organiser des ateliers pour rencontrer les représentants d'organismes afin de les informer des résultats du sondage et du SIGPP, de discuter de l'atteinte des objectifs de suivi par le passé et d'échanger sur les nouveaux besoins en matière de connaissances et les nouvelles préoccupations liées à la qualité et à la quantité de l'eau; (4) rencontrer les citoyens pour obtenir le même type de renseignements (que ceux obtenus de la part des responsables d'organismes); (5) analyser les données et l'information recueillie afin de définir les nouveaux besoins en matière de connaissances et les modes de communication privilégiés; et (6) déterminer, en collaboration avec les personnes responsables des PSQE, les objectifs de suivi à court, à moyen et à long terme ainsi que les stratégies de communication à employer. L'approche participative a été testée dans deux bassins versants différents du Québec, au Canada. Il en est ressorti une série d'objectifs d'optimisation des PSQE existants, de nouveaux objectifs de suivi ainsi que des recommandations relatives aux stratégies de communication des résultats des PSQE. Les résultats de cette étude démontrent que la méthodologie proposée a plu à toutes les parties prenantes et que les objectifs de suivi qui en ressortent sont acceptables. Nous en concluons aussi que l'échelle constitue la clé du succès en matière de gestion par bassin versant, dont chaque aspect doit être adapté aux bassins versants de surface, aux bassins versants souterrains (aquifères) et aux zones de chalandise.

Abstract. Water quality monitoring programs (WQMPs) must be based on monitoring objectives originating from the real knowledge needs of all stakeholders in a watershed and users of the resource. This paper proposes a participative approach to elicit knowledge needs and preferred modes of communication from citizens and representatives of organized stakeholders (ROS) on water quality and quantity issues. The participative approach includes six steps and is adaptable and transferable to different types of watersheds. These steps are: (1) perform a stakeholder analysis; (2) conduct an adaptable survey accompanied by a user-friendly public participation geographical information system (PPGIS); (3) hold workshops to meet with ROS to inform them of the results of the survey and PPGIS; discuss attainment of past monitoring objectives; exchange views on new knowledge needs and concerns on water quality and quantity; (4) meet with citizens to obtain the same type of input (as from ROS); (5) analyze the data and information collected to identify new knowledge needs and modes of communication and (6) identify, in collaboration with the individuals in charge of the WQMPs, the short-, medium- and long-term monitoring objectives and communication strategies to be pursued. The participative approach was tested on two distinct watersheds in the province of Quebec, Canada. It resulted in a series of optimization objectives of the existing WQMPs, new monitoring objectives and recommendations regarding communication strategies of the WQMPs' results. The results of this study show that the proposed methodology is appreciated by all parties and that the outcomes and monitoring objectives are acceptable. We also conclude that successful integrated watershed management is a question of scale, and that every aspect of integrated watershed management needs to be adapted to the surface watershed, the groundwater watershed (aquifers) and the human catchment area.

Abbreviations:

Abrinord *– Organisme de bassin versant de la rivière du Nord;* ***APEL*** *– Association pour la protection de l'environnement du lac Saint-Charles et des Marais du Nord;* ***IDSS*** *– Intelligent decision support system;* ***IWM*** *– Integrated watershed management;* ***PPGIS*** *– Public participation geographical information system;* ***ROS*** *– Representatives of organized stakeholders;* ***W1*** *– Watershed 1 = Watershed of the Saint-Charles river;* ***W2*** *– Watershed 2 = Watershed of the rivière du Nord;* ***WQMP*** *- Water quality monitoring program*

Key words: *Water quality monitoring; monitoring objectives; participative approach; watershed management; scale*

2.1. Introduction

Because declining water quality (WQ) has become a global issue of concern, many countries have begun to remodel water governance towards sustainable development through an integrated approach, as recommended in 1992's Agenda 21 (Browner, 1996; UNEP, 2012). This approach is generally referred to as Integrated Watershed Management (IWM). IWM implies managing all human activities and natural resource uses in a watershed in a coordinated and sustainable manner (Conservation Ontario, 2010). The stakeholders, defined as policymakers, city planners, water conservation organizations, industry and commercial sectors of any kind, educational institutions and the general public should be part of the process in order to take joint decisions and actions to protect the resource (Bartram and Ballance, 1996; Demard, 2007; European Commission, 2003; Islam et al., 2011). Given the growing pressure on water resources, IWM is increasingly being adopted to achieve targets to prevent and manage pollution.

Some of the main challenges posed by IWM are related to a reliable assessment of water quality and quantity (lakes, rivers and groundwater) through water quality monitoring programs (WQMPs). This will allow decision makers to understand, interpret and use this information to support their management activities and involve the public in the process and implementation of WQMPs so that they can play a part of the decision making. The fundamental need for public participation and calls to develop, improve and encourage participatory practices in the context of IWM have been highlighted in several publications and are also part of the policies and regulations of many countries (De Stefano, 2010; EPA, 2014; European Commission, 2003; Mehan, 2002; Moss, 2008; Québec, 2009; Reed, 2008; ROBVQ, 2015). The generally expected benefits of involvement are to raise public awareness, gain a better acceptability of projects and actions intended to protect and improve the resource and learn from local and expert knowledge (Behmel, 2006; Behmel et al., 2016; BMVI, 2014; Reed, 2008).

However, there is neither a blueprint on public participation, nor a clear understanding of when public participation should be solicited (e.g., during the planning phase of a river restoration project; during the knowledge acquisition phase of water issues; or once the management plans are made public). Also, public participation can take many forms depending on the goals pursued, the scope, the participants involved, and on complex local, regional and national structures (European Commission, 2003). Thus, the lack of blueprints and clear guidelines for public participation in IWM leads to little use of participatory practices. Failure to use participatory practices may be specifically noted when planning and optimizing WQMPs, especially during the crucial phase of identifying monitoring objectives, often not representative of the public’s knowledge needs (Government of Australia, 2009; Bartram and Ballance, 1996; Behmel et al., 2016; Harmancioglu et al., 1999; Ning and Chang, 2002). In addition, the communication of WQMPs’ results is difficult and needs to be adapted to the audience and the audience's preferred modes of communication. Accordingly, the acceptance of management strategies based on results from WQMPs, planned without considering the public's concerns and modes of communication on water issues, is difficult (Raadgever et al., 2008; Timmerman et al., 2010). In other words, participatory practices should be adopted for every stage of IWM: the stage of identifying knowledge needs, the knowledge acquisition stage, the planning stage for best management practices and the implementation stage of these practices.

In this paper, we address the specific problem of developing and testing a participative approach to elicit knowledge and communication needs on water quality and quantity within a given watershed to plan and optimize WQMPs. The purpose of the participative approach proposed is to contribute to close the "water information gap" (Timmerman et al., 2011) defined as: "The gap of information production and decision makers' needs to take decisions on management practices and policy making" (Timmerman et al., 2011). We also aim to propose a procedure to enhance public participation for data-gathering projects to minimize future data disputes and provide an opportunity to continue developing cooperation and trust among decision makers and stakeholders based on transparency, information exchange and cooperation (Gerlak et al., 2011). Finally, we evaluate whether the proposed watershed boundaries (namely proposed spatial scales – hereafter: scale) of the two case studies lend themselves to participatory practices.

2.2. Methodology

To achieve the goal of eliciting knowledge needs and concerns and the preferred modes of communication on water quality and quantity from all stakeholders within a given watershed, we propose a participative approach that includes the following steps: (1) establish a project-based definition of participation and participants; (2) perform a stakeholder analysis; (3) conduct an online survey accompanied by a public participation geographical information system (PPGIS); (4) hold workshops to meet with water stakeholders and inform them of the results of the survey and PPGIS; discuss the attainment of past monitoring objectives; and exchange views on new knowledge needs and concerns on water quality and quantity based on the results of the survey and the PPGIS; (5) meet with citizens to obtain the same type of input (as from the representatives of organized stakeholders - ROS); (6) analyze the gathered data and information to identify new knowledge needs and modes of communication and (7) identify, with the persons in charge of the WQMPs, the short-, medium- and long-term monitoring objectives and communication strategies to be pursued. It is important to note that at the outset of this project, several discussions with the individuals in charge of the WQMPs were held in order to understand the existing WQMPs and the initial monitoring objectives (Figure 2.1).

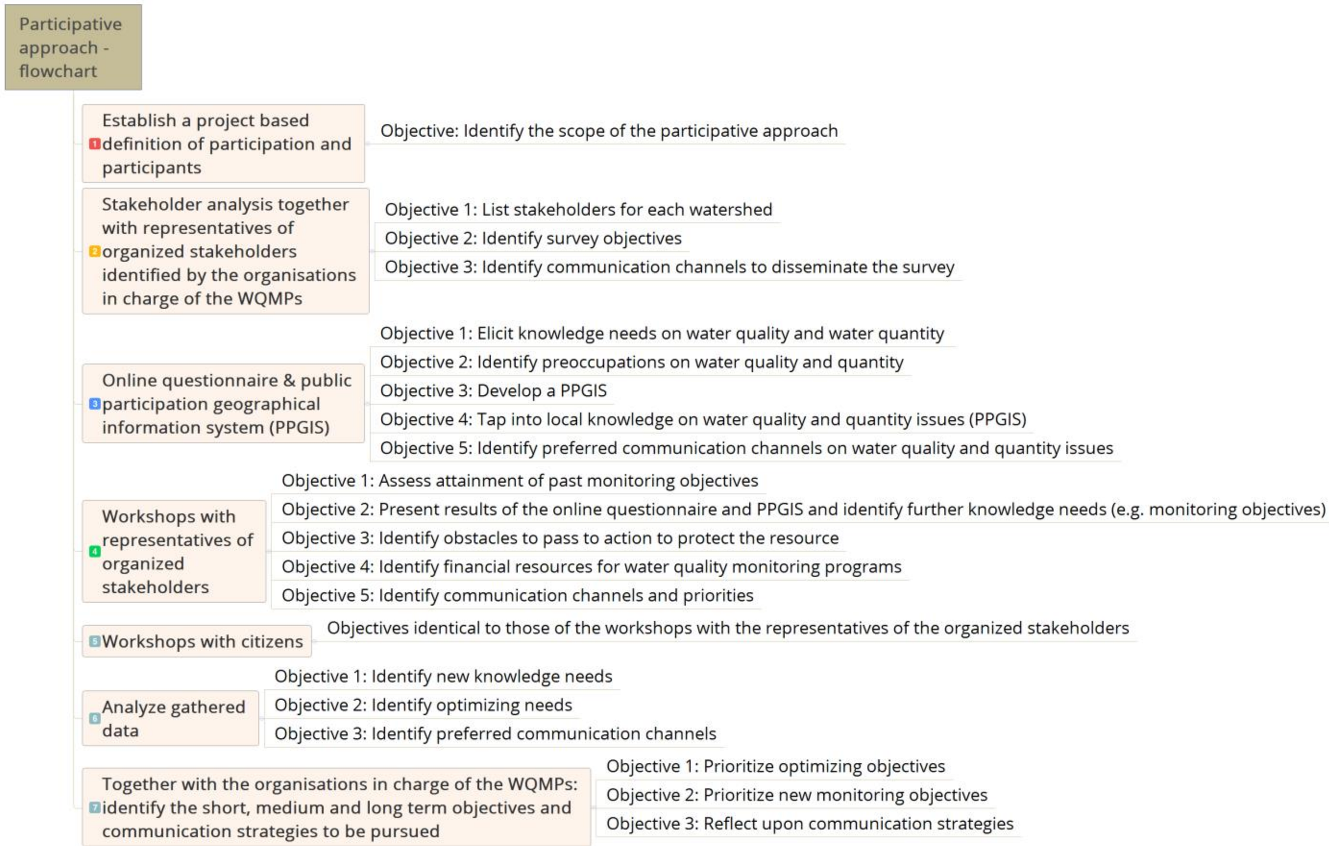

Figure 2. 1: Flowchart illustrating the steps of the participative approach, as well as the objectives of each step.

2.2.1. Project-based definition of participation and the participants

Because participatory practices must be adapted to specific goals, a project-based definition of participation and the participants must be established (De Stefano, 2010). We propose to retain the definition of public participation defined as “allowing stakeholders to influence the outcome of plans and working processes” (adapted from De Stefano 2010). This definition broadens the range of participants and limits the level of participation to inform, consult, involve and cooperate. Therefore, we chose to use the term participative approach since this term relates to participation in a more general way without making the promise of the full spectrum of public participation, which would also include “empower”. We chose not to include the latter since this would imply placing final decision making in the hands of the public (IAP2, 2014) .

Within IWM, "public" is a generic term that includes every citizen, organized or not, representing an industry or a governmental entity, etc. Therefore, everyone and every entity are considered to be stakeholders. Thus, "Stakeholders are defined as those who are affected by, or can affect, a decision" (Reed, 2008). The terms *stakeholders* and *public* could be interchangeable. However, since we wish to address the participants with regard to distinct goals and on different levels we propose the following differentiation:

- General public (hereafter: citizens): citizens living within or outside of a given delimited watershed;
- Representatives of organized stakeholders (hereafter: ROS): representatives of any kind of organization operating within or outside of a given watershed (governmental or municipal entities, non-governmental organizations (NGOs), industries, etc.);
- Stakeholders: used as a generic term for the above (citizens and ROS).

2.2.2. Case studies

Two watersheds in the province of Quebec, Canada, were selected as case studies to test the participative approach: watershed one (W1) of the Saint-Charles river north of the city of Québec and watershed two (W2) of the rivière du Nord, north-west of Montréal (Figure 2). The decision was made to run the participative approaches for both watersheds in parallel, rather than run one and then validate with a second in sequence, since it was relevant to run them in similar political and media contexts for comparison purposes. Both watersheds supply surface water for municipal drinking water plants. Water from treatment plants is intended primarily for the population living downstream from the treatment plant and outside of the watershed, while the population living upstream relies mainly on individual and collective groundwater sources. In both watersheds, the population relying on the surface water as a supply for drinking water depends on best watershed management practices outside of their area of political influence to ensure source water protection. Because of pollution sources associated with municipal wastewater, septic tanks and agricultural activities, the population upstream faces issues such as eutrophication, blue green algae blooms, salubrity of water for fishing and recreational activities and groundwater quality for consumption. The population downstream also faces safety issues (e.g., odours) and lack of access to waterbodies for first and secondary contact sports (e.g., swimming and kayaking) (Abrinord, 2012; APEL, 2009, 2014b; Ballard, 2004; Proulx, 2017).

These watersheds differ from each other in terms of size, population dynamics, geographical configuration, hydrology and land use. W1 covers about 550 km^2. The area includes nine municipalities, one military base and one First Nations reserve. W2 covers an area of 2223 km^2. The area includes 38 municipalities and a First Nations reserve. Both watersheds share one thing in common. They have complex political and administrative boundaries that complicate decision making.

For W1, an extensive WQMP for rivers and lakes was implemented in 2011 by a non-governmental organization, the *Association pour la protection de l'environnement du lac Saint-Charles et des Marais du*

Nord (APEL), financed by the city of Québec. The monitoring objectives for the WQMP were established based on consultation with some ROS, such as the city of Québec, APEL, OBV de la Capitale (watershed organization) and the Ministry of Environment (Behmel, 2010). For W2, a WQMP for rivers was implemented in 2011 by the watershed organization *Organisme de basin versant de la rivière du Nord* (Abrinord). The WQMP is collaboratively financed by the municipalities within the watershed. River monitoring planning was achieved through a roundtable including ROS, as well as experts from universities and the Ministry of the Environment. The monitoring objectives of these WQMPs may be consulted in Table 2.1).

Some of the main problems identified within both watersheds are a lack of communication, conciliation, and shared responsibilities between stakeholders, thereby revealing the need for further efforts to induce and encourage participatory practices to optimize WQMPs and modes of communication (Abrinord, 2012; OBV de la Capitale, 2015).

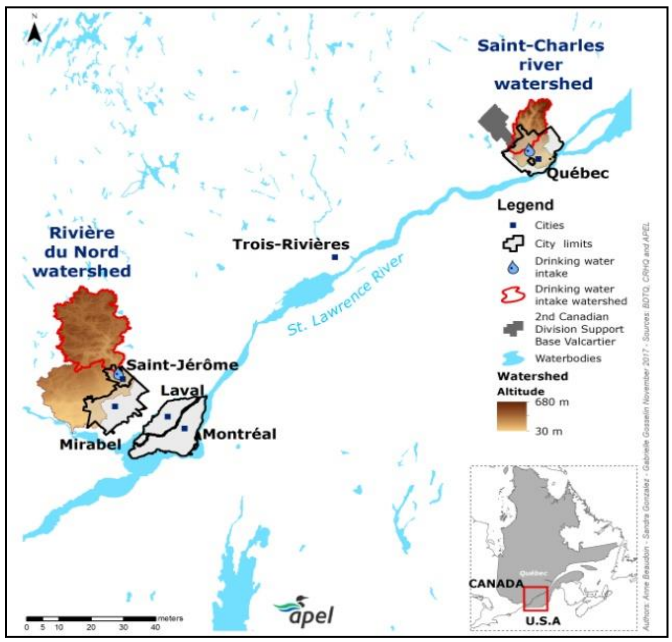

Figure 2. 2: Location of the two case study watersheds within the province of Quebec, Canada, as well as their human catchment areas (areas that use water resources from the respective watersheds): the city of Mirabel is supplied by drinking water from the city of Saint-Jerôme, citizens from the cities of Montréal and Laval who have recreational homes in the north of the rivière du Nord watershed. The city of Québec is supplied by drinking water from the Saint-Charles river watershed (main density of citizens live outside of the watershed boundaries).

2.2.3. Stakeholder analysis

For each case study, the watershed organizations (APEL and Abrinord) were asked to provide a list of ROS working in the water sector to participate in one stakeholder analysis workshop for each watershed. The objectives of these workshops were to list the stakeholders of each watershed, establish survey objectives and topics, and identify communication channels to disseminate the survey. To perform the stakeholder analysis a decision-support tree was prepared to walk the participants through the questions (Excerpt in Figure 2.3).

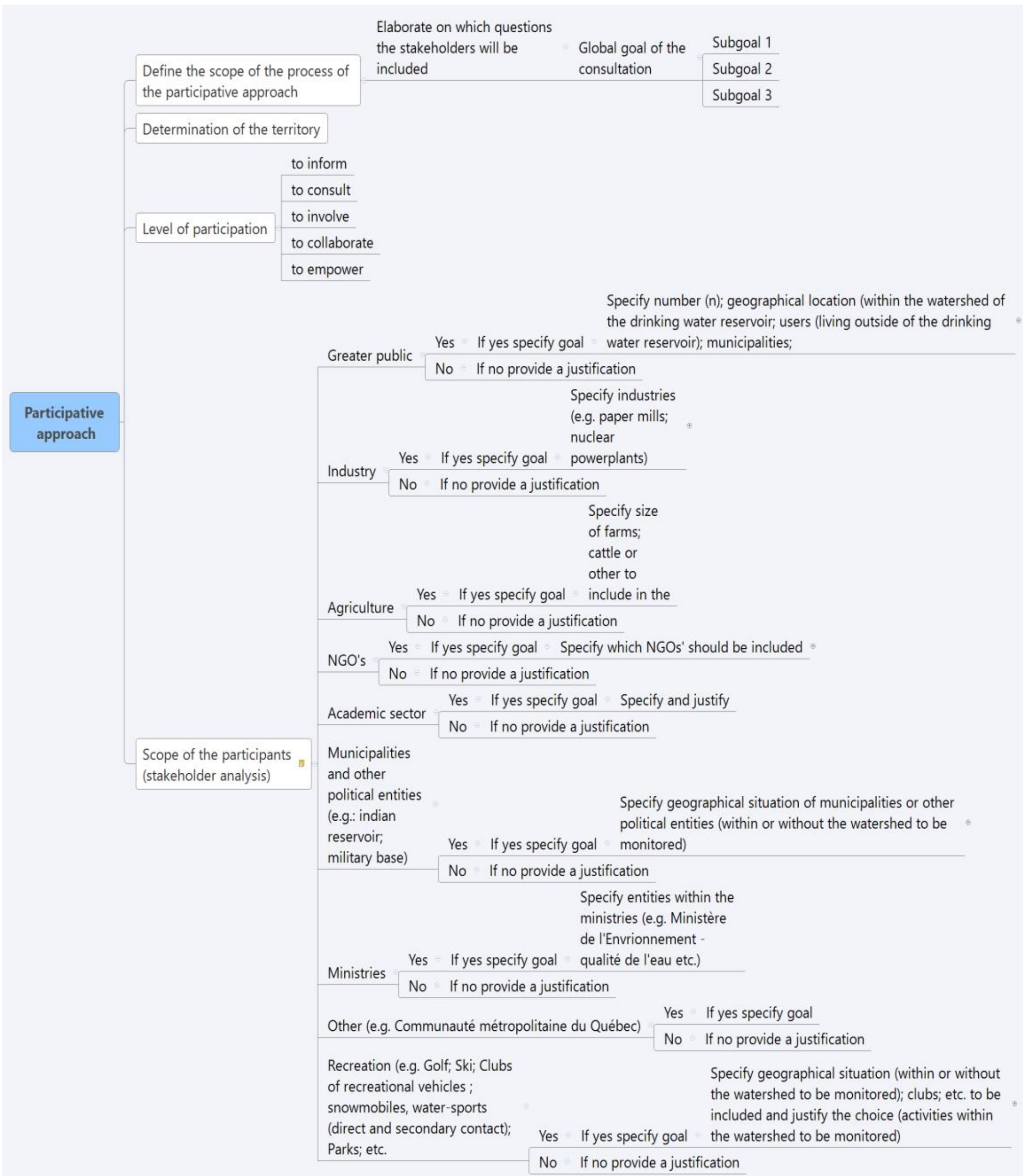

Figure 2. 3: Excerpt from the decision-support tree used during the workshops of the stakeholder analysis.

2.2.4. Online survey and public participation geographical information system

The online survey and PPGIS were built upon the input of the stakeholder analysis. The questionnaire comprised 27 questions on water quality and quantity issues (prepared with Survey Monkey®) – the questionnaire (in French) may be consulted in appendix B. At the end of the survey, a Weblink to an optional PPGIS was inserted (prepared with Enki™). In this map, respondents could identify sectors within their respective watersheds that they viewed as problematic with regards to water quality (see the proposed selections in Table 2.3). The questionnaires contained a conditional embranchment. Respondents could choose to respond as an ROS or as citizens. The questionnaires were tested by the participants in the stakeholder analysis workshops. The communication channels for each of the questionnaires were the respective websites of the watershed organizations APEL and Abrinord, social media, articles in local papers and bulletins disseminated through the Internet and hard copy. Stakeholders identified through the stakeholder analysis workshops were contacted by phone, followed by an email with a link to the online survey. The surveys were online for six month each and several reminders to respond to the survey were made throughout that period (see section 3.1 for the topics of the survey).

2.2.5. Workshops

For both watersheds, workshops with ROS were held after the online surveys were finalized. ROS were identified respectively through Abrinord and APEL. The workshops included a short presentation of the project, a presentation of the monitoring objectives of the ongoing WQMPs and the results of the survey. Then, the participants were divided into working groups to discuss the following topics: What are your concerns regarding water quality and quantity within the watershed?; Is the proposed watershed scale adequate for monitoring and best management practices?; What are the information needs to raise citizens' and decision makers' awareness on water issues, implement and reinforce regulations; validate the efficiency of actions, regulations and policies to protect the resource?; What are the information formats, channels, validations needed and what would be timely information? And who should be financing the monitoring efforts?

The same types of workshops were also held with citizens who provided their emails in the survey for W1. Abrinord preferred to invite citizens to the ROS workshop. rather than holding additional workshops with citizens only. In the analysis, we treated the results of the citizens' workshop along with the ROS workshops for W1.

2.2.6. Information analysis

2.2.6.1. Analysis of the survey and PPGIS

The surveys were analyzed on the basis of three objectives: identify respondents' preferred modes of communication; identify the main concerns regarding water quality and quantity; and explore respondents' profiles, characteristics and trends in order to be able to group them together.

To evaluate the respondents' preferred modes of communication, sunburst and alluvial diagrams were used. The sunburst diagram (Figure 2.5) positions the preferred modes of communication (centre of the sunburst diagram) into relationships with the respondents' other preferences. The least preferred mode of communication is at the outside of the diagram (Stasko et al., 2000). In the alluvial diagram (Figure 2.6 and **Erreur ! Source du renvoi introuvable.**2.6) communication preferences are ordered from the most preferred (left) to the least preferred (right). The height of the blocks shows the size of the sample in favour of a specific mode of communication while the "waves" show the size of the sample diverging from the preceding preferred mode of communication. At a glance, the alluvial diagrams show the preferred communication channels, while the sunburst diagrams illustrate the variety of communication channels consulted by the respondents.

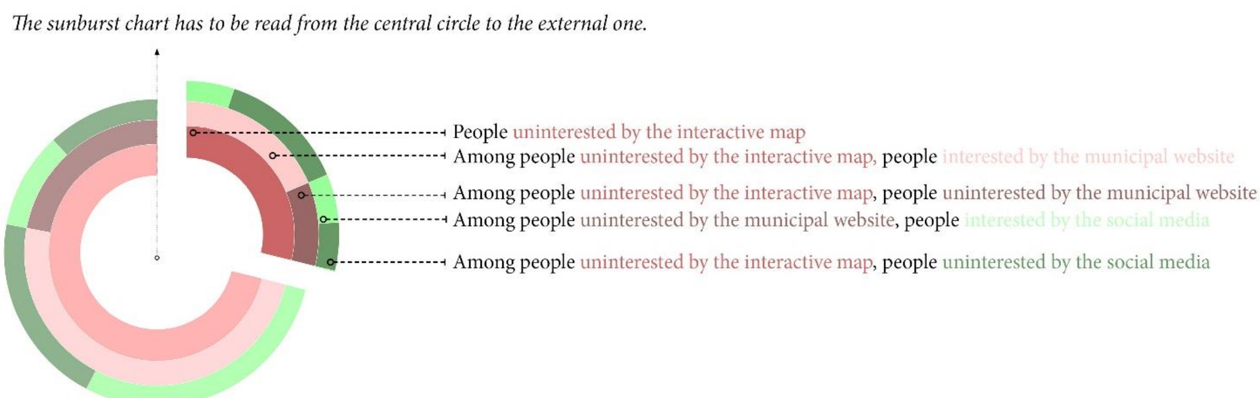

Figure 2. 4*: Example of a sunburst diagram.*

The questions on water quality and quantity concerns generally allowed the respondents to classify their concerns from "does not apply/I don't know", "not preoccupying", "a little preoccupying", "moderately preoccupying", "preoccupying" to "very preoccupying". The answers could then be transformed into a numerical interval from [0; 5] for data analysis by transcribing levels of concern from 0 (modalities "does not apply/I don't know") to 5 (modality "very preoccupying").

The data were submitted to three forms of analysis. First, the median value for each topic (type of concern) was calculated. All the answers where at least half of the values were superior or equal to 4 represent the respondents answering within the categories "preoccupying" and "very preoccupying". Not preoccupying would be all topics for which the median would be ≤ 3. This threshold represents the class "moderately preoccupying". This analysis resulted in a first general classification of the respondents' level of concern with respect to the proposed topics.

Then, in order to classify the main topics of concern, we opted to apply the Cramér's V (which highlights the relations and measures the strength of association between two qualitative variables without being able to identify the direction of the relationship) (Acock and Stavig, 1979). Cramér's V served to determine whether there was a diversification of the respondents' answers and a need to explore the heterogeneity of the respondents' answers with further analysis. As this was the case, an ascending hierarchical classification was used with the Cramér's V matrix since this analysis maximizes the homogeneity of the groups (to which point a group of respondents had the same type of answers to the topics of the questionnaire) (Saporta, 2011). Dice's coefficient was applied to the same data to identify the co-occurrence (similarity) of the respondents' answers (Dice, 1945). A hierarchical grouping analysis based on Ward's method (method that takes the similarity of group members into account when many variables are present) was performed on the Dice coefficient matrix (Saporta, 2011; Ward, 1963). The aim was to group the respondents with regard to the main topics of concern, as well as the level of concern (modality) for the topics. In addition, the linkage of the topics of concern was sought in order to find out whether respondents were concerned by the same topics and whether the level of concern was similar from topic to topic. Depending on the results, knowledge needs on the topics of concern could eventually be prioritized in the optimization of the WQMPs.

Finally, correspondence factorial analysis (CFA) was applied on the semi-quantitative data (modalities) of the survey in order to visualize the differences (and distances) between the respondents in factorial spaces. The objective was to visualize isolated respondents' concerns.

The results of the PPGIS (Figure 2.9 and Table 2.3) were classified according to the concerns identified by the respondents and the geographical distribution of these concerns. No specific association between the respondents' answers to the survey and the results of the PPGIS was sought because the PPGIS was optional. The objective of the PPGIS was to gain insight on very site-specific problems within the watersheds.

2.2.6.2. Analysis of the workshops

The analysis of the workshops was performed using the four steps proposed by (Rabiee, 2004): (1) pooling of the transcriptions and notes taken at each table; (2) categorization of the responses; (3) identification of convergence and (4) communication of the results. The results were discussed with the watershed organizations Abrinord and APEL; the final monitoring objectives and optimization needs of the existing WQMPs were stipulated.

2.3. Results and discussion

2.3.1. Stakeholder analysis

For the stakeholder analysis, eleven ROS were present for W1 and nine ROS were present for W2. For W1, ROS originated from municipalities, ministries, lake and river associations and regional organizations. For W2, ROS originated from lake and river associations, as well as from municipalities and ministries.

The workshops served to identify the objectives of the participative approach (survey and workshops); validate the territory for the dissemination of the survey; identify and justify the stakeholders to be addressed; select questions to be asked both in the general questionnaires, as well as in the follow up workshops; identify communication channels to reach out to the stakeholders and provide contact lists of stakeholders.

During both the stakeholder analysis workshops, it was proposed that survey questions address water quality and quantity concerns. It was also proposed that respondents answer questions on their water-use habits and water bodies, means they take to protect the resource, known means taken to protect the resource, their knowledge of water quality and quantity issues, their awareness of WQMPs in their area, and their water protection priorities and preferred sources of information. The precise questions set for the surveys can be consulted (in French) in the Supplementary materials. Text box 1 presents the topics identified during the stakeholder analysis. It was also suggested to provide a PPGIS where respondents could optionally point out specific areas with issues on water quality.

Respondents were surveyed on the following concerns (hereafter referred to as topics):

- insufficient water quality and quantity for drinking water supply;
- insufficient supply of water for uses other than for drinking water;
- water quality for bathing and boating activities;
- presence of cyanobacteria;
- proliferation of water plants and other algae (eutrophication);
- presence of microorganisms that may cause waterborne diseases;
- decreasing fish stocks;
- flooding;
- impact of surface and drinking water quality on property value;
- wastewater from septic installations or from municipal wastewater treatment plants;
- wastewater from industrial treatment plants;
- illicit discharges;
- fecal contamination (from farm animals, domestic animals, wild animals);
- fertilizers for farm or domestic use;
- pesticides for farm and domestic use;
- impaired water quality due to golf and skiing resorts;
- road salts;
- dust abatement products;
- erosion due to residential construction;
- erosion due to deforestation and forest roads;
- erosion due to the construction of new roads;
- lack of riparian vegetation in farm and residential areas;
- open areas and disturbed areas;
- contamination due to waste landfill sites;
- residues from drugs;
- personal care and household products.

Text box 1: Main concerns surveyed among the respondents. These concerns are referred to as topics in the analysis.

The participants of the stakeholder analysis agreed that the surveys should not be limited to the citizens and ROS living within the watersheds. It was proposed that the surveys should reach out to the communities that use the water (for consumption) and water bodies (for recreation) in the vicinity of the two watersheds in order to cover what might be termed as the “human catchment area” (defined in human geography as the area from which a city, institution, or in this case, water resources in a watershed, attracts a population that uses its services) (Figure 2.2).

In addition to the proposed list of stakeholder groups used in the decision-support tree (Figure 2.3), the participants proposed to contact stakeholder groups such as church communities (as they are important land-owners and influential in both watersheds); insurance companies and mortgagees (as they are interested in housing values linked to the water quality of waterbodies in the vicinity, water quality from private wells and risks of floods). In W2, stakeholder groups such as spa and hotel owners and ROS from the agricultural sector were also identified. The stakeholder analysis identified stakeholders who most probably would not have been invited to respond to the survey and PPGIS. In addition, the stakeholder analysis served to specify the objectives of the participative approach and the mode of communication to disseminate the survey.

The participants of the workshops for W1 were very representative of all the municipalities and organizations involved in water resource management. For W2, representation was limited with respect to municipal representation, possibly due to size of the watershed (distance to travel within a watershed of 2223 km^2) and the number of municipalities (38). However, the organizations were well represented and the municipal representatives present covered the small-and medium-sized municipalities of the watershed, as well as the largest municipality of the territory, the city of Saint-Jérôme.

2.3.2. Results of the survey and PPGIS

Altogether, 191 respondents completed the survey for W1. Of these 191, 22 respondents answered as ROS. Ninety points (90) of concern on water quality were pointed out in the PPGIS. For W2, 79 respondents completed the survey, of which 22 respondents answered as ROS. Forty-five (45) points of concern on water quality were pointed out in the PPGIS. In W2, most ROS were respondents from lake protection associations, while ROS from W1 were respondents from municipalities, universities, church communities, various NGOs, consultants and property developers.

2.3.2.1. Communication preferences of the citizens and ROS of W1 and W2

The sunburst diagrams details which respondents representing the citizens of W1 and W2 preferred given modes of communication (Figure 2.5). The alluvial diagrams illustrate the order of preference of the modes of communication for each watershed (Figure 2.6).

Citizens of W1 prefer interactive maps, followed by municipal websites, notice boards, newspaper articles and social media. However, respondents who prefer interactive maps will not automatically prefer municipal websites, notice boards and newspaper articles or social media. The least preferred modes of communication of the citizens of W1 are special bulletins and television news. Scientific papers and technical reports are of interest to some respondents.

Citizens of W2 also preferred interactive maps and municipal websites. However, the respondents diverge on their preferences, as compared to the citizens from W1 already at the second circle. For instance, those who prefer the interactive map do not prefer municipal websites in the same capacity. Of those interested in the municipal website, only about 50% are interested in notice boards. More than 66% of the respondents not interested in the interactive map are interested in information from the municipal website. More than half of these respondents do not wish to be informed through social media. Scientific papers and television news are the least preferred modes of communication.

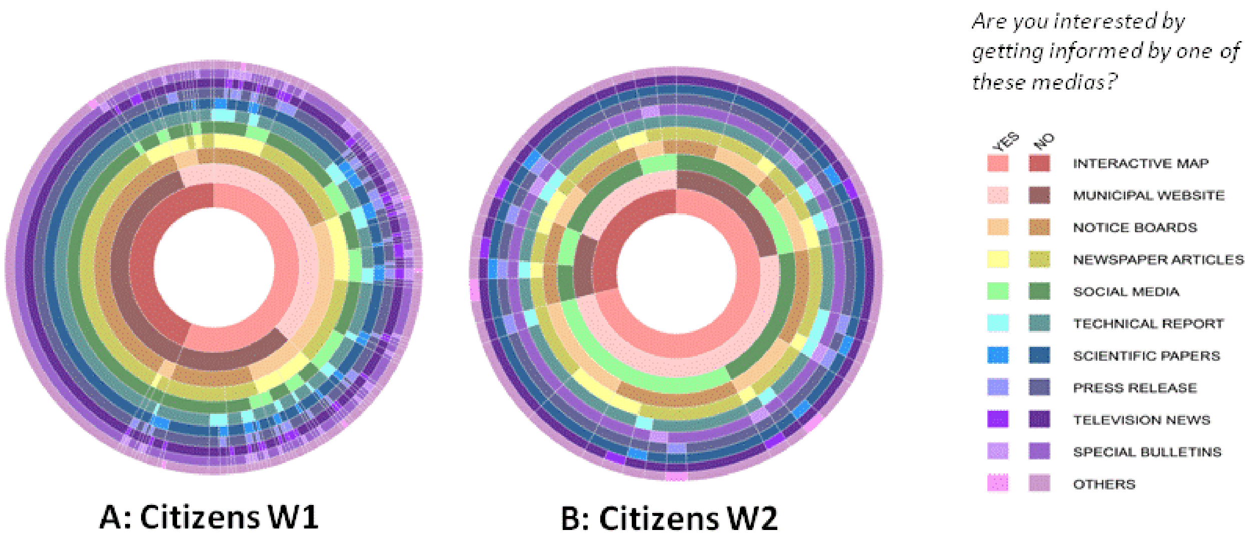

Figure 2. 5: Sunburst diagram showing the preferred modes of communication on water-related issues. A: Citizens of W1; B: citizens from W2.

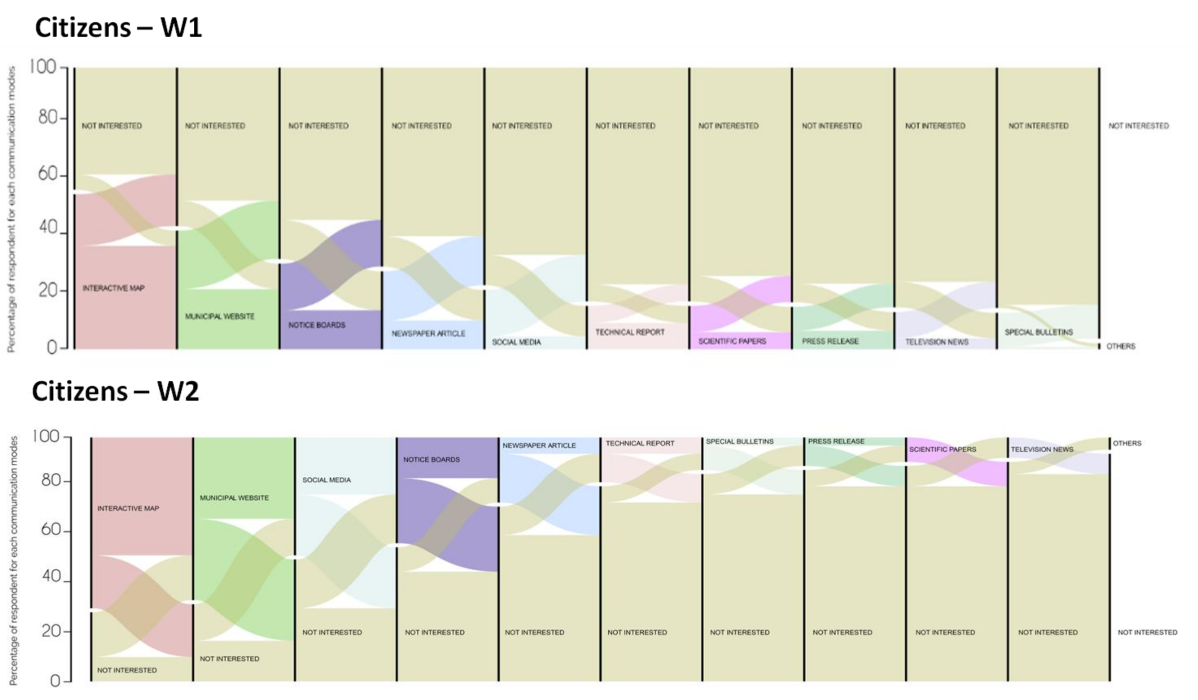

Figure 2. 6: Alluvial diagram showing the preferred modes of communication. Top (A): Citizens from W1; Bottom (B): Citizens of W2

Other modes of communication were proposed by the respondents of W1: radio news; mass communication via e-mail; SMS-alerts; social media referring to reports and scientific papers; specific bulletins for specific organizations. Reservations were expressed regarding the reliability of social media, television and newspapers and the neutrality and veracity of the information. Other modes of communication proposed by the respondents of W2 included mobile apps and information letters.

The sunburst diagrams details which respondents representing ROS of W1 and W2 preferred which modes of communication (Figure 2.7). The alluvial diagrams illustrate the order of preference of the modes of communication of ROS for each watershed (Figure 2.8).

With regard to ROS, the convergence on ROS preferences of the two watersheds ends with their preference on interactive maps. The results show that ROS of W1 prefer interactive maps, newspaper articles, scientific papers and municipal websites. However, not every respondent who prefers the interactive map will automatically prefer municipal websites or scientific papers. Television news and special bulletins are the least preferred modes of communication among those proposed in the survey. The preferred modes of communication for ROS of W2 are interactive maps, municipal websites, technical reports and notice boards. However, there is a major discrepancy in the third circle of the sunburst diagram: a little more than half of the respondents who prefer the municipal websites are not interested in technical reports. Those who prefer notice boards do not automatically prefer technical reports. The least preferred modes of communication are newspaper articles, press releases and television news (Figures 2.7 and 2.8).

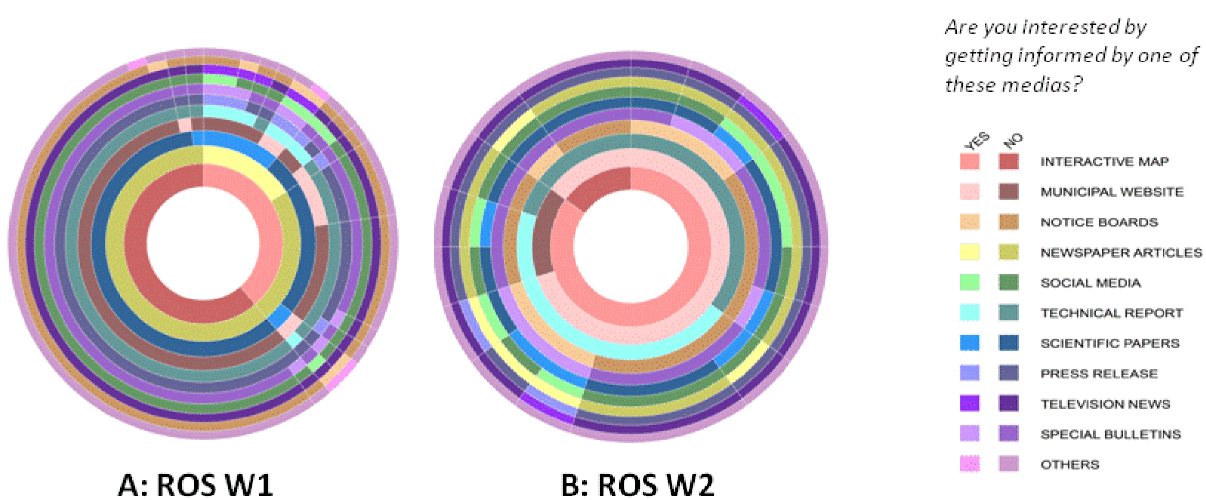

Figure 2. 7: Sunburst diagram showing the preferred modes of communication on water-related issues. A: ROS of W1; B: ROS of W2.

Figure 2. 8: Alluvial diagram showing the preferred modes of communication. Top (A): ROS from W1; Bottom (B): ROS of W2.

The results on the question on the preferred modes of communication show that preferences diverge between citizens and ROS, as well as between the watersheds. The results show that respondents use a variety of sources of information. The specific comments illustrate that this is partly due to the fact that the respondents have little confidence in some modes of communication and are likely to verify the veracity of some of the information through other sources. It has to be noted that there is limited documentation in the literature about successful communication strategies on water quality and quantity issues (Mobley et al., 2010). Yet, the analysis of the responses to this question shows that the diversification of modes of communication is crucial. Also, modes of communication must be adapted to the person(s) or organizations(s) to whom they are intended, yet not limited to one single mode of communication.

2.3.2.2. Concerns of the respondents representing the citizens from both watersheds

The results from the analysis of the surveys for the citizens of both watersheds are represented in Table 2.1. Respondents of W1 are divided into four groups. Groups 1, 2 and 3 are, respectively, very, moderately, or preoccupied by most topics. Only group 4 nuances its concern regarding the different topics. From the three groups of W2, group 1 is very preoccupied by every topic. Groups 2 and 3 from W2 are a little more nuanced regarding their level of concern (Table 2.1). Citizens from both watersheds are not preoccupied by an eventually limited supply of drinking water, in terms of either quantity or quality issues (except for some very isolated respondents). For W2 respondents, there are no isolated respondents preoccupied by these issues. Some isolated respondents from W2 are preoccupied by others concerns (unknown residues).

Table 2. 1: Results of the analysis of the surveys – citizens from both watersheds.

Type of analysis	W1 (citizens)	W2 (citizens)
Medians **Not preoccupied would be all topics for which the median would be ≤ 3.** *Only the* ***<u>non preoccupying</u>*** *topics are listed here as this list is shorter*	• Supply of drinking water (quantity – and quality); • Contaminants linked to wild animals.	• Supply of drinking water (quantity – and quality); • Contamination linked to: wild and domestic animals; • Water supply for any other use than for drinking water (e.g., industrial use and spas); • Floods.
Results based on the Ward's dendrogram build on the Dices' matrix.	***Group 1:*** • Considers almost every topic as "very preoccupying" ***Group 2:*** • Considers almost every topic as "preoccupying" ***Group 3:*** • Much more heterogeneous as to their answers as the first two groups. Generally, this group will consider the topics as "moderately preoccupying". ***Group 4:*** • Even though much more heterogeneous than groups 1-3, the respondents are generally disinterested and not concerned by any of the topics. Note: Four respondents of this group consider several topics "Very preoccupying" (salubrity of water for bathing and water sports, supply of water for uses other than drinking water and fecal coliform contamination by wild animals). These four respondents provided many "I don't know" responses on many other topics.	***Group 1:*** • Considers nearly every topic as "very preoccupying" ***Group 2:*** • Largely expresses moderate to high concern on all topics. • Three topics considered as "very preoccupying" are very closely integrated with the topics considered as "preoccupying". For instance, the very high concern for fecal contamination from wild animals is frequently and jointly expressed with moderate concerns concerning ski resorts, water supply for uses other than drinking water and for floods. These topics are linked to concerns (very preoccupied) such as drinking water supply and fecal coliform contamination from domestic animals. These are some specific concerns of some respondents, but not all the respondents, as the analysis of the median showed. ***Group 3:*** • Includes all the respondents who considered all topics as "little" to "not preoccupying". Some of the respondents had some isolated concerns (very preoccupied) on topics such as water supply for uses other than drinking water. Some respondents of this group were "moderately preoccupied" by topics such as fish stock, wastewater from wastewater treatment plants, golf

		and illicit spillage of waste. This group has influenced the topics considered as “not very preoccupying” in the analysis of the medians.
Visualisation of *__isolated respondents’ concerns__* illustrated through the CFA	Concerns are for • salubrity of water for drinking water production and water sports; • sufficient supply in quantity and quality of drinking water • sufficient supply for uses other than drinking water such as ski resorts.	Concerns are for • other (unknown) residues. Respondents are clearly **__not concerned__** by the quantity of water for drinking water supply

2.3.2.3. Concerns of ROS of both watersheds

The results from the analysis of the surveys for ROS of both watersheds are represented in Table 2.2. The groups of both watersheds are more nuanced in their concerns as citizens. The main difference between the preoccupations of ROS of the two watersheds is that ROS of W1 are preoccupied by water supply for drinking water in quantity and quality, while ROS of W2 are not.

Table 2. 2: Results of the analysis of the surveys – ROS from both watersheds.

Type of analysis	W1 (ROS)	W2 (ROS)
Medians **Not preoccupying would be all topics for which the median would be ≤ 3.** *Only the **non preoccupying** topics are listed here as this list is shorter*	• Salubrity of water for water sports and water supply for other uses (e.g., industrial) which are not for drinking water; • Fecal coliform contamination from wild animals; • Impact of drinking water quality or surface water quality on real estate value of the organization.	• Water supply for uses other than drinking water; • Drinking water supply; • Fecal coliform contamination from wild or domestic animals; • Flooding; • Fish stocks; • Dust suppressants; • Contamination of water by drug residues; • Impact of drinking or surface water quality on real estate value of the organization.
Results based on the Ward's dendrogram build on the Dices' matrix.	***Group 1:*** • Characterized by a strong co-occurrence of being "very preoccupied" by all topics. ***Group 2:*** • Characterized by some heterogeneity. Generally respondents are moderately preoccupied. Some respondents are "very preoccupied" by eutrophication and the presence of fecal coliforms. These respondents are "preoccupied" by most topics. ***Group 3:*** • Shows little or no concern on most topics with only a moderate concern for cyanobacteria. ***Groups 4 and 5:*** • Present a strong co-occurrence on modalities such as "I don't know/does not apply", while group five is closer in the co-occurrence to group six than group four. ***Group 6:***	***Group 1:*** • Respondents generally consider the topics as "very preoccupying". However, some modalities are out of this range: Fecal coliform contamination from domestic animals is considered to be only "moderately preoccupying" and water quality and quantity for drinking water supply is considered as not applicable as a concern. The same respondents who thought that drinking water supply was not applicable thought that water quality and quantity issues would have a strong impact on the property value of their organizations. ***Group 2:*** • Very heterogeneous group which generally expressed moderate to no concern on the topics. Some few respondents of this group express their high concern for fish stock and floods, as well as on water supply for uses other than for drinking water. ***Group 3:*** • Regroups the respondents who

	• Presents very heterogeneous answers which generally express little or moderate concern. Only some topics are considered "very preoccupying": impact of drinking and surface water quality on the property value of their organization, fecal coliform contamination from domestic animals, floods and erosion due to the construction of new roads. This shows that some respondents are very isolated in their classification of some topics.	are generally "moderately preoccupied" to "preoccupied" for most topics (e.g.; concerns regarding erosion, pesticides, etc.). On other topics the respondents answered that some concerns "do not apply" (e.g., salubrity for water sports; flooding, and influence of water quality on property value).
Visualisation of *isolated respondents' concerns* illustrated through the CFA	Concerns regard eutrophication and fish stock	Concerns regard floods, impact of drinking water quality on property value of their clients and their organization, fish stock, water salubrity for water sports, presence of cyanobacteria, presence of pathogenic agents

The concerns related to the various topics differ between citizens and ROS of W1. For instance, in W1, citizens are concerned by issues such as the safety of water for water sports, while ROS are not. Citizens of W1 are not concerned by drinking water supply quality and quantity, while ROS are. For W2, neither citizens nor ROS are concerned by drinking water supply quality and quantity. Generally, in W2, there are fewer concerns regarding topics such as floods and fecal coliform contamination from domestic animals than in W1. The difference in concerns regarding drinking water supply between ROS of the two watersheds may be explained by the difference in the type of respondents. In W1 watersheds, many respondents were representatives of municipalities and NGOs in charge of water supply issues, while ROS of W2 were generally representatives of lake protection associations. For the citizens of both watersheds, it was not possible to attribute topics of concern to their geographical location or other indicators on their behalf (e.g., uses of water). The difference in the perception of water quality for recreational water use is probably due to the fact that water for recreation in W2 is basically used in the north of the city of Saint-Jerôme, where lakes and rivers are generally considered as being of good water quality. However, it should be noted that there are hardly any public beaches; therefore, there is no data available to support this perception. As for the concerns regarding water quality for recreational use in W1, it is publicized by the city of Québec that the river close to the public parks and walkways is not fit for recreational use of any kind (swimming, fishing, kayaking, etc.). The PPGIS (next section) confirmed this hypothesis – the preoccupying points of water colour and odour are nearly all situated in these river sections.

2.3.2.4. Results of the PPGIS

Figure 2.9 illustrates the spatial distribution of the points identified by the respondents on the interactive map as specific points of concern, partly equipped with supplementary comments. Table 2.3 provides a portrait of the concerns. Spatial distribution shows that respondents from all over the watersheds answered. Generally, the less populated areas of the watersheds do not show any points.

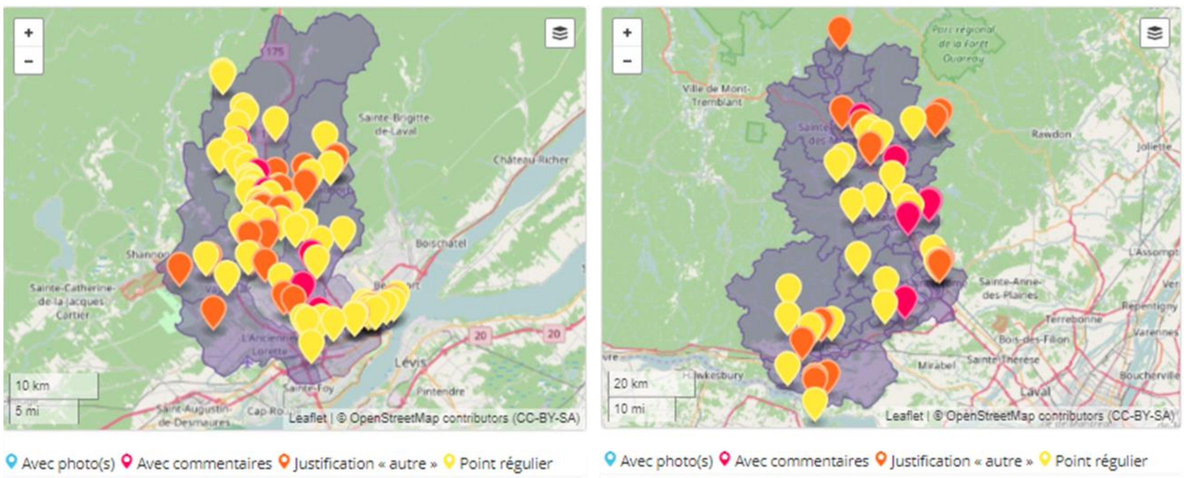

Figure 2. 9: Right: W1 (90 points from 60 respondents and 11 points with additional comments). Left: W2 (45 points from 32 respondents and 8 points with additional comments). Red and orange points: additional information was provided by the respondents; yellow points: the respondents chose one or more of the proposed topics from the list.

For each watershed, all the proposed concerns where signalled at least once. The points accompanied by comments highlighted the fact that concerns in W1 focus more on problems related to urbanization, while W2 respondents signal problems related to agriculture (in the downstream part) and residential (and recreational) development and activities in the upstream parts of the watershed (see Table 2.3 for details).

The responses to the PPGIS were optional. While not all respondents answered, others created several points on the map. Therefore, it was not possible with these results to find a correlation between respondents, their geographical location and the concerns they expressed in the survey. However, it was possible to obtain very specific areas of concern and descriptions of the problems observed. These points could be integrated into an optimized WQMP or be subject to an inspection by the watershed organization.

Table 2. 3: Breakdown of the concerns for each point indicated on the interactive map.

Description (please note that it was possible to provide 1 or more justifications per point)	**W1**	**W2**
Preoccupying water colour	12	8
Preoccupying odours of the water	6	4
Suspect pipe	10	2
Important presence of ducks (20 and more)	16	7
Recurrent presence of cyanobacteria blooms (several times per month during the summer and fall)	13	1
Proliferation of aquatic plants	13	6
Proliferation of green algae	9	3
Decrease of fish stocks	14	2
Decrease in the number of birds	5	3
Important erosion sites (within the river)	11	5
Other with comments	25	18
Other without comments	5	1
Illegal spills	Not in the list	4
Non-compliant septic installations in the vicinity		4
More water turbidity than in the preceding years		1
New residential constructions (upstream)		9
Ground water resurgence		2

2.3.3. Results of the evaluation workshops

The evaluation workshops had two objectives: (1) confront the participants with the results of the survey and PPGIS in order to obtain input from the participants on the orientation of the existing WQMPs and (2) identify the lessons learned from the results of the survey. For each watershed, the information from the discussion tables of the workshops was pooled through transcription into tables. During the transcription, the main categories of the discussions were identified. For each category, recommendations, suggestions and concerns were transcribed and converged when possible. For each workshop, the discussions could be classified into seven categories: concerns regarding water quality and quantity; monitoring needs; actions that should be taken to improve water quality; rules and regulations; financing sources both for actions and monitoring; governance and communication.

For W1, the lack of information on ground water quantity was identified as an issue, while water quantity for surface waters seemed to be sufficiently monitored. The necessity of monitoring ecological integrity was also identified. Other than that, no additional water quality parameters were suggested. However, it was proposed that the monitoring networks should be densified for sub-catchments. Some actions to improve water quality were suggested as a priority: law enforcement; improvement in wastewater treatment (individual and collective) and reduction of road salts. It was recommended that rules and regulations should be applicable to the entire watershed and not just to some lakes, municipalities or areas, as is the case now. The latter issue is also strongly related to governance issues. Indeed, it was mentioned that the organizations (NGOs and governmental institutions) do not follow the established rules of governance in this W1. While financing of the WQMP is entirely in the hands of the city of Québec, investment in actions is in the hands of each municipality. Since the city of Québec imposes rules and regulations as well as actions on their neighbouring municipalities, a severe imbalance of power in this W1 was identified. This imbalance of power is also reflected in the communication of the results of the WQMP. Results are generally first communicated to the city of Québec, and the information can only be relayed by APEL once permission has been received. Thus, a lack of transparency was identified. More localized information was also identified as necessary.

Participants of the W2 workshop were very preoccupied by the fact that neither ROS nor citizens seemed to be aware of water scarcity issues. They proposed optimizing both monitoring and communication on water quantity and quality issues for the drinking water supply. It was also clear that the existing WQMP, while responding to the initial set of objectives, needed to be optimized in order to be able to identify localized issues at the municipal or subwatershed level. In addition, more water quality parameters needed to be added to be able to follow up on road salt contamination, contaminants of emerging interest (e.g., drugs and pesticides) and nutrient loads other than phosporus. With respect to actions to improve water quality, it became clear that the issues differ so much within W2 that it was not possible to provide a detailed list of actions other than improving wastewater treatment (both from waste water treatment plants and septic installations) and addressing the issue of septic installations, starting with an inventory. It was generally accepted that rules and regulations needed to be better enforced. However, a lack of funding for sufficient municipal and provincial inspectors was identified. Issues with governance were identified which might also explain the lack of law enforcement and financing. For instance, not having a "polluter and user pays" system and the breakdown of this income to watershed organizations was considered as part of the problem (for W1). Because the municipalities pay for each of their territory's monitoring stations, it was felt that there was an appropriate breakdown of the funding of the WQMP. With respect to communication, a need for more specific and location-based information was identified. Lack of transparency was not an issue, but participants felt that monitoring results should not only be communicated, but accompanied by more specific recommendations.

For both watersheds, the workshops resulted in the following recommendations:

- information and data should be democratized;
- citizens should be continuously consulted on water quality and quantity issues through PPGIS;
- citizens should be better informed through special events in order to build trust;
- citizens should be informed through workshops and location-based information;

- media and elected representatives should be educated through the involvement of the scientific community to ensure that the scientific message is communicated correctly.

2.3.4. Retained monitoring and optimization objectives

The results of the survey, PPGIS and workshops were discussed with members of Abrinord and APEL in order to prioritize monitoring and communication objectives.

During this last phase of the participative approach, it was agreed that the W1 WQMP seemed to respond to the knowledge needs expressed during the survey and workshops. However, the WQMP must to be evaluated for efficiency (e.g., number of sampling stations and water quality parameters; sampling frequency and recurrence). New information must be acquired on the ecological integrity of the waterbodies and on contaminants of emerging interest (e.g., drug residues, pharmaceuticals). As for the communication strategy, it was agreed to extend information distribution outside of the watershed (especially to inform and educate the population of the city of Québec on issues within the watershed of their main drinking water supply and recreational activities). In addition, APEL wants to strive to optimize the communication strategy focusing on more localized information for the subwatersheds.

The results of the participative approach showed that there is a clear need for W2 to expand the existing WQMP. This was the main topic discussed with Abrinord at this final stage. While some of the expanding can take place on the global WQMP, there is also a need to apply the participative approach to subwatersheds (or on the scale of small municipalities) in order to gain an understanding of more localized knowledge needs and to implement localized WQMPs. In order to implement these monitoring activities, the participative approach tested in this paper must be adapted to these territories. Then it would be necessary to coordinate the localized WQMP with the global WQMP of Abrinord and make sure that the same protocols and, ideally, laboratories would be used. Sharing of a common database was also discussed. In addition, financing should be found at the local scale. The new monitoring objectives and optimization goals of the global W2 WQMP require the addition of water quality parameters, adding or rearranging sampling stations and the acquisition of additional information on the territory (e.g., information on roads and road types; septic installations and updates on industries within the watershed). There is also a need to calculate costs in accordance with these monitoring objectives and re-consider sampling frequency and recurrence. Monitoring of ground water through private wells would also be necessary, as well as the addition of hydrometric stations.

Both organizations decided to opt for short-term optimization of their WQMPs and set aside some knowledge needs and add-ons to their WQMPs for consideration at a later moment due to the necessity of finding additional funding, partners and laboratory capacities. The specific optimization and new monitoring objectives that emerged from these discussions can be consulted in Table 2.4.

Table 2. 4: Summary of the current and new monitoring objectives of both watersheds.

	Monitoring objectives of the current WQMPs (Behmel 2010 for W1 and Abrinord 2012 for W2)	Objectives identified through the participative approach
W1	• Improve knowledge on road salts in lakes and rivers of the watershed; • Monitor fecal coliforms to detect domestic wastewater discharges in rivers from septic installations, wastewater treatment plants and cross connected sewers; • Monitor all rivers for nutrient loads, especially affluents of lake Saint-Charles (main drinking water reservoir of city of Québec); • Monitor lake Saint-Charles and other lakes for eutrophication and cyanobacteria; • Monitor total suspended matter to detect erosion and construction sites in the watershed.	***Optimization objectives:*** • Verify whether the sampling frequency responds to the initial objectives of establishing a global picture on water quality and detect natural and human induced events; • Analyze whether the sampling stations are sufficiently distanced from each other to provide new information between each station; • Assess whether sampling frequency and network density of the WQMP could be reduced in order to be able to implement rotating and intensive monitoring for each of the seven subwatersheds; • Verify whether the existing monitoring network adequately captures problematic zones identified through a recent study on potential contamination sites and through the PPGIS. ***New monitoring objectives*** • Obtain information on the water quality of recreational activities in the urbanized area of the city of Québec (downstream from the drinking water intake); • Acquire knowledge on the status of ecological integrity (including costs and a feasibility analysis); • Carry out a cost analysis to assess whether contaminants of emerging interest in the WQMP (e.g., drug residues) can be added; • Improve coordination of surface water and groundwater monitoring.
W2	• Assess water quality for public health reasons through monitoring of fecal coliforms; • Follow nutrient concentrations in the main rivers of the watershed (total phosporus); • Follow potential erosion in the watershed (total suspended matter).	***Optimization objectives:*** • Evaluate whether the bi-monthly sampling frequency is adequate; • Verify whether existing sampling stations are sufficiently distanced from each other; ***New monitoring objectives:*** • Improve knowledge on road salts and dust suppressants; • Obtain a better picture on the impact of municipal wastewater treatment plants and septic installations; • Acquire more knowledge on pesticides, fertilizers and animal residues used in agricultural areas; • Acquire more knowledge on pesticides, herbicides and

fertilizers used on golf courses, private and public parks;
- Identify impacts of industrial waste discharges;
- Evaluate the possibility of adding hydrometric stations;
- Acquire information on groundwater quality and quantity.

2.3.5. Discussion: are participative approaches contributive to WQMPs and IWM and is scale an issue?

The stakeholder analysis showed that ROS and citizens consulted on water issues do not necessarily correspond to the individuals commonly agreed upon by ROS of the water sector. The variety of ROS proposed during the stakeholder analysis highlights the need to include many different types of ROS on water quality and quantity issues and rethink communication channels according to these ROS. The same applies to citizens. During the stakeholder analysis, it became clear that it is important to extend efforts to implement participatory practices outside of the watershed scale and include the human catchment area and groundwater watershed.

The results of the survey showed that generally speaking, citizens and ROS are aware (and concerned) by issues monitored and communicated in the past; their answers also revealed where ROS and citizens are not concerned. Some issues of non-concern (e.g., drinking water supply – quantity and quality issues for surface- and groundwater) were deemed very preoccupying to the water stakeholders of the workshops, especially for W2. It became clear through the workshops that not only concerns, but non-concerns, need to be addressed when optimizing a WQMP. The workshops also showed that survey outcomes aimed at eliciting knowledge needs on water quality and quantity must be discussed with water resource managers of the respective territories. These workshops also contributed greatly to sharing knowledge and experience between the participants.

The concluding discussions with the watershed organizations were a final and necessary step to finalize the stakeholder analysis, survey, PPGIS and workshops. These discussions served to identify the specific optimization objectives for the existing WQMPs. The points identified through the PPGIS provided additional knowledge on potential contamination sites. The points provided explanations on observed contamination, possible new sampling sites and sites to be inspected.

For communication preferences, the results suggest that diversification of the modes of communication is necessary and needs to be adapted to local issues. Generally speaking, there is a preference for interactive maps to communicate and receive information in line with the principal which might be referred to as “intelligent and learning communities”. This general preference does not exclude the fact that all other means of communication must be explored and used to their full potential. The main premises are that information must be made available, under various forms, and targeted to different scales and types of public.

In sum, the process of eliciting knowledge- and communication-mode needs must include several steps the least of which are a stakeholder analysis, a survey, a PPGIS, workshops and wrap-ups with the organizations responsible for the WQMPs. In addition, it is necessary to think in terms of scale when applying a participative approach. Scale will influence the stakeholder analysis and survey questions. The results and comments of the participants showed that for large watersheds, heterogeneous in land use and political boundaries, it would be beneficial to apply and adapt participative approaches to the global watershed and homogenous subcatchment areas. While this may seem like a huge step, stakeholder responsiveness to every step of the proposed participative approach showed that citizens and ROS wish to be consulted and informed. The process of the participative approach, as such, serves to help build trust and raise awareness on water issues.

Finally, scale seems to be an issue in IWM. The results suggest that some watersheds are too large in size and too heterogeneous for effective IWM, when considering participative approaches, effective communication, WQMPs and the implementation of management activities to protect the resource. For effective IWM, the differences in surface water watersheds, groundwater watersheds and human catchment areas need to be taken into account. Effective IWM should also take into account local homogenous areas, such as watersheds of individual lakes, areas of comparable land-use, or within political boundaries (e.g., municipal level, First Nations territories, etc.) Participative approaches, communication strategies and management activities must be adapted and applied to these scales, and not limited to either the global or localized scale. In addition, rules, regulations and governance should be less bound to the political boundaries that these scales may include. Finally, sound sources of financing and information transparency must be ensured. The integration of these different levels of scale considered in effective IWM is illustrated in Figure 2.10.

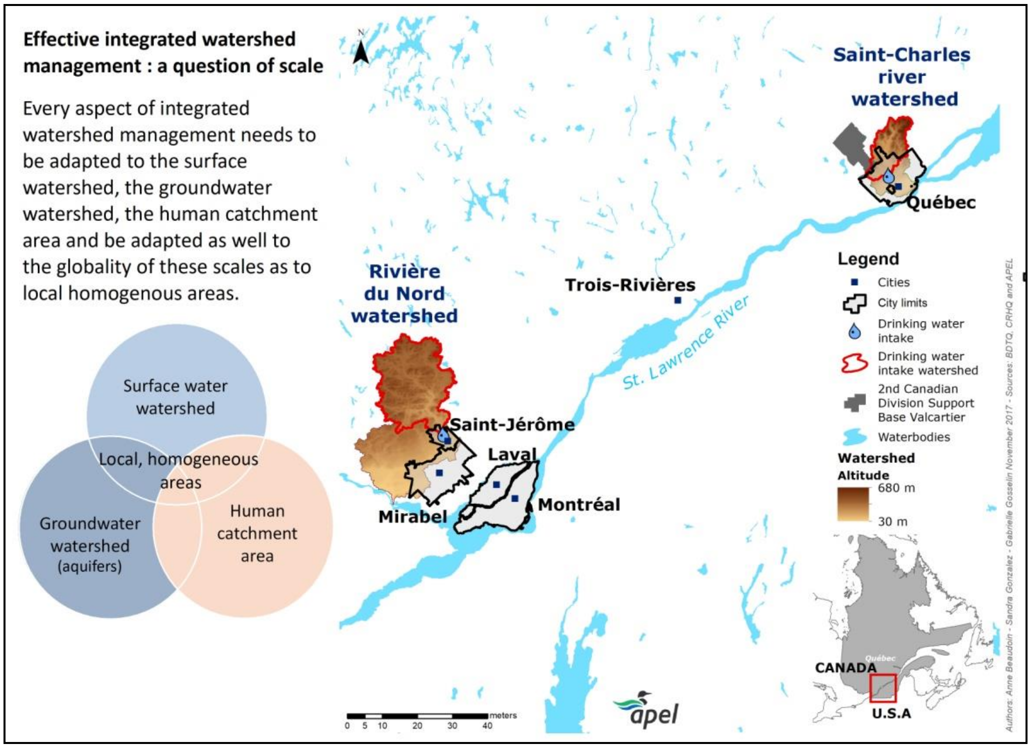

Figure 2. 10: Scales of effective integrated watershed management.

2.4. Conclusions

IWM is based on best management practices to protect and restore water resources. These management practices must be based on sound data on water quality and quantity obtained through WQMPs. For every aspect of IWM (e.g., knowledge acquisition, information dissemination, land-use planning and implementation of best management practices) public participation is necessary to obtain acceptance of the proposed strategies to protect and restore the resource. However, for the stages of identifying knowledge needs (monitoring objectives) and the planning of information dissemination in particular, participatory practices have not been considered sufficiently. Therefore, trust in the data obtained and the acceptance of projects and regulations to protect and restore the resource is often very limited.

The results of the proposed participative approach revealed that scale needs to be considered, as scale will influence the stakeholder analysis and have repercussions on objectives and specificities of the participative approach as well as on the results; in this case monitoring objectives for WQMPs and communication strategies. The participative approach proposed resulted into specific short-, medium- and long-term monitoring objectives and suggestions for communication strategies that the watershed organizations of the two case studies in charge of the WQMPs will be able to implement. For W1, the responsiveness was excellent. The coverage of the stakeholders within and outside of the watershed covered all main ROS and a good number of citizens. In W2, the responsiveness of the stakeholders and citizens who participated was very good; however, the coverage of the territory, ROS and the number of citizens' responses was limited. The feedback from W2 was that the survey was too general for their specific concerns and that a more location-based participative approach, WQMP and communication on water issues would be desirable.

The results of the participative approach allow us to conclude that:

- Participative approaches need to consider the population that lives outside of the proposed watershed limits who use the water resource (human geography catchment area), as well as the groundwater catchment areas.
- Participative practices must be administered and adapted to homogeneous (localized) areas based on political or subwatershed boundaries with comparable land use characteristics.
- Monitoring objectives emerging from a participative approach are relevant as an input to optimize existing WQMPs.
- WQMPs for localized areas must be integrated into the WQMPs covering the entire watershed.
- Planning and optimizing WQMPs must be based on the concerns and non-concerns of all stakeholders within a watershed and the human catchment area.
- WQMPs need to be optimized to close some information gaps on water quality and quantity on a temporal and spatial scale in order to help implement best management practices to protect the resource.
- WQMPs should cover surface and groundwater.
- Watershed as a scale on which to circulate information is insufficient when some of the main users of the resource live outside of the watershed.
- Modes of communication need to be adapted to the targeted person(s) or organizations(s), while not limiting them to a single mode of communication.
- Modes of communication need to be localized to specific areas and not only address the entire watershed or population living close to the waterbodies.
- Interactive maps that communicate information to stakeholders must be put into place and, at the time, be able to receive information from the stakeholders (according to the principle of intelligent and learning communities).
- Disputes arise as a result of a lack of information transparency, unequal financing and regional inequality (the latter stemming from issues on water governance and financing issues which can be attributed to the scale of IWM).

- The proposed participative approach is adaptable to various scales and regions.

An important question which remains to be discussed in the future is whether IWM practices are operating on an appropriate scale (figure 2.10). We suggest that IWM should be practiced on an area that combines the surface and groundwater watershed scale and the human catchment area. Therefore, a definition of IWM should include questions on scales outside of proposed watershed boundaries.

The monitoring objectives identified through the participative approach presented herein will be used in the near future to feed an Intelligent Decision Support System (IDSS) to plan, optimize, and manage WQMPs.

2.5. Acknowledgements

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Transition between chapter 2 and chapter 3

In Chapter 2, it was possible to demonstrate that the participative approach developed and tested yielded a series of precise new monitoring objectives for the two WQMPs of the case studies. It was also possible to identify several very precise optimization objectives. These objectives are necessary to guide the WQMP manager through the complex decision-making process to renew the WQMP. In Chapter 2, the complexity of the planning, management and optimization of WQMPs was shown through the literature review. The conclusion of the literature review was that an IDSS was necessary to guide WQMP managers through this decision process. It was also made clear that such an IDSS must include subject matter expert knowledge (tacit knowledge), as well as information from the literature (explicit knowledge). In addition, the IDSS must incorporate existing methods. The aim is to obtain a system able to integrate all this information, yet remain adaptable to new information. Another main feature of the system is its capacity to permit parameterization to specific local and regional realities in terms of regulations, policies and access to resources. The following chapter describes the design methodology of the conceptual model of the IDSS and presents parts of the conceptual framework (Also consult Appendix A).

3. CHAPTER 3: Intelligent decision-support system to plan, manage and optimize water quality monitoring programs: design of a conceptual framework

Système intelligent d'aide à la décision destiné à la conception, à la gestion et à l'optimisation des programmes de suivi de la qualité de l'eau : élaboration d'un cadre conceptuel

Résumé. Cet article se penche sur le cadre conceptuel d'un système intelligent d'aide à la décision (SIAD) basé sur une approche holistique et destiné à la conception, à la gestion et à l'optimisation des programmes de suivi de la qualité des eaux de surface. Les programmes de suivi de la qualité de l'eau (PSQE) constituent une composante primordiale de la gestion de l'eau. En effet, l'information sur la qualité de l'eau est essentielle pour agir sur les plans de la conformité législative, des projets environnementaux, du développement urbain et de l'aménagement des infrastructures. La conception, la gestion et l'optimisation des PSQE forment un processus complexe qui dépend de nombreuses variables, de divers règlements et des connaissances d'experts en la matière. Les objectifs spécifiques de cet article sont les suivants : (1) évaluer la pertinence d'un SIAD dans le domaine qui nous intéresse (les PSQE); (2) décrire le processus d'élaboration du cadre conceptuel; (3) présenter les principaux éléments de l'architecture de système; (4) présenter deux études de cas qui ont servi d'utilisateurs finaux potentiels; (5) illustrer l'applicabilité du SIAD; et (6) décrire les étapes subséquentes pour tester le SIAD de manière plus approfondie. Le SIAD a été développé à partir du principe que le système proposé pourrait (1) améliorer la qualité; (2) emmagasiner une expertise non documentée rare ou dont la durée de vie est limitée (connaissances tacites); (3) fournir une expertise accessible aux utilisateurs débutants; (4) servir à former les utilisateurs; et (5) prouver son utilité, même s'il n'est que partiellement complété. Nos hypothèses de départ concernant ces éléments ont été évaluées au moyen d'entrevues avec des experts en la matière. Pour élaborer le cadre conceptuel, nous nous sommes basés sur une revue de la littérature, des entrevues avec 44 experts en la matière originaires d'Europe, du Canada et des États-Unis, ainsi que sur des interactions avec les utilisateurs finaux de deux études de cas réalisées au Québec, Canada, et cinq experts des technologies de l'information originaires du Canada et de l'Allemagne. Le SIAD présenté dans cet article facilitera la conception, la gestion et l'optimisation des PSQE. Il pourra être transposé à de nombreux bassins versants et tiendra compte de la nécessité, pour le gestionnaire du PSQE, de pouvoir rapidement mettre à jour le système en cas de changements sur le plan des ressources humaines, financières ou techniques.

Abstract. This paper presents the conceptual framework of a holistic, intelligent decision-support system (IDSS) to plan, manage and optimize water quality monitoring programs (WQMPs) for surface waters. WQMPs are a crucial component of water management because information on water quality is essential when taking action such as legislative compliance, environmental projects, urban and infrastructure development. Planning, managing and optimizing WQMPs is a complex process and requires multiple variables, rules and subject matter expert knowledge. The specific goals of this paper were to (1) assess to which extent the subject domain (WQMPs) is deemed appropriate for an IDSS; (2) describe the design process of the conceptual framework; (3) present the main elements of the system architecture; (4) present two case studies that served as potential end users; (5) illustrate the applicability of the IDSS and (6) describe subsequent steps to further test the IDSS. The IDSS was developed on the premise that the proposed system could (1) improve quality, (2) capture undocumented expertise that is perishable or in short supply (tacit knowledge), (3) provide accessible expertise to novice users, (4) have a training effect on users, and (5) show that the system, even partially complete, could still be useful. Our initial assumptions regarding these points were evaluated through interviews with subject matter experts. The conceptual framework was designed based on a literature review, interviews with 44 subject matter experts from Europe, Canada and the United States, interaction with end users from two case studies in the Province of Quebec, Canada, and five information technology experts from Canada and Germany. The IDSS presented in this paper will facilitate the planning, management and optimization of WQMPs. It will be exportable to various watersheds and consider the WQMP planner's need to update the network rapidly if changes occur in human, financial and technical resources.

Highlights

Holistic and adaptable decision-support system to plan, manage and optimize surface water quality monitoring programs

Management and decision support system for knowledge acquisition processes on water quality

System integrates tacit and explicit knowledge on water quality monitoring challenges

Management and decision support system based on tacit knowledge from 44 experts and two case studies

Adapted design methodology for an Intelligent decision-support system

Keywords: *Water quality; monitoring; knowledge acquisition; decision support system; design process*

Abbreviations: APEL - *Association pour la protection de l'environnement du lac Saint-Charles et des Marais du Nord;* **Abrinord** - *Organisme de bassin versant de la rivière du Nord;* **IDSS** - *Intelligent decision support system;* **IT** - *Information technology;* **UML** - *Unified Modeling language;* **WQMP** - *Water quality monitoring programs.*

3.1. Introduction

Since the 1960s, decision support systems (DSS) for various domains have been developed to be able to more efficiently take increasingly complex decisions in a world of growing data, information and knowledge. These types of systems comprise financial planning systems (Power, 2003), clinical decision support systems (Alagiakrishnan et al., 2016), design support systems (Chamberlain et al., 2012), planning support systems such as models for best management practices and predictive models for water quality (Geertman and Stillwell, 2009; Slaughter et al., 2017), and navigation support systems ((Huang et al., 2012; Münzer et al., 2012), but to name a few. We propose to design a DSS to support watershed managers, researchers, and other actors in the water sector in the process of planning, managing and optimizing water quality monitoring programs (WQMPs) for surface waters. Thus, the type of decision support system we propose is a hybrid of a planning and management DSS for WQMPs.

WQMPs are a crucial component of water management because information on water quality is essential when taking action in many domains such as legislative compliance, environmental projects, urban development strategies, infrastructure development, etc. Water quality data issued from WQMPs is based on many decisions taken in the planning, implementation and optimization phases of the WQMP. It is important to make decisions taken in all phases of a WQMP as transferable, transparent and communicable as possible, since it may be necessary to endorse the data based on these decisions when the time comes to implement costly and unpopular measures to protect water resources (Behmel et al., 2016; Gerlak et al., 2011; Raadgever et al., 2008; Strobl and Robillard, 2008; Timmerman et al., 2000).

The complexity of planning, managing and optimizing WQMPs has been described extensively in the literature (Behmel et al., 2016; Harmancioglu et al., 1999; Strobl and Robillard, 2008; Ward et al., 1990). Behmel (2016), shows many approaches to plan and optimize WQMPs. However, none of these approaches consider all the use cases that must be addressed when tasked with every aspect of planning, managing and optimizing a WQMP: delimit the watershed subject to a WQMP; for example, determine and assess monitoring objectives; classify waterbodies; establish a sampling site network; select and classify water quality parameters; establish sampling frequency and recurrence; evaluate the required human resources; identify technical resource needs; estimate financial resources; plan quality control and quality assessment; define sampling routes and sampling calendars; prepare data handling, storage, analysis and reporting; identify communication channels. Indeed, Strobl and Robillard (2008) and Behmel et al. (2016) suggest that a DSS could assist watershed managers in planning, managing and optimizing WQMPs.

DSS generally share certain features and integrate (1) data, (2) information and (3) knowledge in order to accelerate and ensure knowledge transfer (Carvalho and Ferreira, 2001). Thus, decision support systems (1) facilitate the decision-making process, (2) promote transparency of the decision-making process and (3) promote knowledge transfer. *Knowledge*, according to Carvalho and Ferreira (2001), is "[...] the reunion of rules, principles, mental models, memories in which human action is embedded". This knowledge is divided by Rhem (2006) and Vigenschow (2015) into (1) explicit knowledge (transferable through words and numbers) and (2) tacit (implicit) knowledge. The latter is divided into (1) technical knowledge (acquired through experience, thus competences that are difficult to describe) and (2) cognitive knowledge (mental models and notions that form our perception). The iceberg model (Figure 3.1) shows that the amount of tacit knowledge is greater than the amount of explicit knowledge, thus providing an argument in favour of systems integrating tacit knowledge into decision-support systems.

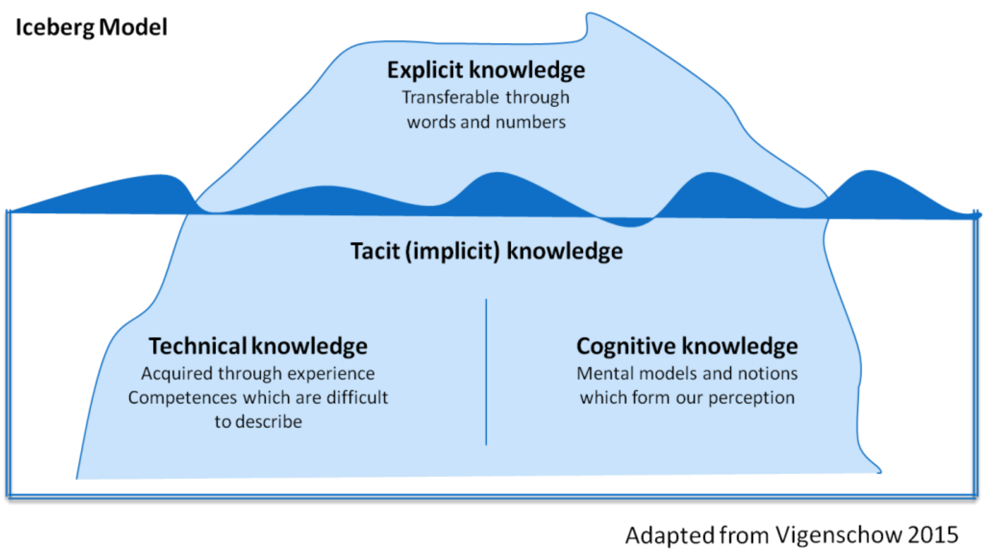

Figure 3. 1: Iceberg Model showing the various types of knowledge and their accessibility (adapted from Vigenschow 2015).

Systems that capture both explicit and tacit knowledge while integrating data and information for the decision-making process are also known as intelligent decision-support systems (IDSS) (Gupta et al., 2006; Power, 2001). IDSS are also interactive tools that integrate data, information, and explicit and tacit knowledge to allow the decision maker to choose among a number of possibilities that the system suggests for a given problem. The system then provides several options for the decision maker to choose from, until an acceptable solution is generated (Carvalho and Ferreira, 2001; Van Leeuwen, 2012). The system is designed to retain the user's choices (machine learning), since the main purpose of the system is to provide decision aid and record decision steps. The latter is important in order to render decision steps transparent and communicable to those who (1) need to make decisions on the subject without having all the data, information and knowledge and (2) were not involved in the decision making, but need to understand the rationale behind the decisions.

Before programming an IDSS, three main issues must be addressed: (1) circumscribe a field, i.e., a complex organizational process that requires an IDSS, (2) assess whether the subject domain is appropriate for an IDSS, and (3) design the conceptual framework (Rhem, 2006; Van Leeuwen, 2012). In the case of an IDSS, the latter implies a knowledge acquisition and elicitation process (Rhem, 2006; Wood and Ford, 1993) where knowledge acquisition refers primarily to acquiring explicit knowledge and knowledge elicitation refers to obtaining tacit (implicit) knowledge from subject matter experts (Wood and Ford, 1993).

After having circumscribed a field that requires an IDSS, the main task for the system architect is to carefully design and efficiently communicate the processes, decision-problem scenarios, cause-effect relationships and various indicators to be considered for the IDSS in order to facilitate interaction between end users, domain experts and software programmers for its implementation (Hahn et al., 2009; Kautish and Thapliyal, 2012; Lange and Diercks, 2015).

Since the literature review has shown that the planning, management and optimization of a WQMP is a complex process that entails the use of multiple variables, rules and perspectives, as well as subject matter expert knowledge, we state that an IDSS is required to holistically support watershed managers in their decision-making processes.

The aim of this paper is to present the conceptual framework of an IDSS to plan, manage and optimize WQMPs. The specific goals are to (1) assess to what extent the subject domain and the external conditions are deemed appropriate for an IDSS; (2) describe the process of designing the conceptual framework for the IDSS; (3) present the main elements of the system architecture; (4) present the two case studies that served as potential end users; (5) illustrate the applicability of the IDSS and (6) describe subsequent steps to further test the IDSS.

3.2. Methodology

The following sections provide the methodology used (1) to assess the appropriateness of the subject domain and project context, and (2) in the design process of the conceptual framework of the IDSS.

3.2.1. Appropriateness of the subject domain and project context for the proposed IDSS

In order to verify whether the subject domain (i.e., the planning, management and optimization of a WQMP) is appropriate for an IDSS, we used the evaluation framework proposed by Rhem (2006) for the development of knowledge management systems (consult appendix D, figure 1 to see the complete framework as well as the answers). The framework provides a number of statements which aim at evaluating whether the subject domain is appropriate for an IDSS. These statements need to be answered by the project managers. The statements are divided into six evaluation categories: (1) Desirable task (19 statements to assess technical feasibility of the proposed system as well as sufficient complexity of the subject domain for 25 possible points); (2) Payoff (11 statements to assess whether the financial and human resources are available to develop the system for 20 possible points); (3) Customer management (13 statements to assess benefits of such as system for an organisation – 20 possible points); (4) System designer (9 statements to assess the expertise of the designer in the field of knowledge acquisition and system design for 14 possible points); (5) Domain expert (7 statements to assess the availability of subject matter experts for 9 possible points) and (6) User (5 statements to assess the interest of the users in such as system and to contribute to the development of the system for 10 possible points). One to four points can be scored for each category and each checked statement. If the proposed system scores less than 50 % in the desirable task category, the domain is not appropriate for a system where knowledge is a key element.

To be able to provide an answer to the statements (yes, no, or not sure), it was necessary to analyze the subject domain and assess the involvement and availability of the parties. This process became an inherent guideline during the kick-off phase of the conceptual framework's design process.

3.2.2. Conceptual framework design process

Figure 3.2 illustrates the four phases of the iterative and evolving design method that we proposed to design the conceptual model of the IDSS. The kickoff phase consisted of identifying the system's users and establishing the system's purpose. Parallel to this, we evaluated the appropriateness of the subject domain and project context for the planned IDSS as proposed by Rhem (2006). During the development phase, we defined common terms and tried to establish a common terminology in order to structure, integrate and interlink information of the application domain. The construction and design phase served to develop the conceptual framework in order to present the system as a whole, as well as in subsections. Note that the transition and integration phases were not yet part of the project.

Some of the work during the kickoff, development, construction and design phases was completed in parallel. This included an extensive literature review of what had been published previously (see Behmel et al. 2016), as well as interviews with end users, subject matter experts and IT specialists. Also note that we have previously developed, tested and implemented a database, Enki™, a cloud-based software designed to store, organize, contextualize, analyze, publish and share all types of water quality data to which the IDSS is going to be connected (Behmel, 2010). In the final phases of the construction and design phase, we proposed workshops with the staff of each of the watershed organizations from the two case studies.

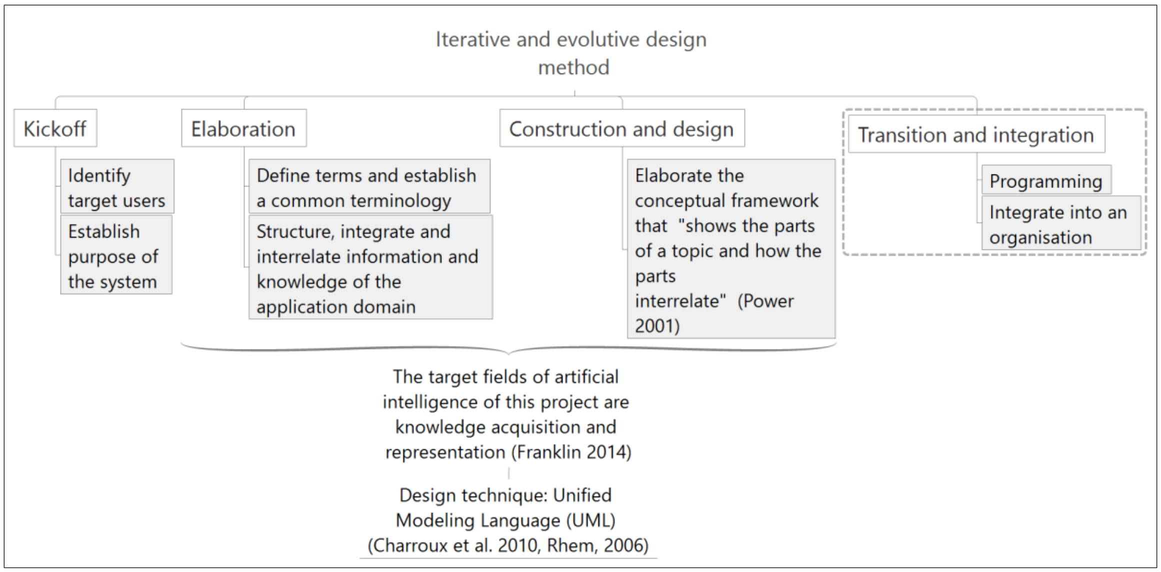

Figure 3. 2: Iterative and evolving design method (Sources cited in this figure: (Charroux et al., 2010; Franklin, 2014; Power, 2001; Rhem, 2006)).

In the following sections, specifications are provided on the methodology used for (1) the selection of the system architect, information technology (IT) specialists, subject matter experts and end users; (2) the interaction with the IT specialists, subject matter experts and end users, and (3), the illustration and description of the conceptual framework.

3.2.2.1. Selection of the system architect, IT specialists, subject domain experts and end users

The first step was to appoint a system architect. Ideally, the system architect has knowledge on the subject domain and experience in software architecture (Hahn et al., 2009; Rhem, 2006). The system architect's tasks are to identify the potential end users, subject matter experts and IT specialists; conduct the interviews and workshops; develop the conceptual framework of the IDSS; and, identify gaps in the framework.

The IT specialists were chosen for their knowledge in artificial intelligence, agile software development processes, and knowledge on commercial off-the-shelf software elements.

Potential end users and subject matter experts cannot always be strictly separated; however, we elected to keep them apart. One of the reasons was that the end users were going to be solicited throughout the process and we anticipated that subject matter experts might not have the same availability. The subject matter experts were selected based on their geographical distribution and specialization in specific aspects of WQMPs. With regard to geographical distribution, we sought to interview experts from Canada, the United States and Europe in order to gain insight into fundamental differences related to water governance, water quality monitoring strategies, local realities, legal obligations, policies, budget constraints, etc. With regard to the specialization of the subject matter experts, we looked for expertise in river and lake monitoring and expertise in specific use cases identified for a WQMP, such as choosing laboratories and probes, establishing communication channels, etc. (see the list of use cases in the introduction section).

The end users were chosen as members of watershed organizations partly or fully involved in ongoing WQMPs. The two organizations chosen as potential end users are from distinctive watersheds within the Province of Quebec, Canada: (1) Association pour la protection de l'environnement du lac Saint-Charles et des Marais du Nord (APEL) of the Saint-Charles river watershed (north of Québec City) and (2) Organisme de basin versant de la rivière du Nord (Abrinord), of the rivière du Nord watershed (north of Montréal) (Figure 3.3). Besides the distinctive character of the two watersheds (size, land use, demographics, etc.), the main reason for choosing these two organizations as case studies was the distinctive scope of each of the monitoring programs and the difference in each organization's mandate with respect to WQMP management. The idea was that differences between the two case studies could have an impact on these potential end users' perceptions of the problems that an IDSS could help them solve in a WQMP.

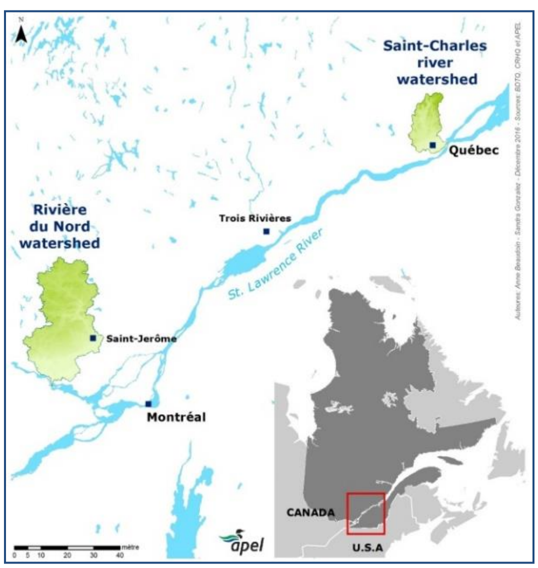

Figure 3. 3: Location of the two case studies.

3.2.2.2. Interaction with the IT specialists, subject domain experts and end users

3.2.2.2.1. Discussions with the IT specialists

The interviews with the IT specialists were guided by the system architect's specific needs on how to present the knowledge and system requirements in order to be able to design the conceptual framework in a way that would (1) satisfy the needs of the IT specialists potentially involved in the programming; (2) be able to communicate the system architecture to the end users and subject matter experts, and (3) serve to identify the elements that need not be developed (by using off-the-shelf components and functionalities included in Enki™). The work products presented here were validated with one of the IT specialists based on criteria such as (1) ease of comprehension of the subject domain and (2) purpose of the system.

3.2.2.2.2. Interviews with the subject matter experts

The interviews with the 44 subject matter experts were based on individually prepared semi-structured interviews. Prior to each interview, research was conducted on the experts' specific expertise on water quality monitoring and his or her role in the organization. In addition, some fact-finding was done on the WQMP in which the expert was involved and the local regulations and policies guiding WQMPs. The interviews were generally conducted in compliance with the four phases of tacit knowledge elicitation as proposed by Wood and Ford (1993): (1) Descriptive elicitation; (2) Structured expansion; (3) Scripting and (4) Validation. Wood and Ford propose a differentiation of tacit knowledge into declarative knowledge and procedural knowledge – which they define as "knowledge of 'what' *vs.* knowledge of 'how'" (Wood and Ford, 1993) - which corresponds to the technical and cognitive knowledge respectively proposed in the iceberg model (Figure 3.1).

Descriptive elicitation focuses on helping the expert expand on his or her declarative knowledge of the problem-solving domain. Structured expansion focuses on the "expansion and integration of the fragmented portions of the expert's declarative knowledge" (Wood and Ford, 1993). Scripting aims at using the declarative knowledge in order to obtain inferences of the experts' procedural knowledge. Validation is the phase where the system architect (interviewer) strives to validate his or her understanding of the declarative and procedural knowledge obtained from the expert (Wood and Ford, 1993).

3.2.2.2.3. Interaction with the end users

The initial meetings with the end users were based on semi-structured interviews to cover the end users' WQMP planning, managing and optimizing tasks within their organizations. These interviews also served to identify elements where most needs for an IDSS were situated. The end users were encouraged to communicate with the system architect during the entire project (2 years) with any questions they might have during the regular exercise of their tasks. The purpose here was to identify additional use cases and needs for the IDSS during the entire development process.

At the end of the knowledge acquisition process, a one-day workshop was organized with each of the end users' organizations to validate the use cases, enlarge on user stories, propose test cases and suggest priorities for use cases to be developed. At our suggestion, managers, field workers, data managers and analysts were present during each of the workshops.

3.2.2.3. Illustration and description of the conceptual model

The general design methodology of the IDSS was guided by the Agile software development. Agile software development involves reducing the description of the system's requirements to a minimum and focusing instead on the essentials and on interactions with the end users. Therefore, to depict the system, we decided to adopt the Use-Case 2.0. approach as proposed by Jacobson et al. (2011, 2014 and 2016). We combined the suggestions from Use-Case 2.0. with elements from Cohn (2004); Rhem (2006); Balzert (2011) and the recommendations resulting from the interviews with the IT specialists. Definitions of the terms referring to the elements and their properties used to design the conceptual model of the IDSS are provided in Table 3.1. They widely influenced the design of the conceptual model.

Table 3. 1: Definitions of the terms referring to the elements used to design the conceptual model of the IDSS as well as the main elements and properties of these elements

Term	Definition	Main elements & properties
Use case	"A use case is a sequence of actions a system performs that yields an observable result of value to a particular user" (Jacobson et al., 2016) A use case is a sequence of actions to achieve a goal (Balzert, 2005) A use case is a specific way to use a system. A use case fulfills a service to the actor interacting with the system with a triggering action, a sequence of operations and a result at the end for the initiating actor (Charroux et al., 2010)	A use case always starts with a verb in the infinitive and must contain the purpose of the use case and should be described through a basic sequence of underlying actions and interactions leading to its realization (use-case narrative) (Balzert, 2005)
Use-case slice	"A slice is a carefully selected part of a use case" (Balzert, 2005; Jacobson et al., 2016) "A use-case slice is one or more stories selected from a use case to form a work item that is of clear value to the customer" (Jacobson et al., 2011)	Use-case slices help divide the use case up into scalable pieces of the main use case. They facilitate the establishment of priorities and can be used for the back-log (nice-to-have items for instance) "The essential properties of a use-case slice are: a list of its stories; references to the use case and the flows that define the stories; references to the tests and test cases that will be used to verify its completion; estimate of the work required to implement and test the slice" (Jacobson et al. 2011)
User story	"A user story describes functionality that will be valuable to either a user or purpose of a system or software" (Cohn, 2004)	User stories have three elements: Card – Conversation – Confirmation (Jeffries, 2001) A user story should fit on a card and "represent customer requirements rather than document them" (Davies 2001). An example of a large user story also called epic: *A user can search for waterbodies* Such a user story can be refined into smaller stories: *A user can search for waterbodies by attributes like watershed, type of waterbody, related sampling stations, monitoring objectives, etc*. (Adapted from (Cohn, 2004))
Use-case model (or use case diagram)	"the use-case model represents the functional requirement of the system" (Jacobson, 2004) and "(...) is a simple way of presenting an overview of a system's requirements" (Jacobson et al. 2016)	The model should show what the system has to do. A use case model can show the system as a whole and can also be split up to illustrate specific fractions of the system (as use-case slices split up a use case). A functional requirement should show what the system has to do, who starts the interaction and with whom the system interacts (actors can be persons or other systems). (Jacobson et al., 2016)

Use-case narrative	A use-case narrative captures the basic and alternative flow of a use case (Jacobson et al., 2013)	A use-case narrative describes a use case and should include the basic flow and the alternative flow as well as special requirements. The use-case narrative outlines and influences the user story and provides detailed information to the elements of the use-case model (Jacobson et al., 2011)
Test case	A test case proposes, for a use case or use-case slice a scenario of the expectations of the user, that is the expected outcome of an interaction with the system (Cohn, 2004)	The test cases can be noted on the reverse of the cards of the user stories and be as short as concise as the user story (Cohn, 2004). “A test case defines a set of test inputs and expected results for the purpose of evaluating whether or not a system works correctly” (Jacobson et al. 2011)
Ladders	“Ladders are hierarchical (treelike) diagrams. Some important types of ladders are the concept ladder, composition ladder, decision ladder, and attribute ladder. Laddering provides a way to validate efficiently the knowledge of the domain” (Rhem, 2006)	Depending on the type of ladder, the content my be different: Concept ladder : IS-A relationship (e.g., car is a vehicle) Composition ladder: HAS-PART or HAS-PART-Of relationship (e.g., wheel is part of car) Decision ladder: “shows the alternative courses of action for a particular decision” Attribute ladder: Can show the properties which can be associated with a concept Process ladder: “Shows processes (tasks and activities) and the sub-processes (sub-tasks and sub-activities) of which they are composed” (Rhem, 2006)
User	A user is who the system is built for	A group of users can be represented as an actor (Charroux et al., 2010)
Actor	An actor can be anyone, represented as a person (user) or a class of users or another system interacting with the system	An actor should be described with regards to the interaction with the system: role of the user and interaction with the system.(Charroux et al., 2010)
Stakeholder	A stakeholder is defined as a citizen or representative of an organization within a watershed. A stakeholder may influence the knowledge needs on water quality, but does not interact with the system	

We started to define the system’s requirements elicited through the literature review (Behmel et al. 2016), as well as the interviews with the subject matter experts and interactions with the end users.

More specifically, we aimed to depict the system in a comprehensive use-case model where the system can be seen as a whole that includes the external actors, yet limits the illustration of the interactions for ease of comprehension. Then, for each use case we prepared user stories and test cases (Cohn, 2004), as well as detailed use-case models inspired by Balzert (Balzert, 2005). Then, the use cases were sliced. For each slice we developed a use-case narrative based on Use-Case 2.0 (Jacobson et al., 2016) (see table 3.1 for the definitions inspired by these authors). For each of these use-case slices, user stories were written in order to simplify the communication with the end users for which the use-case narratives might be too abstract. Relating use-case slices to user stories is at the "core of Use-Case 2.0" as they "bridge the gaps between the [...] users and developers, the use-cases and the use-case slices" (Jacobson et al. 2016). On the back of use-case cards, we proposed test cases. Finally, we used process ladders for some of the use-case slices in order to illustrate some of the decision-making processes according to the method proposed by Rhem (2006). The illustrations were prepared with the help of XMind Pro, a mind-mapping tool with which all the work products can be easily designed and illustrated (XMind, 2006-2016).

3.3. Results

3.3.1. Appropriateness of the subject domain and project context for the proposed IDSS

The total possible score to evaluate the appropriateness of the subject domain and the project context for the proposed IDSS was 98 points (100%) of which 69 points (70%) were obtained. Highest scores were obtained for the categories Desirable task (76%); Payoff (75%); Domain (Business Expert (100%) and User (70%). Lowest scores were obtained for the categories Customer Management (55%) and System Designer (57%). Neither the individual nor the total score were less than 50%, the critical bench mark for proceeding with the project, according to Rhem (2006) (also see section 4.1 and appendix D, figure 1).

3.3.2. Conceptual framework design

3.3.2.1. Results of the interaction of the system architect with the IT specialists subject domain experts and end users

Since the system architect did not have any experience in designing an IDSS, cognitive psychology or artificial intelligence, the system architect only scored 57%. However, the appointed system architect is a potential end user and a subject matter expert on WQMPs with previous experience in designing the data- driven decision-support system Enki™ (Behmel, 2010). This expertise offset the low scores for the system architect. Also, the availability of subject matter experts and end users added to the total scores. Figure 3.4 presents the end users, IT specialists and subject matter experts' organizations consulted.

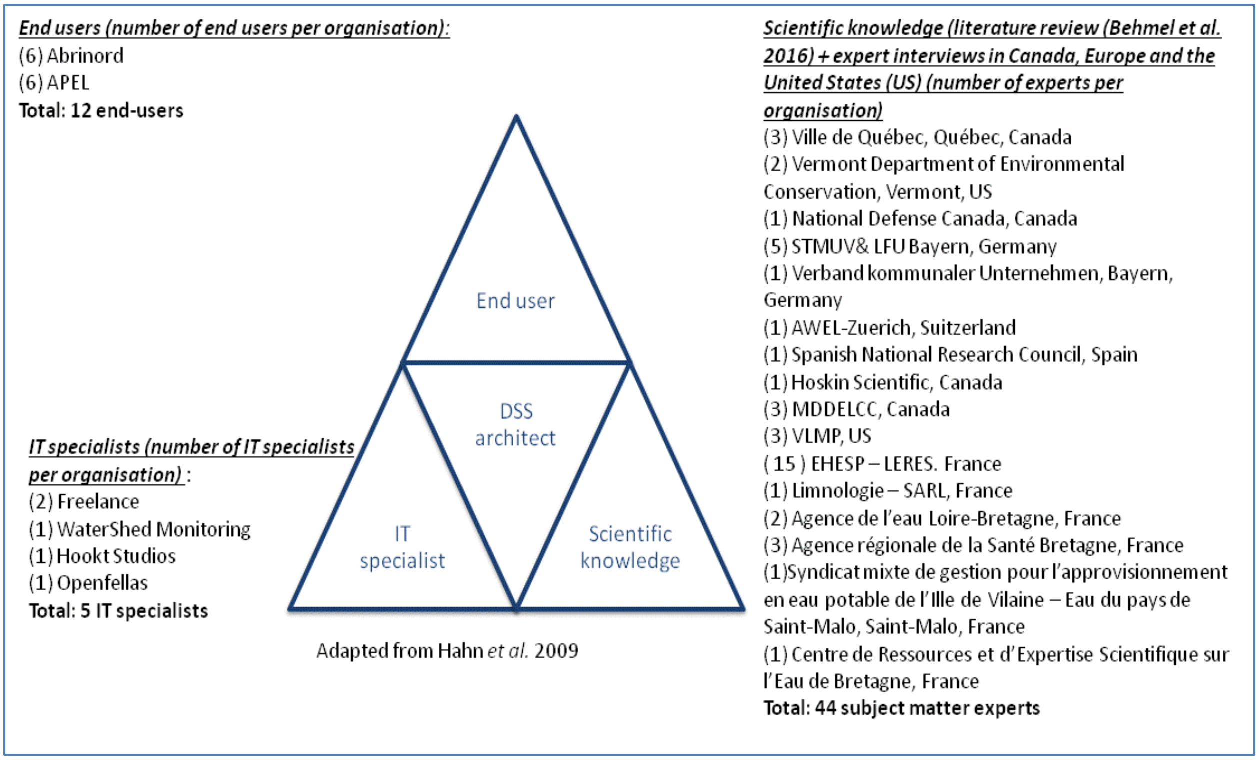

Figure 3. 4: Upper left hand: End users consulted by the DSS architect from 2015 to 2017Lower left hand: IT specialists consulted. Right hand: List of organizations with the number of subject matter experts consulted for each organization. (Abbreviations: APEL – Association pour la protection de l'environnement du lac Saint-Charles et des Marais du Nord. STMUV: Bavarian State Ministry of the Environment and Consumer Protection. LFU : Landesamt fuer Umwelt Bayern. MDDELCC: Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques. VLMP: Maine Volunteer Lake Monitoring Program. EHESP-LERES: École des hautes études en santé publique - Laboratoire d'étude et de recherche en environnement et santé.

Altogether, three end users each from Abrinord and APEL provided input and feedback throughout the process starting at the onset of 2015. For each of these organizations, one-day workshops were held with respectively 6 to 7 participants (November 2016) (Appenix D, figure 3).

Five IT specialists with expertise in artificial intelligence, agile software development techniques, IT project management, knowledge on existing software modules and databases from Canada and one from Germany agreed to be interviewed.

Forty-four subject matter experts were interviewed. Interviews were person to person, semi-directed and individually prepared and adapted to the expertise of the subject matter experts and to their working environment. The interviews were spaced from June 2015 to February of 2017 and lasted between two to four hours. The adaptation to the expert's specific domain as well as the different interview languages used (German, English, Spanish and French) did not allow the use of any qualitative content analysis. However, they resulted in a very broad range of tacit knowledge on planning, managing and optimizing WQMPs reflected in the work products describing the IDSS (see appendix D, figure 2).

3.3.2.2. Conceptual framework, use-case model and example outputs and applications

The system's requirements are presented as a combination of (1) a general conceptual framework (Figure 3.5); (2) a global use-case model of the IDSS (Figure 3.6); (3) user stories (Text box 1); (4) use-case slices, (4) use-case (slice) models (Figure 3.7); (5) use-case narratives (example provided in the text) and (6) ladders (Figures 3.8 and 3.9).

Figure 3.5 presents the main use cases identified during the literature review. It shows the main use cases with simple relationships between the users and actors. No relationship between the use cases is shown in this version in order to simplify the presentation. Only three main actors communicate with the system in this illustration: the user represented as the WQMP's project manager (influenced by the stakeholders' knowledge needs), a database (Enki™) and a system of business intelligence modules. This model, although simple, proved to be very helpful in exchanges with the end users, especially during the workshops, where every use case was chosen according to the staff's individual interest in the subject represented in the use case

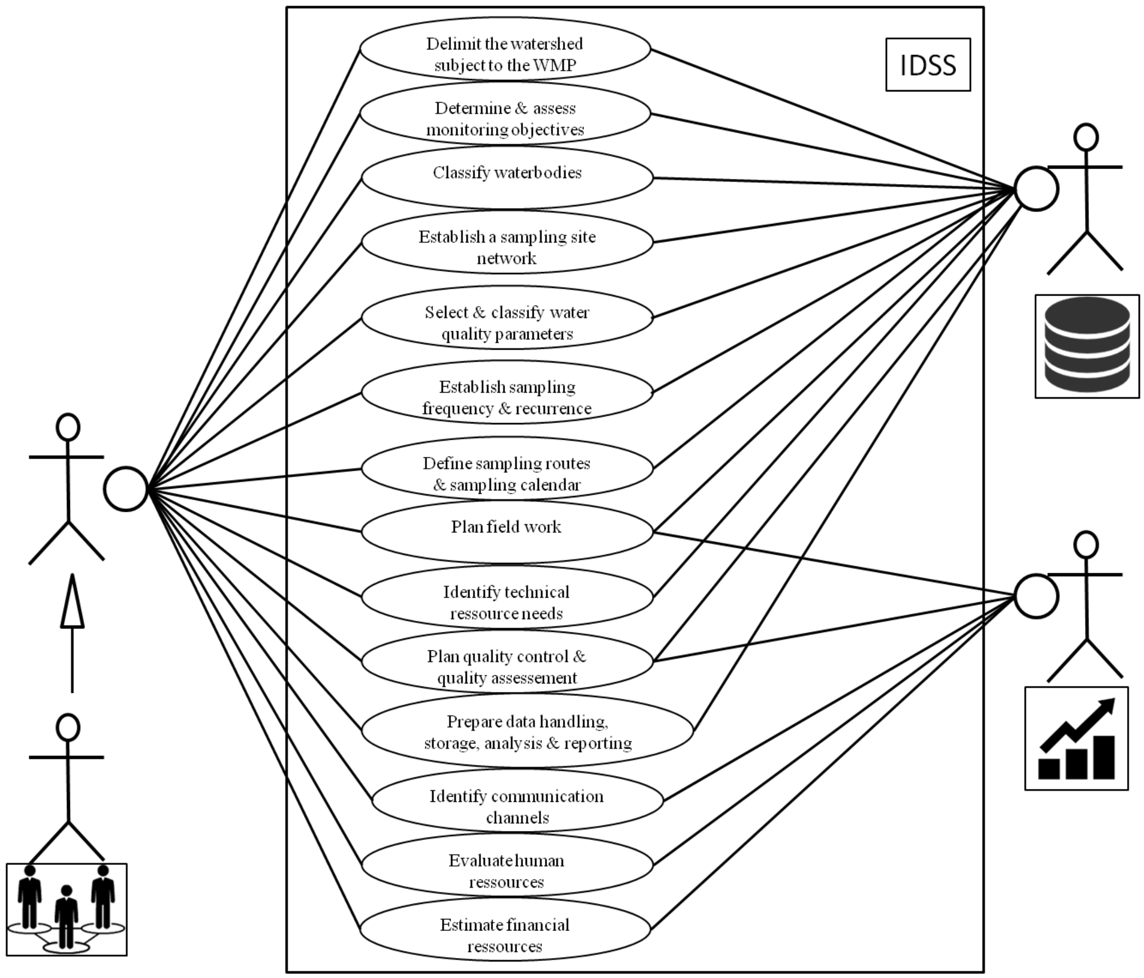

Figure 3. 5: General conceptual framework of the IDSS (design inspired by UML) based on the literature review and the expert interviews. The elements in the box describe the use-cases addressed by the IDSS. The actors on the right side are the interaction of the IDSS with a database and business intelligence system. The actor on the left side represents the users of the IDSS (e.g. the WQMP manager) who is influenced by the stakeholder's knowledge needs.

In the following, we will first describe and illustrate the more complex global use-case model of the IDSS. Since showing the entire system would be beyond the scope of this paper, we chose to focus on one the use-case model for the use case *Delimit a watershed subject to the WQMP* (section 3.2.2.2) and on a use-case slice: *Evaluate a river station network* (section 3.2.2.3).

3.3.2.2.1. The global use-case model

The global use-case model and the users interacting with the system are illustrated in Figure 3.6. The main actors and users interacting with the system on different levels were identified as: the organization responsible for the WQMP (influenced by the stakeholders), the WQMP project manager, a database, a business intelligence system and a team of scientific reviewers. On a more specific level, the following potential users were identified according to their roles within an organization in charge of a WQMP: statistician, limnologist, hydrologist, geomatics specialist, biologist, ecologist, communication specialist, technician, accountant, database manager, quality control & assessment manager, laboratories, and probe and tool providers. The roles of each of these actors also influenced the design of the conceptual model.

The global use-case model in figure 3.6 reads as follows: The first element that needs to be chosen is the watershed or territory subject to the WQMP. This decision, supported by a series of discussions, data and information (see section 3.2.2.2 for more details) must be taken by the stakeholders who mandate the organization in charge of the WQMP. This organization appoints a project manager for the WQMP. According to the suggestions of the IDSS, the organization in charge of the WQMP and the project manager might come up with a proposal for the territory to monitor. Once the territory is chosen, the stakeholders, supported by the organization in charge of the WQMP and the project manager, must define the monitoring objectives. The process of defining the monitoring objectives is also supported by the system. The monitoring objectives need to be as precise as possible (Chapman et al., 2016) and should be elicited through a participative approach (Behmel et al., 2016). Depending on the monitoring objectives, the information on the territory subject to the WQMP might need to be refined (e.g., additional information must be collected on the land use for instance). The monitoring objectives, as well as local policies and legislation (e.g., the European water framework directive (WFD) (Directive, 2000/60/EC)), will influence the type of classification of the waterbodies. The classification of the waterbodies will also depend on the information gathered through the process of delimiting a watershed subject to the WQMP. The waterbodies to be monitored, as well as the specific monitoring objectives and the policies, will influence the choice of water quality parameters and composite indicators such as water quality indices (Hébert, 1997; Sutadian et al., 2016; Walsh and Wheeler, 2013). The monitoring objectives, as well as the classification of the waterbodies, will influence the sampling site network. The sampling sites may influence the specific water quality parameters to be measured as well as the sampling strategy (Thomas et al., 1996). In addition, the type of waterbodies, monitoring objectives, water quality parameters, policies and type of information to be produced will influence the sampling frequency and recurrence. Sampling frequency and recurrence may also be influenced by the management plans (implementations of actions which need to be monitored, for instance). All these elements will also depend on the available financial, technical and human resources. Once all these elements are established, it is time to plan the field work, quality control and assessment. At all phases of the process, it is necessary to keep the communication channels open within the organization mandated to put the WQMP in place, as well as with the stakeholders of the watershed subject to the WQMP. Depending on the point in time during the process, external actors (e.g., project manager, data base manager, technicians, quality control and quality assessment manager, etc.) will intervene and they will either enter information or question the system.

In order to show how the processes work within these use cases, the next section will illustrate the use case *Delimit a watershed subject to the WQMP*.

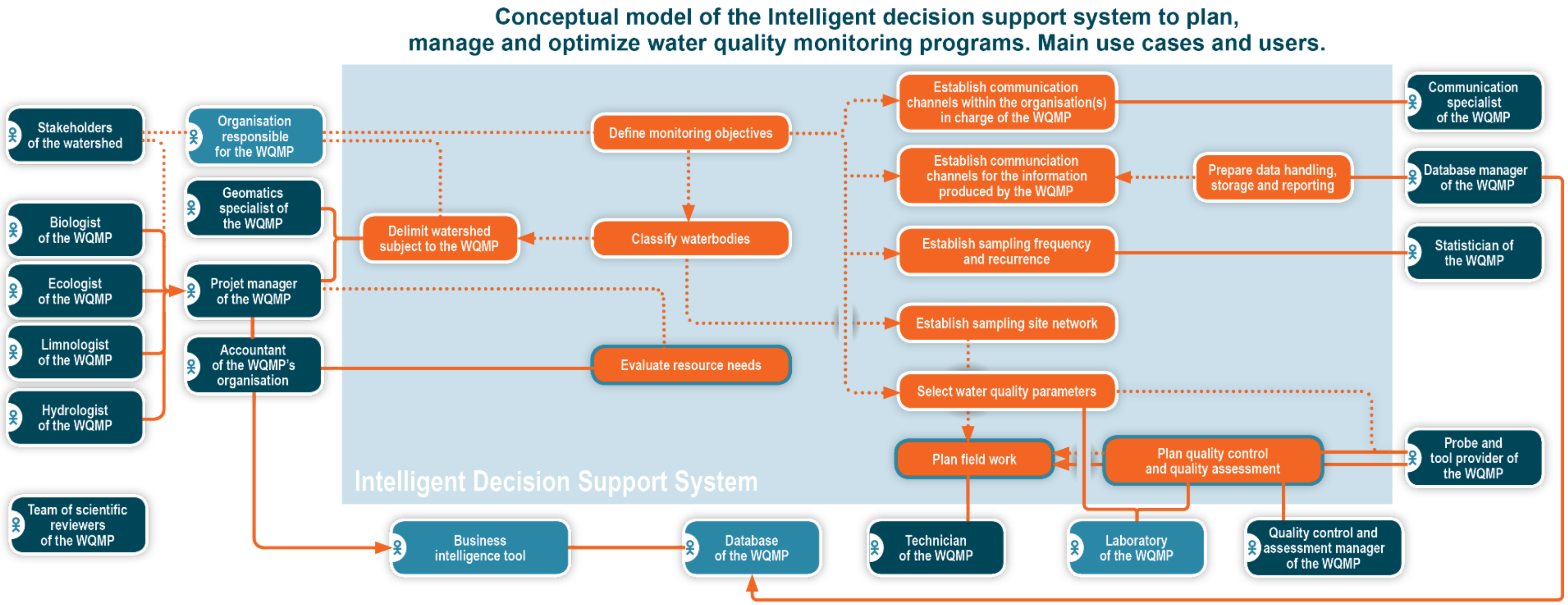

Figure 3. 6: Use case model of the IDSS and actors and users interacting with the system (the light blue fill defines the limits of the IDSS).

3.3.2.2.2. Example output of the use case: Delimit a watershed subject to the WQMP

We chose the use case *Delimit a watershed subject to the WQMP* since it seemed to be the use case that raised the least interest during the interviews with the subject matter experts and the workshops at the onset, but led to heated debates once the subject was addressed during the interviews and the workshops. Also, through the discussions, this use case became the first element to consider when planning, managing and optimizing a WQMP. It was also suggested substituting the use case title: *Delimit a watershed subject to the WQMP* for *Delimit the territory subject to the WQMP.* It has to be noted that both case study watershed organizations have been subjected to changes within their territory which led to reassessing their WQMPs. Also, several papers have discussed the issue of (re-)scaling the territories of some WQMPs in order to improve management and communication (Chapman et al., 2016; Quevauviller et al., 2005; Raadgever et al., 2008; Timmerman and Langaas, 2005).

The discussions on the use case (now referred to as) *Delimit a watershed (territory) subject to the WQMP* during the workshops led to several user stories, Some may be consulted in Text box 2. These user stories are close to epics. Epics are user stories that are too big to be implemented and need to be broken down into smaller sets. However, these user stories make it evident that the IDSS needs to be connected to a database and that many questions on a WQMP are still very much related to data acquisition and storing. Indeed, these stories refer to series of information that should be obtained and verified at the onset of the planning or optimizing process, as well as during the execution phase. The information referred to should be updated constantly while a WQMP is underway. Therefore, one of the underlying use cases would be: *Update the information on the watershed*. This implies the need for an updating procedure and a database (elements which we addressed in earlier work and through the implementation of Enki™ (Behmel, 2010)). Thus, these user stories led to a variety of use cases related to both data storage possibilities and procedures to be followed. In addition, they showed the necessary connexions to other use cases, such as *Define monitoring objectives* and *Establish communication channels.*

A user is guided through the process of the necessary steps of the use case *Delimit a watershed (territory) subject to the WQMP*, can use a checklist and follow progress on a dashboard.

A user can see the progress of the tasks to be completed in order to achieve his goal to delimit a watershed (or area) subject to his WQMP

A user can store all the necessary information in a common database

A user can visualize all the necessary metadata of the collected information

A user can visualize actor networks within a given watershed according to attributes such as: political boundaries (local, regional & transboundary); inventory of actors (watershed organisations, universities, municipalities, non-governmental organizations, transboundary organizations, etc.)

A user can choose from a set of watersheds in a given continent in order to visualize the official delimitations of the watersheds and sub-watersheds.

A user is guided through the process of the necessary procedures to complete a stakeholder analysis.

A user is guided through the process of the process of assessing management regimes.

A user is guided through the process of establishing a communication plan

A user can view the metadata (source) of the information he is visualizing, according to attributes such as organization which provided the information, history of changes, origin & reason for changes, etc.

A user can view information on existing WQMPs within a watershed according to attributes such as organizations implicated in monitoring activities and water quality studies.

A user can view information about each watershed such as land use, political boundaries, waterbodies, climatic regions, hydrology, topography, groundwater, stakeholders, monitoring activities, sampling stations, hydrological stations, weather stations, existing databases, etc.

A user can choose watersheds and sub-watersheds according to attributes such as: river names, lake names, waterbody type, geographical location (GPS points), cities, political boundaries, watershed organizations, predominant land use, etc.

A user is guided through the reflection process of delimiting the area subject to the WQMP (advantages and disadvantages).

A user is guided through the reflection process of choosing an appropriate database

A user is guided through the process of identifying monitoring objectives

Text box 2: List of the user stories established for the use-case: Delimit a watershed subject to the WQMP during the workshops (non exhaustive and non structured).

The discussions on these user stories led to the use-case model illustrating the use case *Delimit a watershed (territory) subject to the WQMP* (Figure 3.7). The actors interacting with this part of the IDSS are the organization responsible for the WQMP, the project manager, the data base manager, and the geomatics specialist. The aim of this use case is to *Choose the watershed (or territory) subject of the WQMP* or to *Evaluate whether the watershed (or territory) is covered adequately by the WQMP.* In order to do so, there are several preconditions to meet. These can be described through a Use-case narrative.

In this case, a very general (still non-structured) use case narrative could read as follows: in the planning process of a WQMP, the main preconditions involve having the necessary information to plan a WQMP. Therefore, it is mandatory that the essential information to be acquired be listed and that progress made be shown. This information can be classified as necessary, optional and nice to have (depending on the monitoring objectives, policies or legislation). In the case where the necessary information is not available, this first step of the WQMP will have failed and the user will have to fulfill all the requirements to obtain the information needed for a WQMP. In the event that the required information has been collected, the user can move ahead to the subsequent step, *Define monitoring objectives*. The task (or the results) of *Define monitoring objectives* may require more information not identified in the first cycle of information acquisition (e.g., information that was first classified as optional, but is now necessary in order to be able to respond to the monitoring objectives). If the organization in charge of the WQMP cannot make this information available, they have to rethink their monitoring objectives).

The use-case model for the use case *Delimit a watershed (territory) subject to the WQMP* illustrated in Figure 3.7 can be read as follows: The organization responsible for the WQMP is tasked with (1) mandating a scientific committee to follow up on the WQMPs activities and reports issued from the WQMP; (2) identifying funding sources & partners and (3) suggesting a territory to work on. The latter means that the initial state of knowledge on the watershed is established. Again, this includes an inventory of land use, weather stations, hydrological stations, geology, climatic region, topography, etc. This information must be collected and integrated by the geomatics specialist in a common database. Upon establishing the territory to work on, it is also necessary to identify political boundaries – which will influence the monitoring programs through specific policies (for example). The WQMP project manager is tasked with identifying past monitoring activities and relevant studies conducted in the watershed. All this information needs to be integrated into a common database managed by a database manager. Finally, the organization also has to establish management regimes. This use case includes identifying all policies and regulations that apply to the watershed (or territory), identifying existing management plans and proceeding with a stakeholder analysis. The results of the latter can be used to establish the participative approach to elicit monitoring objectives. The results can also influence the composition of the organization or add additional stakeholder groups to the organization responsible for the WQMP.

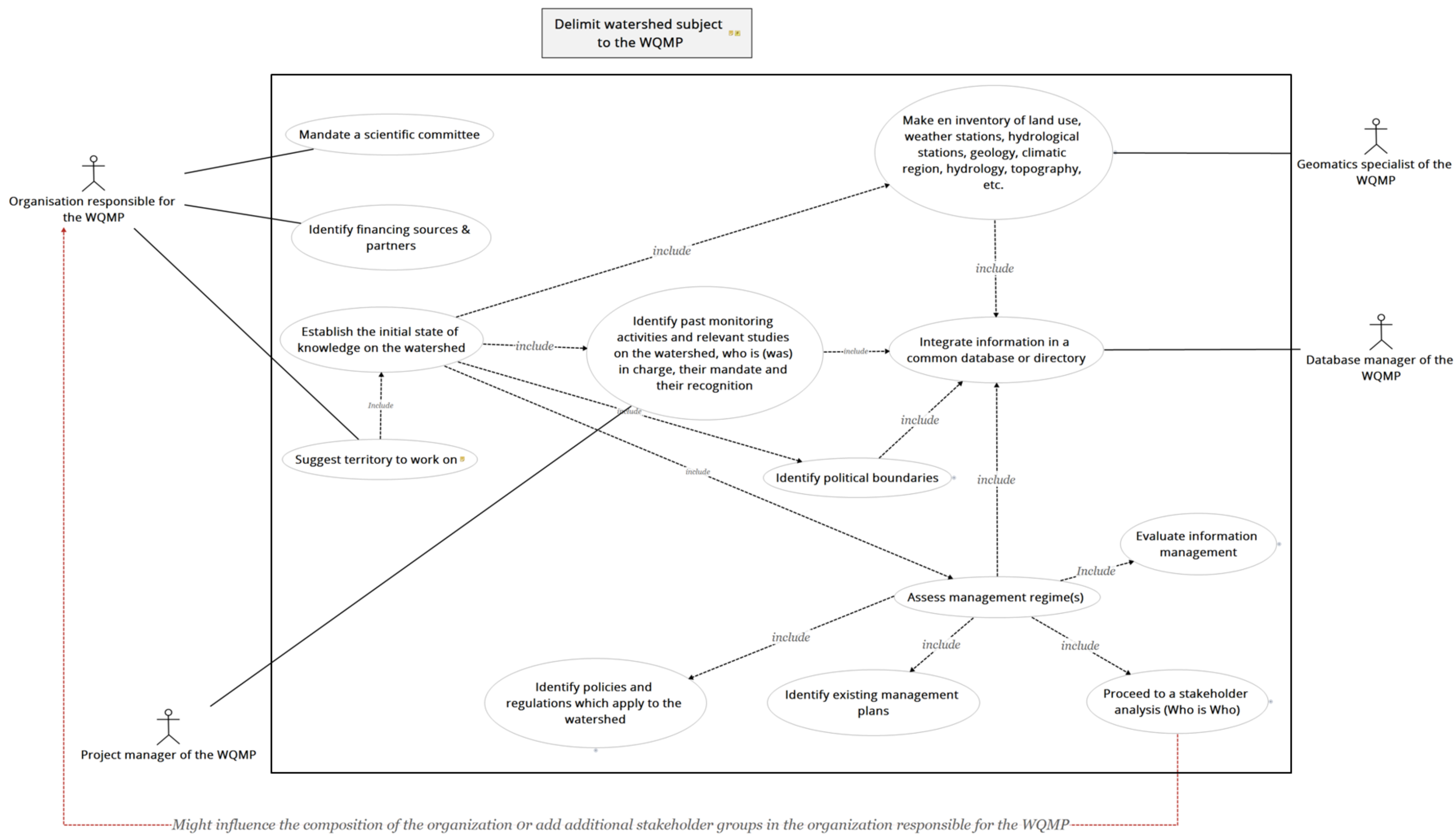

Figure 3. 7: Use-case model for the use case: Delimit a watershed (territory) subject to the WQMP.

Each of the use-case slices lead to process ladders as shown in Figure 3.8. In this figure, a fraction of the process ladder assigned to the use-case slice: *Identify political boundaries* is illustrated. The diamond-shaped end point of the process ladder refers to another use-case slice of the system. The user will be referred to another use-case slice until an acceptable result is reached regarding the user's initial demand for information or decision support for the specific use case. Each of the use-case slices in a use-case model is described with regard to the thought process and steps that must be taken to achieve the purpose of the original use case which, in this case, is *Delimit a watershed (territory) subject of the WQMP*. This use case serves to assess the scalability of the WQMP (scalability refers to verifying whether the organization in charge of the WQMP has the capacity to handle the amount of work related to the WQMP, assessing whether the information collected through the WQMP can be used to implement measures to protect the resource, and judging whether the stakeholders within the territory adhere to the WQMP, etc.). Further purposes of this use case include: coordinating river basin management; coordinating monitoring objectives; acquiring information on the watershed; ensuring that the WQMP is able to provide the required information in a timely and adequate manner; ensuring that the spatial coverage is adequate; verifying that the acquired data is comparable, etc. These purposes were identified through the literature (Chapman, 1996; Chapman et al., 2016; Davies-Colley et al., 2011; Directive, 2000/60/EC; Fölster et al., 2014; Raadgever et al., 2008; Timmerman and Langaas, 2005; Ward et al., 1990), the interviews with the subject matter experts and discussions during the workshops. When all the reflection cycles have been fulfilled within a use-case model, the next use case can be addressed.

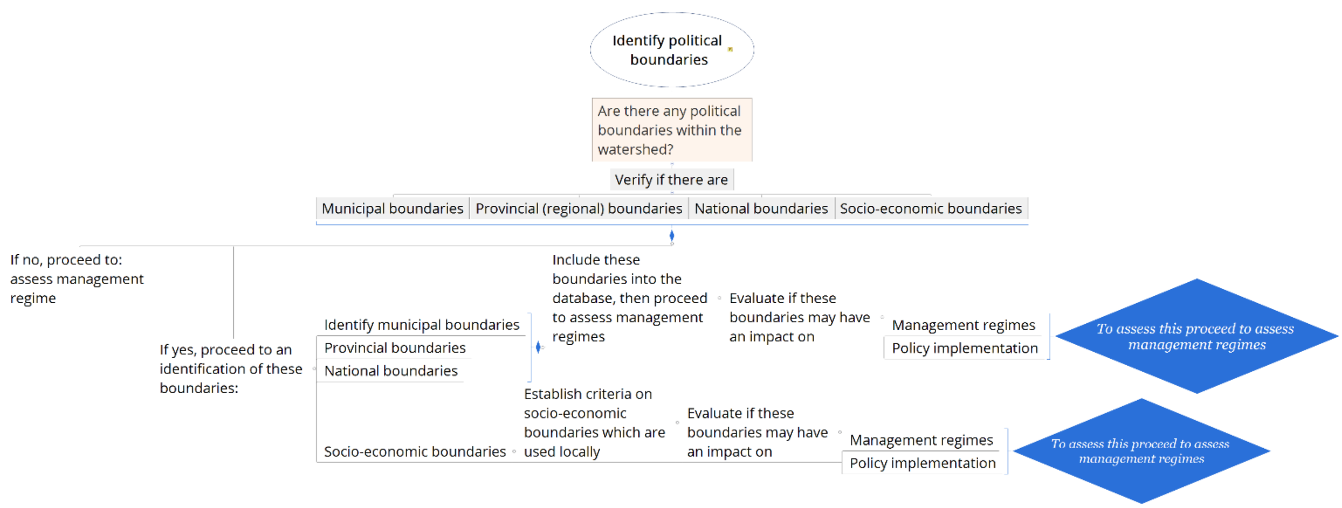

Figure 3. 8: Fraction of the process ladder assigned to the use-case slice: Identify political boundaries. The diamond-shaped end point of the process ladder refers to another use-case slice.

3.3.2.2.3. Example output of the use-case slice: Evaluate a sampling site network

In the following two sub-sections, we illustrate the use-case slice *Evaluate a sampling site network* followed by an example of how the IDSS might be applied to an optimizing scenario of a sampling site network.

3.3.2.2.3.1. Selection of the use-case slice: evaluate a sampling site network

The use-case slice, *Evaluate a sampling site network* was chosen since this is the subject that appeared to be the most sensitive during the workshops (participants' unwillingness to question the existing sampling site network for several reasons). The main reason was that downscaling or changes might result in loss of information (APEL and Abrinord). Other reasons included difficulties in taking decisions on the network changes: How to justify changes in the network? How to come about such an analysis? It was argued: *it took us such a long time to come up with this network, we don't really want to proceed with any changes.* Indeed, Abrinord and APEL's concerns reflect the reality of many other organizations in charge of WQMPs. Therefore, it is not a coincidence that the challenge of optimizing a WQMP has been discussed extensively in the literature and that many different approaches have been proposed to address this problem (Beveridge et al., 2012; Khalil et al., 2011; Ou et al., 2012; Strobl and Robillard, 2008; Strobl et al., 2006a; Strobl et al., 2006b). Each optimizing approach pursues different goals and has different preconditions to fulfil. In addition, the degree of difficulty and expert input for final decisions varies (Behmel et al., 2016).

Any organization wishing to evaluate an existing sampling network and not create a new independent one starts with what has been acquired over time: the accumulated data from the existing sampling network. From the analysis of this data emerge important indicators that will lead to the optimization approach that should be used for the sampling site network. The statistical methods applied to the data (e.g., in order to validate the location of sampling sites or the sampling frequency) are never chosen at random and correspond, above all, to the optimization objectives. Generally, the reasons that lead to the need to evaluate an existing monitoring network are changes in policy and regulations that result in new sets of requirements and adjustments to financial means, time and resources allocated to the WQMP; issues concerning the precision of the data sets; new monitoring objectives; assessment of the attainment of the objectives, etc.

Depending on the reasons that lead to the need for an evaluation of the existing sampling site network, the organization may wish to change the number of sampling sites, the location of the sampling sites, the sampling frequency and the number and type of water quality parameters considered. In addition, the organization may wish to re-evaluate human resource needs, technical means (e.g., types of probes, laboratories) and related financial considerations. The challenge is to evaluate and optimize a sampling site network with the adequate optimization approach and decision support, yet ensure that the monitoring objectives continue to be met.

The use of analytical tools specifically designed to evaluate an aspect of the sampling site network is strictly controlled by the conditions of application specific to each tool. The methodological path to choose the appropriate optimization method proposed in the literature (according to the reasons which led to the need to evaluate the sampling site network) is illustrated in figure 3.9.

3.3.2.2.3.2. Illustration of water quality monitoring program optimization procedure

In this section, we illustrate the fictional case of a river basin for which a WQMP has been underway for several years in order to show how a user can be guided through the task of evaluating the sampling site network with the help of this specific use-case slice of the IDSS.

First, assisted by the IDSS, the user verified that the sampling methods had not changed over the years and that the sampling strategy had remained constant. The user also verified the integrity of the data series (consistency, reliability, and relevance of data). In order to reach these preconditions, a systematic series of actions or 'processes' are built into the IDSS. These processes include questions such as: *Have there been any changes to the WQMP that may have affected the comparability of the data (change of laboratories, change of analysis methods in a laboratory, changes to the field work protocol, change of probes, change of probe calibration methods, change to the micro-location of the sampling sites, etc.)? Treatment of outliers (systematic inclusion, systematic exclusion or process to verify plausibility of the outlier according to a checklist (depending on the type of outlier (probe or laboratory data; continuous or grab sampling, etc.) a checklist is proposed to verify if the outlier should be included or excluded. How to consider missing data (e.g., reconstitute information about water quality variables at discontinued locations)?* The IDSS is designed to guide the user through these questions in order to indicate appropriate optimization tools (appropriate to the data sets and appropriate to the optimizing objectives).

Second, it is also assumed that the organization managing the WQMP wishes to obtain a full optimization assessment of its network of sampling points, without an *a priori* of adding or reducing the number of stations, water quality parameters or sampling frequency. Third, it is assumed that the organization has set three optimization objectives: verify whether the number and nature of the observed variables (variables can be water quality parameters, biological indicators, stream flow, field observations, field measurements such as temperature, transparency and pluviometry, etc.) is optimal (objective 1); validate the relevance of the number of sampling stations (objective 2); and validate whether the sampling frequencies for each station are optimal (objective 3).

If these are the set preconditions for data series and optimizing objectives, the IDSS will propose a set of optimization approaches, as follows:

Objective 1 (verify if the number and nature of the observed variables is optimal): this leads the user to the lever *Water quality parameters* and to a number of possible statistical approaches to optimize the existing network (Figure 3.9). According to the optimizing objective, the IDSS will propose the appropriate approach for this specific case. For example, factor analysis methods such as the principal factor analysis (PFA), principal component analysis (PCA), canonical correlation analysis (CCA) and correlation analysis proposed by (Noori et al., 2010; Ouyang, 2005; Pinto and Maheshwari, 2011) provide an efficient representation of the redundancy of certain variables measured or observed within the WQMP. In other words, the authors identify important and relevant variables in the discrimination between stations. The factor analyses used by these authors require the fulfillment of certain preconditions. The multi-normality of the variables is sought, as is the linearity of the relations between the variables. Moreover, the analysis reacts poorly to punctual missing data within the records of the same sample. Any departure from these rules requires the use of other analyses more suited to the data series, such as Non-Metric multidimensional Scaling (Legendre and Legendre, 1998) These types of adaptations can be proposed by the IDSS. Correlation analyses can complement the results obtained with factor analysis methods. This results in the identification of secondary parameters because it provides a high redundancy of information with another variable. When the relationships between the variables are particularly strong, it is possible to stop sampling one among them (a variable can be a water quality parameter, a field observation or measurement included in the analysis): by way of example, the redundancy observed between turbidity quantified by an optical probe, and the concentration of suspended matter measured in the laboratory for some WQMPs (APEL, not published). When verified, this observation makes it possible to remove a water quality parameter at little risk. In this particular case, it would be suspended matter which requires additional field handling and laboratory analysis, while the probe is already in use and the probe data have been accepted for their precision by the decision makers. This is only one example of the type of alternative that the IDSS proposes in order to ensure that the user is always aware of the verifications made before taking a decision, in this case the elimination of a water quality parameter.

Objective 2 (validate the relevance of the number of sampling stations): this leads the user to the lever *Number of stations* (Figure 3.9). A number of methods will be proposed to the user that must be chosen according to the user's ability to apply them (e.g., degree of difficulty, available statistical tools), questions about the available data sets, monitoring objectives, original sampling site justification and optimization reasons. Based on the user's answers, the IDSS will propose methods such as those developed by (Ouyang, 2005) and (Park et al., 2006) to identify the most representative stations within a network. However, the degree of difficulty is very different. While Ouyang (2005) proposes the use of principal factor analysis (PFA), Park et al. (2006) use the analysis associations of spatial and genetic algorithms to identify the best stations within a network. While the IDSS can propose specific steps to walk the user through each of these methods, it does not (yet) provide the tools to automate them, but does provide the data storage, validation and extraction tool (Enki™). If the user chooses the option to reduce the number of stations to be sampled, the IDSS may propose the method suggested by Chen et al. (2012) which relies on a numerical model to reduce the number of stations sampled by cutting the stream into homogeneous sections. The system may also propose a method to access the optimal number of stations to be sampled using hybrid cluster analysis (Khalil and Ouarda, 2009). The choice of one method rather than another will depend on the reliability of the data and on the degree of subjectivity that the manager is willing to accept. The IDSS can also propose additional (complementary) methods.

Objective 3 (validate if the sampling frequencies for each station are optimal): this will lead the user to the lever *Frequency* (Figure 3.9). In this case, the organization may seek to save money by reducing the sampling frequency or refine its observations by intensifying the sampling frequency. In this case, the IDSS would suggest the grouping and correlation analyses used by (Khalil et al., 2010) or the General Linear Model regression and detectable difference analyses proposed by (Levine et al., 2014). Again, the user must verify many conditions in order to arrive at the final choice. The IDSS is designed to ensure that the user is aware of these conditions (for instance available data necessary of each method) before making his final choice. In addition, the IDSS will integrate cautionary remarks: for example, that the reduction in sampling efforts may lead to an increase in the uncertainty associated with the estimation of certain values.

In any case, the final decision on the method or combination of methods can be supported by the IDSS. The IDSS is designed to be able to allow the integration of new optimizing and sampling design (e.g.: (de Brauwere et al., 2009) approaches validated by the scientific community.

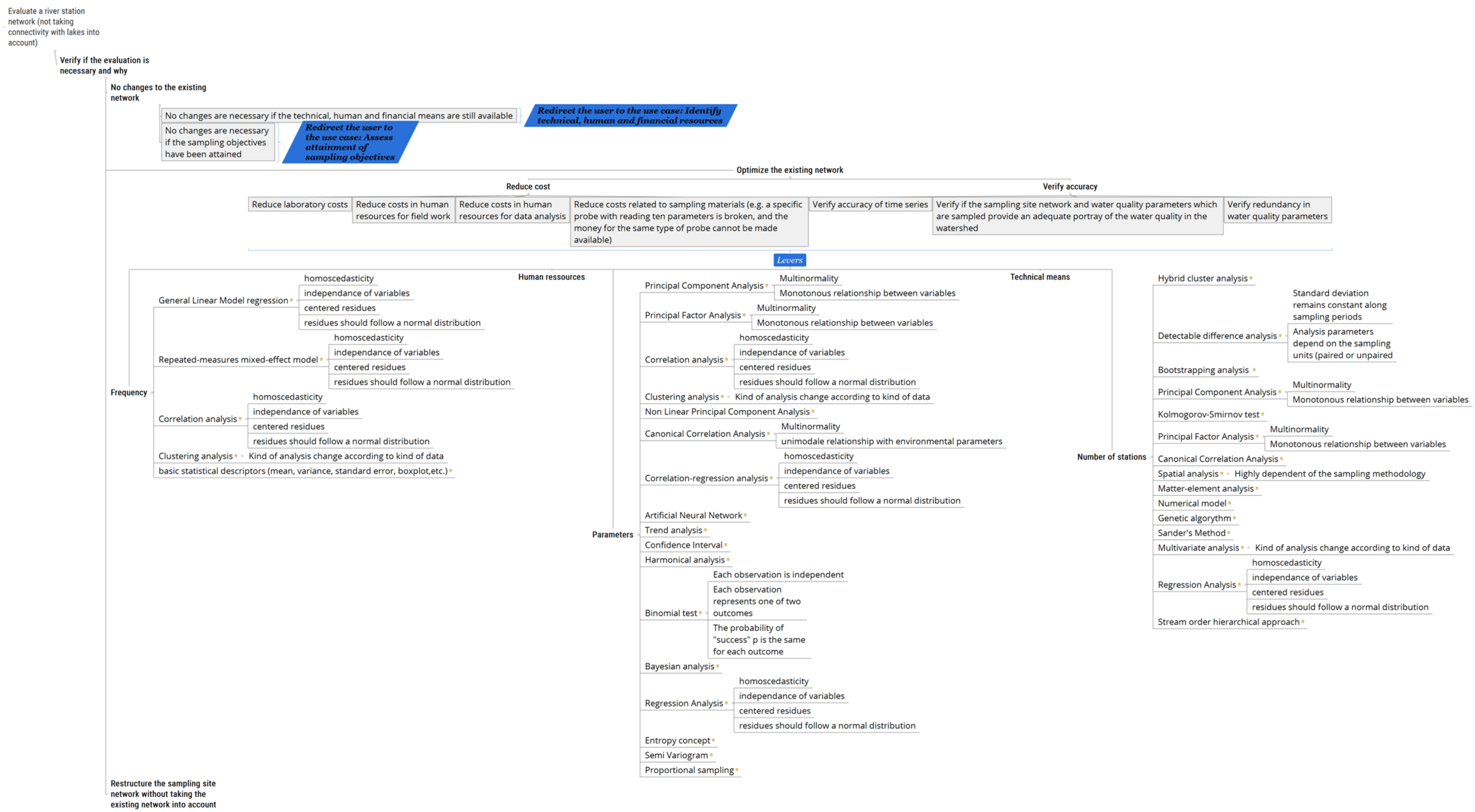

Figure 3. 9: Use-case slice: Evaluate a river station network.

3.4. Discussion and subsequent steps

3.4.1. Appropriateness of the subject domain and project context for the proposed IDSS

At the onset of the project, the analysis of appropriateness of the subject domain and project context was an important aspect to address. The results of this analysis provided very useful guidelines to continuously assess the weaknesses and strengths of the project and the system designer, thus orienting the amount of effort to be deployed and invested during the kickoff, development, construction and design phases.

The results of the high scoring categories were influenced significantly by the analysis of the complexity of the domain (Desirable task category), the implication and willingness of all the parties involved in the project to contribute (Payoff category), the availability of the subject matter experts (Business (domain) Expert category) and the users' enthusiasm to support the project (User category).

The results in the low scoring categories showed the lack of experience of the system designer at the onset of this project. This lack of experience concerned capabilities related to the design and development of systems and a background in artificial intelligence and cognitive psychology. However, this lack of experience was offset by the designer's experience in the subject domain. Another item with low scoring was the customer management category: the lack of information on revenue and cost benefits of such a system was clearly shown. The low scores in this category were offset by the scores obtained for the other statements. These statements were that the proposed IDSS could (1) improve quality, (2) capture undocumented expertise that is perishable or in short supply, (3) provide accessible expertise to novice users, (4) have a training effect on users through usage, and (5) the fact that the system, even partially complete, could still be useful. We were able to validate our initial assumptions on these points through the interviews with the subject matter experts.

This analysis showed that efforts had to focus on acquiring knowledge on conceptual framework design methodologies as well as on adapting them. This was achieved through the continuous interaction with the IT specialists and consultation of the literature on the subject (Abdullah et al., 2005; Adziz and Evans, 2014; Balzert, 2005; Charroux et al., 2010; Cohn, 2004; Jacobson, 2004; Jacobson and Seidewitz, 2014; Jacobson et al., 2011; Jacobson et al., 2016; Jacobson et al., 2013; Lange and Diercks, 2015; Patton, 2014; Rhem, 2006; Rupp, 2013; Stol et al., 2016).

3.4.2. Conceptual framework

We proposed a combination of work products to describe the IDSS: a global conceptual model of the IDSS, use-case models, use-case slice models, epics, user stories; use-case narratives and decision support trees in the form of ladders. Additional material was provided through definitions and supplementary information, when deemed necessary, to understand some system requirements. Indeed, the proposed approach proved successful: when tested, we were able to efficiently communicate the system's requirements to the IT specialists, and the system's functionalities to the end users. Therefore, the work products produced to date will enable efficient and productive programming for the key elements of the IDSS.

The system architect scored high for knowledge on the subject domain. led to efficient exchange with the end users from the two case studies in order to probe their needs – keeping in mind that the IDSS should be able to solve specific problems. At the geographical level, it was important to meet subject matter experts who worked with different types of constraints regarding regulations and policies: experts from countries subject to the European water framework directive (WFD) (Germany, France and Spain) as opposed to European countries not subject to the WFD, such as Switzerland. We also aimed to meet with experts from two different states in the United States with very different realities regarding resources and obligations related to bordering water bodies. These were experts from the Maine Volunteer Lake Monitoring Program and experts from the Vermont Department of Environmental Conservation. Finally, we met with several experts from the Province of Quebec, Canada, again with very specific realities regarding monitoring. Even between countries subject to the WFD, the difference between a centralized state (e.g., France) and a federation (e.g., Germany) had an effect on WQMPs. This difference was also apparent in the federations of Canada and the US. In addition to these geographical considerations, we also sought to meet with experts with varying expertise and roles.

Since we adapted the interview guidelines to the specific backgrounds of each of the subject matter experts, we believe that we were able to (1) fill the knowledge gaps on the subject matter that continued to exist after we had completed the literature review, and (2) narrow the multitude of information and needs down to the priority requirements of the IDSS..To a certain extent, it was also possible to identify the continuing challenges of WQMP planning, managing and optimizing to which watershed managers and end users of the IDSS will be exposed. Therefore, it was possible to identify the use cases that needed to be prioritized for the IDSS while retaining some elements in a backlog for a later development phase.

It proved helpful to involve the IT specialists from the very onset of the project. During our discussions with the IT specialists, we explained the objectives of the project and informed them of the limits of the system designer's abilities to use a given design process. This resulted in in-depth discussions with the IT specialists: they spent a great deal of time asking questions about the projected system's requirements in order to be able to (1) point out existing software modules, (2) propose ways of designing the system in order to ensure efficient communication between the system architect, the end users and the IT specialists and (3), validate the proposed material.

Key to the success of this project was the enthusiasm of the end users who wanted to be part of the project. This had a direct impact on their involvement, especially during the workshops. To promote enthusiasm and involvement from the onset of the project, the end users were encouraged to contact the system designer with any questions they might have during the operation of their respective WQMPs. This actually led to the system designer identifying additional use cases and use-case slices. The discussions held during the workshops revealed many questions regarding the specific users of the system and how they fit in. These discussions influenced the list of actors and specific users, their interaction with specific use cases and the interaction of the use cases between them. Several fundamental questions were also raised during the workshops: Who is responsible for the WQMP and why? Who should pay? How to establish credibility? How to build trust between the stakeholders? Other questions focused primarily on practical questions such as data management, data exploitation and field work. One key point in all the interviews and workshops involved questions regarding the territory to monitor and the monitoring objectives.

3.4.3. Discussion on the conceptual model, the example outputs and applications

The general conceptual framework (result of the literature review) with its high level of abstraction proved very useful in explaining the projected IDSS to the subject matter experts, the IT specialists and the end users (Figure 3.5). This framework was used to quickly introduce the project during the interviews and workshops. It served as a guide during discussions. This simple conceptual framework already illustrates that there are two necessary components of the IDSS that need not be part of the IDSS itself as long as the IDSS can communicate with theses systems: the database and the business intelligence modules. Thus, this conceptual framework illustrates what the IDSS must do and which modules already exist. Also, this conceptual framework illustrates that the system must be driven by stakeholders' knowledge needs and a participative approach to gain insight into the stakeholders' knowledge needs (Behmel et al., 2016; Raadgever et al., 2008; Timmerman, 2005).

The workshops with the end users from Abrinord and APEL helped draw up the global use-case model (Figure 3.6). The approach of first having end users from these two organizations team up in pairs, followed by a group exchange on the results, was instrumental in developing the global use-case model. Indeed, during these workshops the key use cases were identified: the port of entry into the system - *Delimit a watershed (territory) subject to the WQMP,* and the use case that would provide the key feedback loop to which every decision taken within the system must refer: the monitoring objectives. The workshops were also fundamental in identifying the variety of possible users for the IDSS, which again influenced the design of the global use-case model. In addition, the workshops served to identify a plenitude of additional use-case slices, user stories, as well as decision processes and local realities which very much enriched the IDSS.

3.4.3.1. Discussion on the example output of the use case: Delimit a watershed (territory) subject to the WQMP

The development of the use-case model *Delimit a watershed (territory) subject to the WQMP* served as a reminder that the ultimate purpose of completing the steps illustrated in this use-case model (Figure 3.7) was to assess the capacity of the regimes in the territory chosen for a WQMP to effectively manage their water resource and adapt to new problems through policy making. This is directly linked to monitoring, since monitoring should be able to evaluate whether the policies (actions) implemented have improved or degraded water quality, or if no change might be assessed (Armitage et al., 2015; Gerlak et al., 2011; Raadgever et al., 2008). This premise implies that monitoring objectives must be very precise in order to properly assess policy outcomes, since this process will also influence decisions concerning the territory under consideration, and send the user to the use cases *Define monitoring objectives* and *Assess attainment of monitoring objectives.*

This use-case model also highlighted the fundamental need for an encompassing database in order to pool varying types of data and information and allow a huge variety and liberty of queries. In addition, it was made clear that it is indispensable to share data, information and decision processes between stakeholders. This is also necessary in order to implement efficient monitoring programs, build trust and implement effective management plans (Armitage et al., 2015; Gerlak et al., 2011).

3.4.3.2. Discussion on a sample output of the use-case slice: Evaluate a sampling site network

The illustration of the use-case slice *Evaluate a sampling site network* showed how existing approaches developed to assist an organization plan, manage and optimize a WQMP can be integrated into such a system and help the user make informed decisions during the process. It also showed how the IDSS will guide the user towards specific optimization methods according to optimization objectives and available data sets. Since there are no absolute methods to decide the relevance of a sampling site network or the sampling at a specific station, some choices must be made and the IDSS is designed to guide the user through possible choices and reflections. However, one must bear in mind that the IDDS does not take the decision on the final sampling site network. Some verifications proposed by the IDSS can be made mandatory through a user-configurable setting (e.g., minimum requirements a sampling station has to comply with, such as mixing, accessibility, availability of stream flow gauge, etc.) or through settings at the programming stage (e.g., make it mandatory that a user identify a justification for a sampling site). The set of restrictions in the settings of the IDSS can be adapted to specific users' realities. It is important to understand that compromises must be made at some point and that these compromises are documented in the decision process

3.4.4. Subsequent steps for the testing and implementation of the IDSS

The next main step in the implementation of the IDSS (transition and programming) is to prioritize the use cases to be implemented first. This will be achieved through further testing of the system with the data of the two case studies described in this paper. The testing will be performed in two steps. The first step will be to elicit, for each of these watersheds, stakeholder knowledge needs for an optimized WQMP. In addition, the attainment of past monitoring objectives will be assessed. In order to achieve these goals, we propose a participative approach in which each step is suggested in the IDSS's use cases: *Define monitoring objectives* and *Assess monitoring objectives*. The second step will be to test the IDSS's use case: *Establish a sampling site network* for each of these watersheds with the input from the results of the participative approach. Note that the use case *Establish a sampling site network* can direct a user to the use-case slice discussed in this paper: *Evaluate a river sampling site network*. The workflow generated through this testing will further guide the prioritization of use cases to be implemented on a scale from *essential* to *desirable.*

3.5. Conclusions

The goals of this paper were to present the design methodology of a conceptual framework of an intelligent decision support system (IDSS) to plan, manage and optimize water quality monitoring programs (WQMPs) for surface waters and to provide a conceptual framework of such a system ready for implementation. These goals emerged as a result of a previous literature review which revealed that presently, there is no holistic, adaptable and evolvable tool to assist a watershed organization in every aspect of planning, managing and optimizing a WQMP.

The following aspects are to be retained for the design methodology of the IDSS :

- It is crucial to assess to which point the subject domain and external conditions to develop an IDSS are appropriate in order to identify the strengths and weaknesses of such a project and to identify the needs and potential pitfalls;
- Existing design methodologies for software can be adapted to specific design needs and can be fairly easily assimilated and adapted by a system designer who is not familiar with these methodologies;
- Profound knowledge of the subject domain by the system designer was probably more crucial to the success of designing the IDSS than the knowledge on design methodologies;
- The availability and interest of the end users (12 members from two case studies), subject matter experts (44 subject matter experts and five IT specialists was crucial to the success of such a project and confirmed the need for the IDSS;
- It was necessary to integrate as much subject matter expert knowledge as possible into the IDSS in order to cover (1) the tacit knowledge not available in the literature and (2) to be able to understand how such a

system can formalize the planning, managing and optimizing processes of a WQMP, yet remain adaptable to the regional specificities of potential end users;

- Active inclusion of end-users throughout the process was key to the success to designing such a system and in obtaining use-cases and user stories;
- Integration and understanding of existing tools (databases, software modules) and approaches (e.g. to optimize sampling site networks) is crucial to attain the goals of such a holistic project and to valorize past, current and future work.

The proposed IDSS which is presented in part in this paper:

- Addresses every aspect of planning, managing and optimizing a WQMP;
- Provides a common framework to plan, manage and optimize WQMPs while allowing some flexibility so that the users might set the system to local, regional, national and international settings;
- Allows to parameterize adjustments to the system in order to respond to local, regional, national and international specificities;
- Can be adapted to different types of monitoring challenges: compliance monitoring, surveillance monitoring, investigative monitoring, as well as to the planning and managing of short term studies on water quality, and to the planning of sampling campaigns to feed models on water quality and quantity;
- Can be parameterized to fundamental differences related to water governance, water quality monitoring strategies, local realities, legal obligations, policies and, budget constraints;
- Renders decision steps related to planning, managing and optimizing WQMPs transparent and communicable to those who (1) need to make decisions on the subject without having all the data, information and knowledge and (2) are not involved in the decision making, but need to understand the rationale of the underling decisions which have been taken;
- Provides decision support to a variety of users tasked with planning, managing and optimizing WQMPs;
- Is able to evolve, grow and allows for the implementation of new features;
- Can be expanded, updated and can integrate new and old methods, tacit and implicit knowledge and end users' needs for each of the use cases;
- Contributes to increasing the value of both explicit and tacit knowledge of the subject domain;
- Contributes to improve quality, to capture undocumented expertise that is perishable or in short supply, provides accessible expertise to novice users and has a training effect on users through usage;
- Can be used for WQMPs for lakes and rivers and can eventually be adapted to groundwater monitoring WQMPs.

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Transition between chapter 3 and chapter 4

In Chapter 3, the design methodology of an IDSS to support WQMP managers in the planning, management and optimization process of WQMPs was presented. The system was developed based on a literature review of scientific and practical literature, subject matter expert knowledge and close collaboration with potential end-users from the two case studies. The system was designed to be driven by precise planning and optimization objectives. As stated earlier, these objectives must be elicited through participative approaches. Such an approach was developed and tested on the same case studies as those with which the IDSS was designed (Chapter 3 and Chapter 4). In Chapter 4, the IDSS was tested based on the results of the participative approach and the data from the WQMPs of the two case studies.

4. CHAPTER 4: Optimization of river and lake monitoring programs using a participative approach and an intelligent decision-support system

Optimisation de programmes de suivi de rivières et de lacs à l'aide d'une approche participative et d'un système intelligent d'aide à la décision

Résumé Nous avons développé un système intelligent d'aide à la décision (SIAD) basé sur une approche holistique afin de fournir une aide à la décision à toutes les étapes de la conception, de la gestion et de l'optimisation de programmes de suivi de la qualité de l'eau (PSQE). Le SIAD a été partiellement implanté et connecté à une base de données développée antérieurement, Enki^MD^. Il a été conçu de manière à proposer des méthodes d'optimisation existantes tirées de la littérature qui correspondent aux divers types d'objectifs d'optimisation, comme évaluer le nombre de sites d'échantillonnages, les paramètres de la qualité de l'eau et la fréquence d'échantillonnage. Toutes ces approches d'optimisation ont le même dénominateur commun : elles n'abordent pas clairement les questions qui doivent être posées avant, pendant et après leur application. Ces questions touchent la compréhension de la conception du PSQE existant, la génération d'objectifs d'optimisation, le choix de la stratégie d'optimisation appropriée, la validation, le stockage et le traitement des données avant l'analyse statistique, la génération de résultats ainsi que le choix des critères de validation et la validation subséquente des résultats. Le SIAD proposé intègre les connaissances d'experts à ces décisions de manière à standardiser les étapes et à les rendre transparentes et transposables. Dans le cadre de cet article, nous avons testé les fonctionnalités d'optimisation du SIAD sur un programme de suivi d'un lac et celui d'un programme de suivi de rivières, qui ont fait l'objet d'études de cas au Québec, Canada. Nous avons été en mesure d'illustrer la manière dont le SIAD aide à la prise de décision au cours des étapes suivantes : compréhension des raisons qui justifient l'existence des PSQE actuels, validation et intégration des données (contrôle de la qualité et stockage), choix du processus d'optimisation parmi ceux proposés par la littérature, mise en œuvre et parachèvement du processus d'optimisation. Nous avons aussi démontré qu'une base de données robuste est nécessaire dans le cadre de chaque PSQE afin de permettre la gestion des données et la prise de décisions. De plus, un SIAD est essentiel pour prendre et documenter tout type de décision durant les étapes de conception, de gestion et d'optimisation dans le but de savoir précisément quand et pourquoi des changements sont apportés, puis de déterminer les tâches concrètes du processus d'optimisation qui sont documentées et font l'objet d'un suivi sur les tableaux de bord.

Abstract. We developed a holistic intelligent decision-support system (IDSS) to provide decision support for all steps in planning, managing and optimizing WQMPs. The IDSS was partially implemented and connected to a previously developed database, Enki™. The IDSS was designed to propose existing optimization methods from the literature that correspond to different types of optimization objectives, such as evaluating the number of sampling sites, water quality parameters and sampling frequency. All these optimization approaches have the same common denominator: they do not clearly address the questions that must be asked before, during and after the application of these methods. These questions include: understanding the network design; generation of optimization objectives; selection of the appropriate optimization strategy; data validation and storing prior to statistical analysis; data treatment prior to statistical analysis; generation of results; selection of threshold criteria and post-validation of the results. The proposed IDSS integrates expert knowledge on these decisions to standardize the steps and make them transparent and transferable. In this paper, we tested the optimization features of the IDSS on two WQMPs, a lake and a river WQMP from two case studies in the province of Quebec, Canada. We were able to illustrate how the IDSS provides decision support for the following steps: understanding the underlying rationale of the existing WQMPs; validating and integrating data (quality assessment and storage); selecting optimization procedures proposed in the literature; applying the optimization procedures and finalizing the optimization procedure. We also demonstrated that every WQMP needs a solid database for data management and decision making. In addition, an IDSS is necessary to take and document any type of decision during the planning, management and optimization phases in order to obtain a clear idea of when and why changes are made and determine actionable tasks in the optimization process documented and monitored by dashboards.

Keywords: *intelligent decision support system; water quality; monitoring; data management; database; expert knowledge*

Abbreviations:

Abrinord – *Organisme de bassin versant de la rivière du Nord;* **APEL** – *Association pour la protection de l'environnement du lac Saint-Charles et des Marais du Nord;* **FC** – *Fecal coliforms;* **IDSS** – *Intelligent decision support system;* **IWM** – *Integrated watershed management;* **TSS** – *Total suspended solids;* **TP** – *Total phosporus;* **PPGIS** – *Public participation geographical information system;* **W1** – *Watershed 1 = Watershed of the Saint-Charles river;* **W2** – *Watershed 2 = Watershed of the rivière du Nord;* **WQMP** *- Water quality monitoring program*

4.1. Introduction

Water quality monitoring programs (WQMP) are essential in order to provide decision makers with the necessary information to implement best management practices; they are also essential to gain citizen and stakeholder support by disseminating the relevant information (Gerlak et al., 2011; Timmerman, 2005; Timmerman and Langaas, 2005). WQMPs can be defined as a long-term, spatially distributed, standardized surveillance and quality assessment of all the activities surrounding water quality monitoring. WQMPs also need to be updated continuously in order to respond to new knowledge needs and adapt to new technologies, policies, constraints and opportunities in human, technical and financial resources (Fölster et al., 2014).

When planning a WQMP, the following issues must be addressed: (1) setting realistic and representative monitoring objectives; (2) determining sampling sites; (3) choosing water quality parameters; (4) establishing sampling frequency and recurrence; (5) considering logistics; (6) assessing technical, financial and human resources; (7) identifying information diffusion channels and (8) assessing how the information can be put to use (move on to action) (Government of Australia, 2009; Behmel et al., 2016; Strobl and Robillard, 2008; Ward et al., 1990). When optimizing a WQMP, it is necessary to evaluate whether the existing WQMP (1) has covered all planning criteria; (2) if monitoring objectives have been met or have emerged and (3) if technical, financial and human resources have evolved and been used adequately (4) whether changes in laboratories, laboratory methodologies, probes and field observations have occurred, etc. It is also of the utmost importance to verify whether the information produced within an existing WQMP has been properly channeled, put to use and prompted management action to protect water resources (Behmel et al., 2016; Harmancioglu et al., 1999; Ward et al., 1990).

The planning, management and optimization of a WQMP is a complex process involving many decisions that must be documented and supported through decision-support systems and adequate data management systems (Behmel, 2010; Behmel et al., 2016; Strobl and Robillard, 2008; Tennakoon et al., 2011; Ward et al., 1990). In addition, the planning and optimization of WQMPs should be based on precise monitoring and optimization objectives (Behmel et al., 2016; Beveridge et al., 2012). The literature stresses the fact that many WQMPs are based on imprecise and assumed monitoring objectives that fail to respond to representative or realistic knowledge needs. In addition, WQMPs are rarely optimized in hindsight to monitoring objectives that influenced the design of these networks, nor are WQMPs optimized according to clear-cut optimization objectives (Bartram J. and R. Ballance, 1996; Harmancioglu et al., 1999; Strobl and Robillard, 2008; Wilkinson et al., 2007).

Many handbooks and guidelines exist to plan WQMPs and many optimization methods have been developed. However, they are not part of a holistic solution addressing every aspect of WQMP planning, management and optimization (Behmel et al., 2016). Therefore, it was suggested that a holistic decision support tool should be developed to account for all steps all steps in planning, managing and optimizing WQMPs (Behmel et al., 2016; Strobl and Robillard, 2008). The conceptual model of such an Intelligent Decision-Support System (IDSS) was developed and connected to a previously developed database Enki™ (Behmel et al. submitted and Behmel, 2010).

The purpose of this paper is to test some of features of the IDSS implemented and test decision-support workflows prior to implementation. More precisely, the optimization process proposed by the IDSS is tested herein using the data of two watershed case studies from the province of Quebec, Canada. The optimization process is based on a selection of optimization objectives elicited through a participative approach conducted on both case studies (Behmel et al. submitted).

The IDSS was designed to propose existing optimization methods from the literature which correspond to different types of optimization objectives, such as evaluating the number of sampling sites, water quality parameters and sampling frequency (Beveridge et al., 2012; Khalil et al., 2010; Levine et al., 2014; Ouyang, 2005). The proposed IDSS is extending on existing procedures by considering the following elements before, during and after the application of these methods: understanding of the network design; generation of optimization objectives; selection of the appropriate optimization strategy; data validation and storing prior to statistical analysis; data treatment prior to statistical analysis; generation of results; selection of threshold criteria and post-validation of the results (Behmel et al., 2016; Olsen et al., 2012; Strobl and Robillard, 2008).

4.2. Methodology

The global workflow of the entire optimization process of a WQMP is illustrated in Figure 4.1.: (1) Identify stakeholder concerns through a participative approach to elicit knowledge needs supported by a public participation geographical information system (PPGIS); (2) identify new monitoring and optimization objectives and validate the attainment of past monitoring objectives; (3) understand the rationale behind the existing WQMP; (4) integrate data from the existing WQMPs into the database connected to the IDSS; (5) interrogate the IDSS on optimization suggestions based on the input from the first three points; (6) propose optimized WQMPs and validate proposals with the decision makers of the existing WQMPs. Stakeholders, as illustrated in this figure, are defined as citizens and representatives of organized stakeholders (e.g., industry; agriculture; ministries; municipalities; watershed organizations; associations, etc. that were identified through the stakeholder analysis) (Behmel *et al.* submitted).

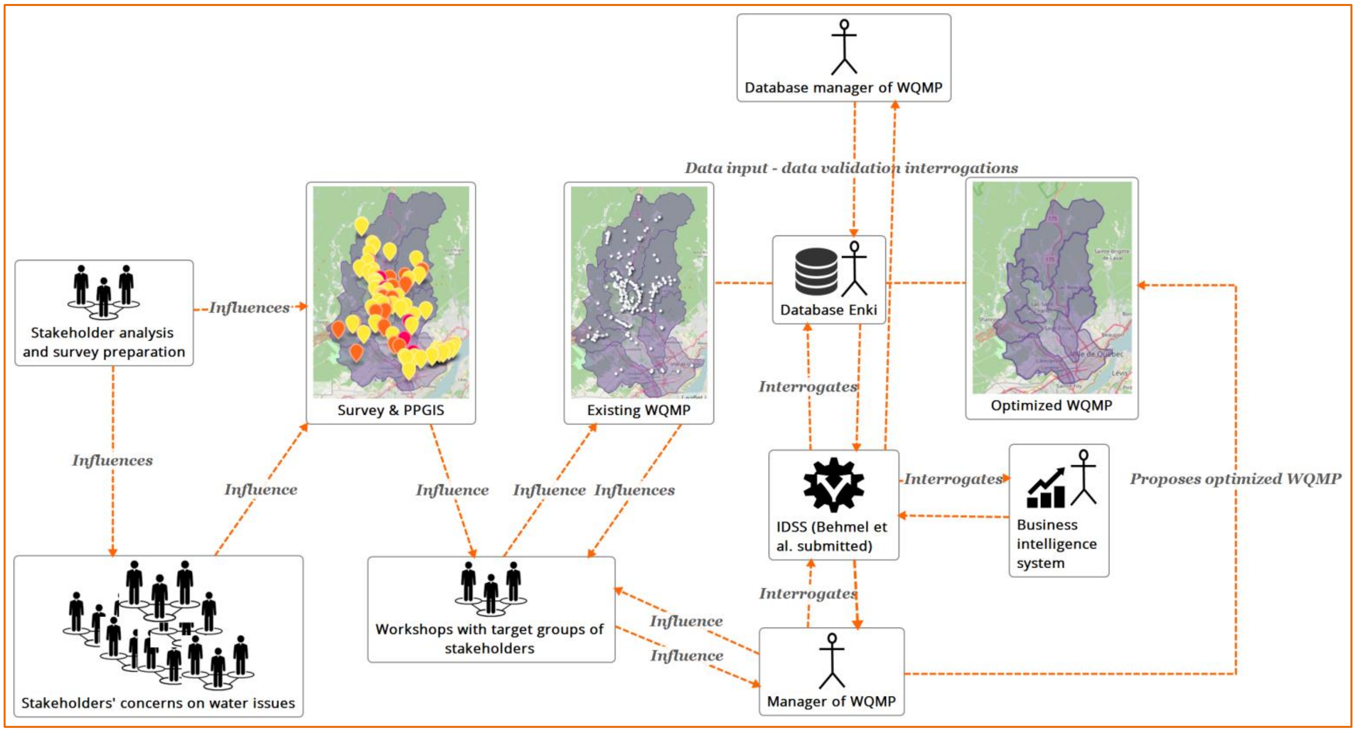

Figure 4. 1: Global workflow of the optimization process of the WQMPs. The purpose of the participative approach is to assess the attainment of past monitoring objectives and yield new monitoring objectives and optimization objectives. The results will influence the questions that the WQMP manager asks the IDSS to help the WQMP manager redesign the WQMP.

(1) In this paper, we present the test of the IDSS and show how it contributes to understanding the initial WQMPs (Method section 2.1);

(2) Supplies decision support in data validation, data quality assessment and storage (Method section 2.2);

(3) Proposes optimization procedures (Method section 2.3);

(4) Contributes to the application of the optimization procedures (Method section 2.4);

(5) Provides decision support to finalize the optimization procedure (Method section 2.5);

(6) Is instrumental in the redesign of the WQMPs (Results and discussion section 3).

The IDSS was tested with two watersheds in the province of Quebec, Canada. The optimization objectives were specific to each watershed. The first to be tested was Lac Saint-Charles, a lake WQMP (size of the watershed: 198 km^2 – hereafter W1). This lake is the main drinking water reservoir of the city of Québec where an extensive cyanobacteria monitoring program was implemented in 2011 to obtain a spatio-temporal portrait of the cyanobacteria community in the lake (APEL, 2014a). This WQMP is operated by the *Association pour la protection de l'environnement du lac Saint-Charles et des Marais du Nord* (APEL) and financed by the city of Québec. Given the cost of the analysis of the cyanobacteria species of nearly 300 samples per year, the main optimization objective here was to evaluate whether a reduction in sampling frequency, sampling points and number of samples per sampling station for cyanobacteria (up to three at different water depths) would result in a loss of information. The general characteristics of the W1 WQMP are presented in Figure 4.2.

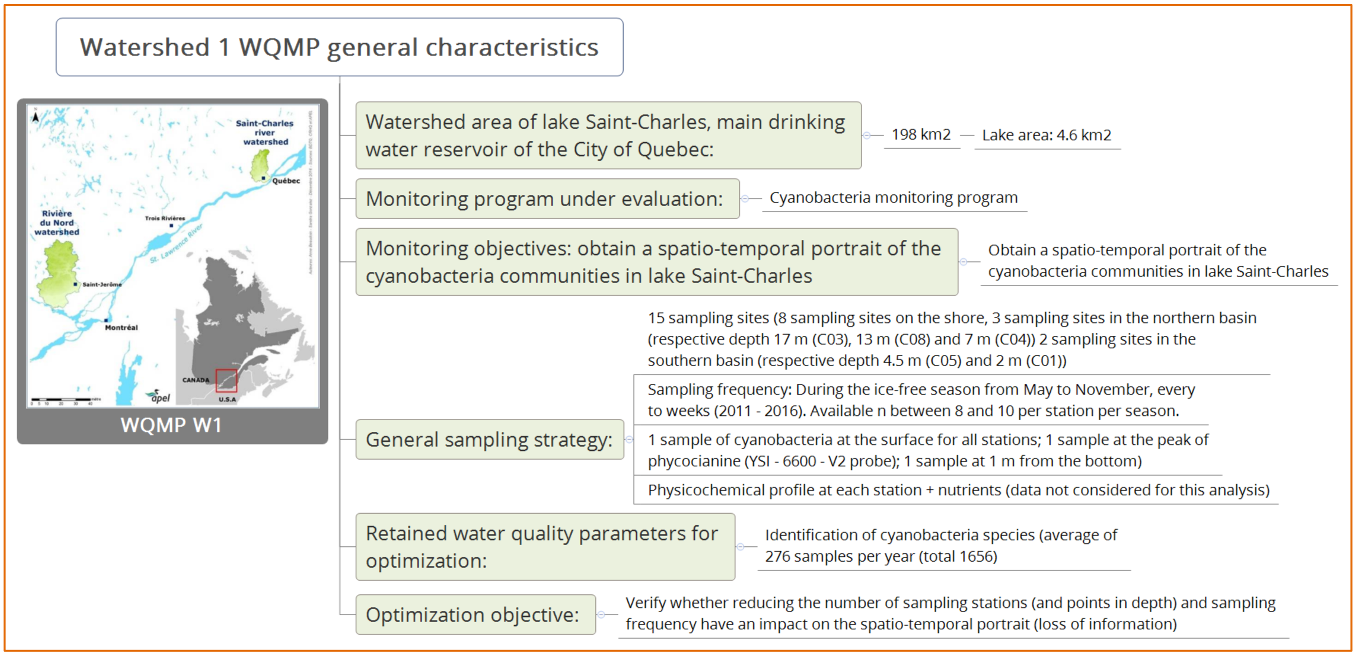

Figure 4. 2: Outline of the Lac Saint-Charles WQMP (W1) and the optimization objective tested in this paper.

The second watershed was the watershed of the river, Rivière du Nord (hereafter W2), north-east of Montreal. In this watershed (size of the watershed: 2222 km^2), a river monitoring program was implemented in 2009 to assess water quality to protect public health and follow nutrient concentrations and erosion (Abrinord, 2012). This WQMP is operated by the *watershed organization of the Rivière du Nord river* (Abrinord) and financed by several municipalities within the territory. Given the vast territory, financial limitations and new monitoring objectives, the optimization objective was to evaluate whether a reduction in the number of sampling sites would be possible. In addition, the objective was to find out whether sufficient samples had been taken in wet weather conditions and whether the sampling frequency was sufficient to respond to the initial monitoring objectives. The objective of capturing wet weather conditions is to capture water quality impairment due to runoff from non-point pollution sources (USEPA, 2001). The general characteristics of the W2 WQMP are presented in Figure 4.3.

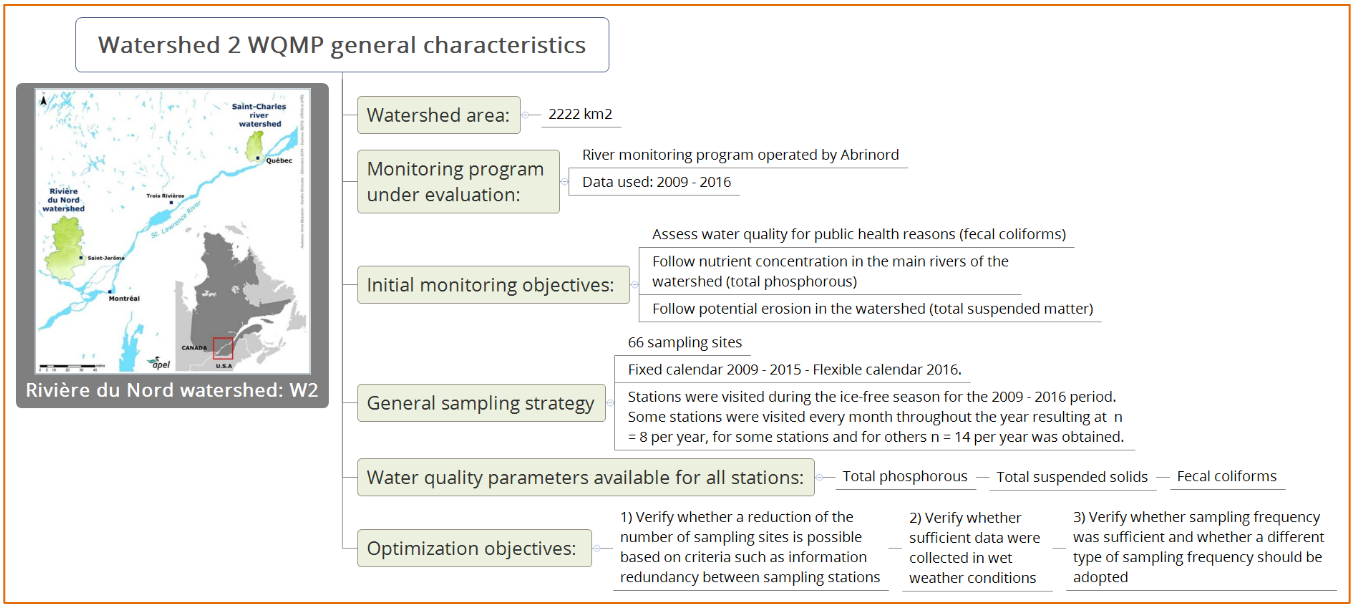

Figure 4. 3: Outline of the Rivière du Nord WQMP (W2) and the three optimization objectives retained for this paper.

4.2.1. Understanding the initial WQMPs and data validation and integration

Figure 4.4 illustrates the questions raised by the IDSS in order to understand and evaluate the existing WQMP. These questions include queries on the initial incentives and stakeholders that led to the WQMP and the underlying objectives. Further questions focused on the rationale behind the choice of sampling sites and water quality parameters, sampling frequency, laboratories, probes etc. All the answers to these questions were documented in the system. Understanding the initial WQMP is closely linked to the data validation and integration procedure. Figure 4.5 provides an illustration of the dashboard of the W1 WQMP, as well as the features that may be consulted to understand the WQMP and the available data sets.

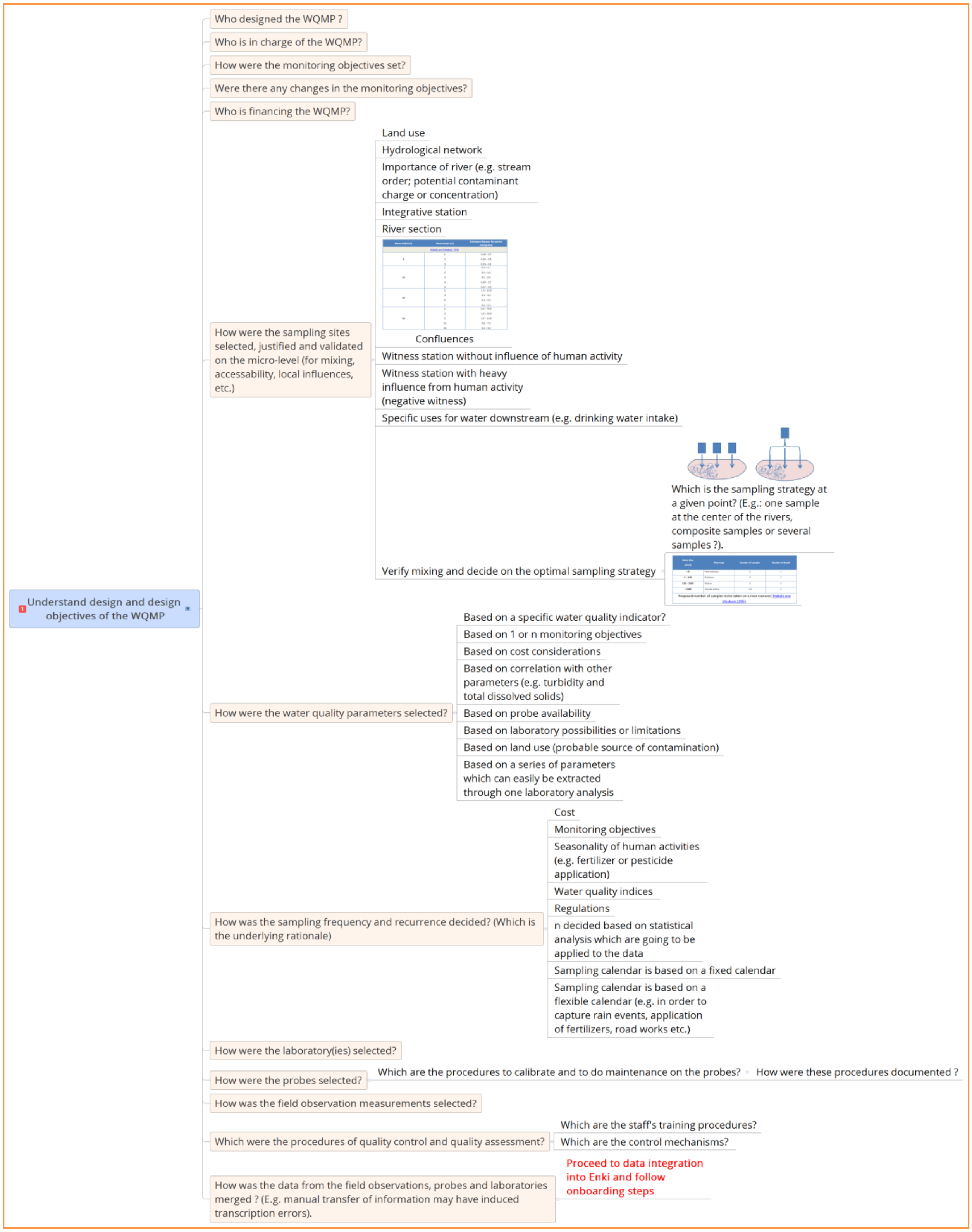

Figure 4. 4: Questions to be asked (and integrated) into the system in order to understand the design of a WQMP.

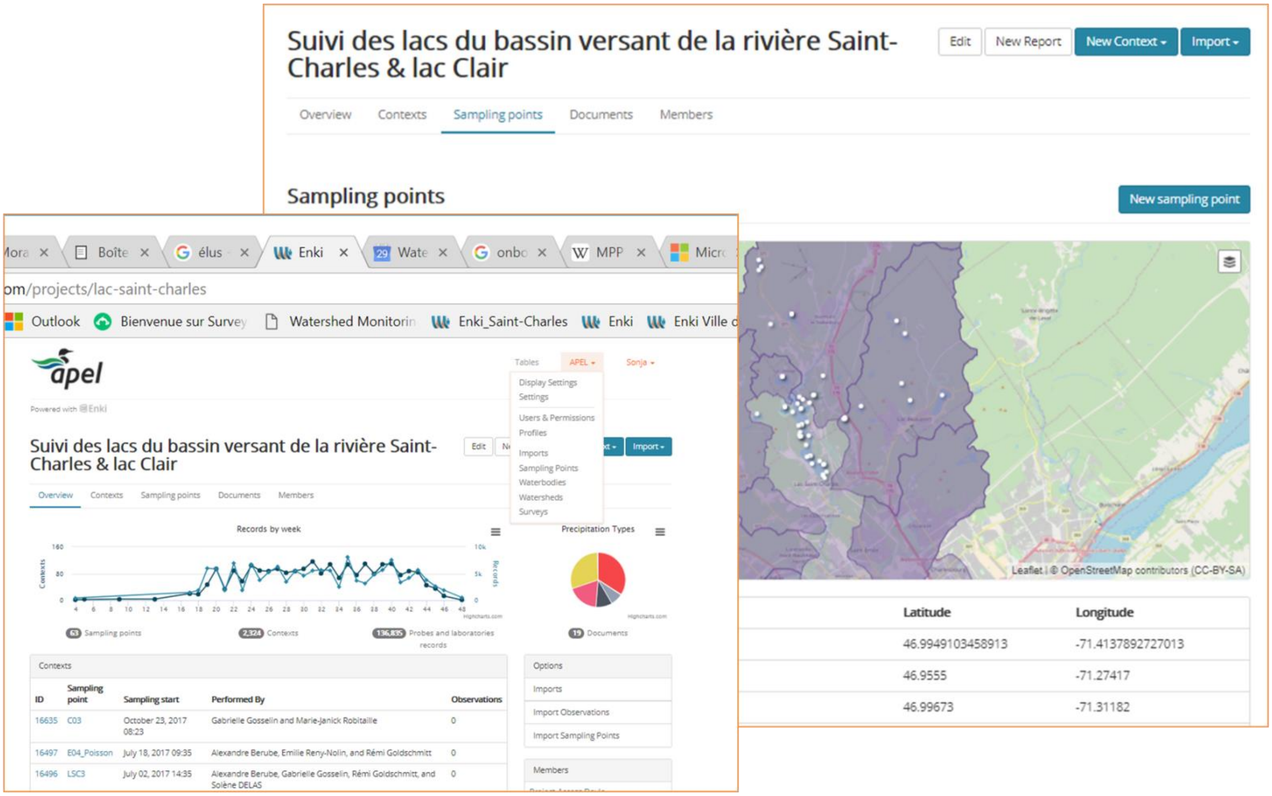

Figure 4. 5: Illustration of the dashboard of the W1 WQMP, as well as the features that may be consulted to understand the WQMP and the available data sets.

The procedures to understand the rationale of the initial WQMPs, as well as the data validation and integration process were tested on the lake data from W1 and on the river data from W2. Also, the continuous updating of the data was tested on users from both APEL and Abrinord. The data validation and integration processes, based on six steps, are illustrated and described in Figure 4.6.

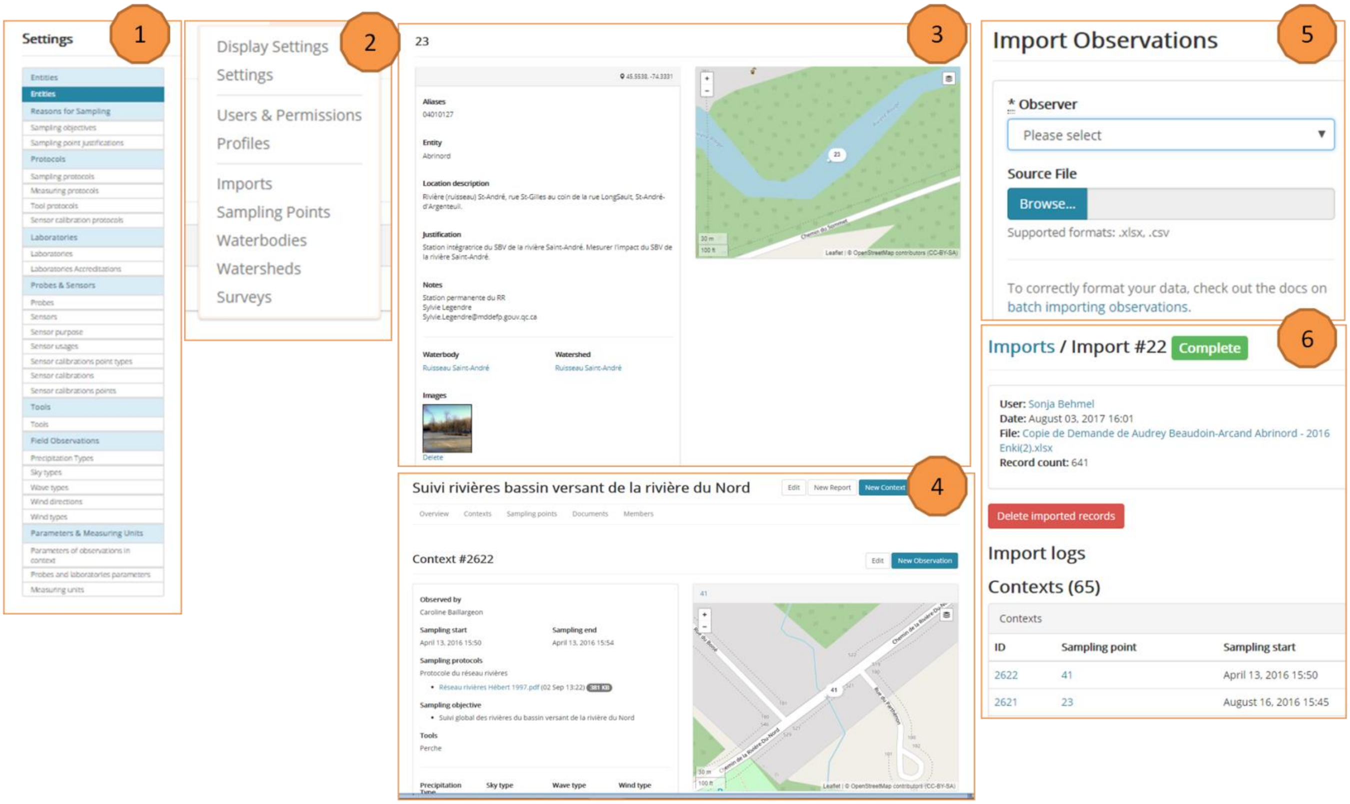

Figure 4. 6: Onboarding the data of a WQMP: Step 1: Setting (e.g., sampling objectives; sampling site justification; protocols; tools; probes; probe calibration protocols; laboratories; laboratory specificities; field observations; parameters and measuring units. Step 2: Importing shapefiles of watersheds and waterbodies, metadata on shapefiles; waterbody descriptions (e.g., bathymetry, length, fetch, volume, perimeter etc.). Step 3: Creating sampling sites (e.g., geographical location, justification, waterbody (from drop down lists created during steps 1 and 2. Step 4: Entering measurement contexts – field work (e.g., field personnel, time frame spent in the field, sampling protocols; sampling tools; probes and laboratories used; field measurements taken (e.g., transparency); field observations (e.g., rainfall and wind) etc.). Step 5: Importing data from Excel and CSV files from probes and laboratories automatically connected to the contexts. Step 6: Validating import reports and corrections if necessary.

All data for the W1 WQMP were batch imported from the Enki™ prototype, an ACCESS database, built and tested previously (Behmel, 2010). Data included information from sampling contexts, laboratories and probes from 2011 to 2015. Data from 2016 were integrated directly into Enki™ during the testing phase. For the cyanobacteria monitoring program, 15 sampling sites were created and some 2000 sampling contexts and more than 100,000 probe and laboratory records were entered.

Data from the W2 WQMP were stored in an Excel file with several sheets created in 2009 and continuously adapted and updated. This Excel file combined information on the sampling sites, field observations and the results of the laboratory analysis. However, not all information needed to complete the onboarding process to Enki™ was available in these files to complete step 1 (system setting) (**Erreur ! Source du renvoi introuvable.** 4.6). For instance, the sampling site justifications had to be retrieved from old paperwork related to the W2 WQMP.

Also, the results from the laboratories had been transferred manually into the Excel files. Several incongruities were detected when comparing the original files from the laboratories with the Excel files serving as data storage for the WQMP.

In addition, some of the changes in laboratories and analysis methods were not documented in these files. Therefore, we opted to integrate all sampling contexts manually by retrieving the missing information from different source files, such as probe data results and precipitation regimes. Laboratory data was then batch imported from the original Excel files of the laboratories. The origin of the data was attributed to the respective laboratories. All in all, 66 sampling stations and more than 2500 sampling contexts were created. Approximately 10,500 probe and laboratory records were batch imported and connected to the sampling contexts and sampling stations.

4.2.2. Selection of optimization methods

In order to be able to propose optimization procedures, it is necessary to understand the available methods, their analysis and their degree of difficulty. We strived to do so for several optimization methods in a previous literature review (Behmel et al., 2016). Based on new monitoring and optimization objectives, it was then possible to select an appropriate optimization method (Behmel et al., submitted).

The optimization objective of the W1 WQMP was to *Verify whether reducing the number of sampling stations (and points in depth) and sampling frequency have an impact on the spatio-temporal portrait (loss of information*) of the cyanobacteria species (Figure 4.2). For this optimization objective, we chose to apply the method proposed by (Legendre and Gallagher, 2001) which consists of visualizing species (in this case cyanobacteria) distribution through factorial correspondence analysis and then comparing a series of years (in this case 2011 to 2016) to be able to decide whether the sampling strategy will serve to obtain a spatio-temporal distribution and whether it is possible to reduce the sampling frequency and the number of sampling sites.

For the W2 WQMPs of the case studies, we chose to apply the optimization approaches proposed by Beveridge et al. (Beveridge et al., 2012) and Levine et al. (Levine et al., 2014) (Figure 4.3). Beveridge et al. (2012) propose a combination of multivariate analysis / principal component analysis (NMDS/PCA) and Kriging and Moran's index to quantify information redundancy for neighbouring sampling sites in a lake or river station network in order to reduce the number of sampling sites. We chose this method to respond to the first optimization objective of the W2 WQMP: *Verify whether a reduction of the number of sampling sites was possible based on criteria such as information redundancy between sampling stations.* Levine et al. (2014) propose a general linear regression model to assess the increase in uncertainty for reduced sampling frequency and evaluate statistical confidence in trend detection. We applied this model to the W2 WQMP to respond to the optimization objective: *Verify whether* *sampling frequency was sufficient and whether a different type of sampling frequency should be adopted.* We also applied the Kruskal-Wallis test to the data of W2 to verify whether the fecal coliform (FC), total phosporus (TP) and total suspended solid (TSS) concentrations were different depending on the observed precipitation classes of W2 (Kruskal and Wallis, 1952). The objective was to *Verify whether sufficient data were collected in wet weather conditions*, as this information would have an incidence on the choice of a fixed sampling calendar, as opposed to a flexible sampling calendar. The objective to sample in wet weather conditions was to obtain water quality data following run-off. For the W2 watershed only two hydrological stations are available and river flow is not measured during water quality sampling. Lack of river flow data for W2 was identified as an issue which must be addressed in the future (Behmel et al. submitted). Therefore, the only means of obtaining some information on the impact of run-off on water quality is the analysis of precipitation data. Here, the analysis used the information of semi-qualitative precipitation classes based on field observation and data from weather stations, when available.

The thresholds and the precipitation classes were developed through discussions with the City of Quebec and APEL and were also used by Abrinord (APEL, 2014). The approximate threshold for a wet weather event was considered 10 mm for each class. These classes were: *0 - no rain for 48 hours*; *1- rainfall the same day*; *2- rainfall 0-24 hours prior to sampling*; *3- rainfall 24-48 hours prior to sampling*; *4- rainfall 0-48 hours prior to sampling*. This information was also entered in the sampling contexts of Enki™.

It has to be noted that wet weather criteria differ in the literature and are adapted to specific monitoring objectives. For instance, non-point source monitoring aims at monitoring effects of land use on water quality in a variety of weather conditions and point-source monitoring may aim at monitoring the retention capacity of a sewer system. The wet-weather conditions can be defined through time spans and precipitation (in mm). In some cases, intensity and geographical distribution are also part of the definition (ALCOSAN, 2012).

4.2.3. Application of optimization procedures

In order to apply the optimization procedures, it was first necessary to retrieve the data through a selection and extraction process. This selection and extraction process was implemented and tested for the data of both case studies. This step allows the user (statistician) to understand the available data series, their origin and field observation contexts, such as precipitation classes and other type of observations which may also explain outliers (Figure 4.7.).

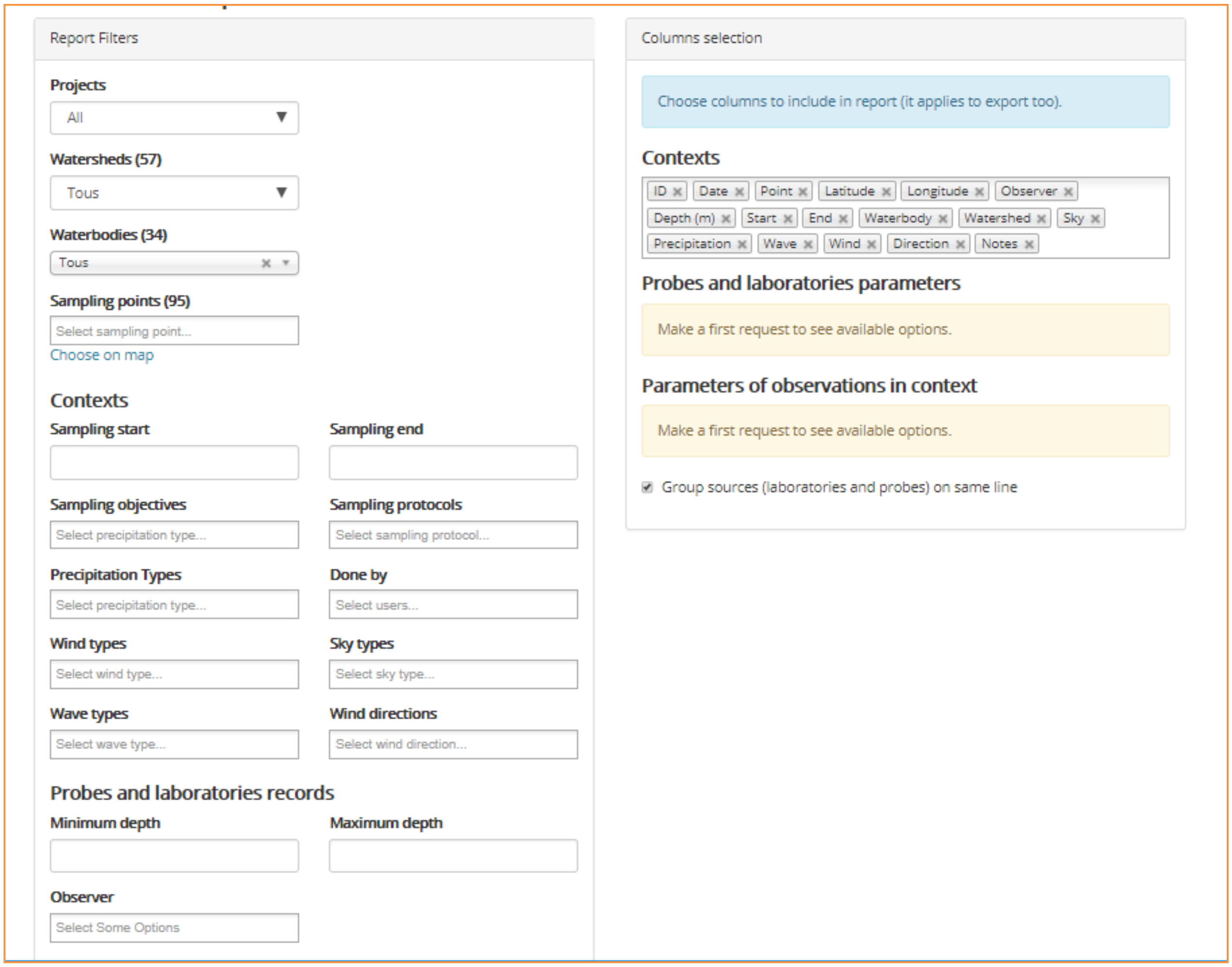

Figure 4. 7: Illustration of the available filters for data extraction. It is possible to make 1 or n selections to visualize data series or to export selection to EXCEL or CSV files.

4.2.4. Decision support during the optimization procedures

The IDSS provides decision support for questions related to the data used for the optimization. The essence of these questions is illustrated in Figure 4.8. The purpose of these questions is to support the person in charge of the statistical analysis and validate whether any kind of change in the WQMP has had an effect on data series, data integrity and comparability of data. This also includes understanding outliers through the integration of field observations in the data series, thus contributing to decisions of necessary outlier elimination for some types of analysis. It also includes decisions to be made on reconstructing missing data.

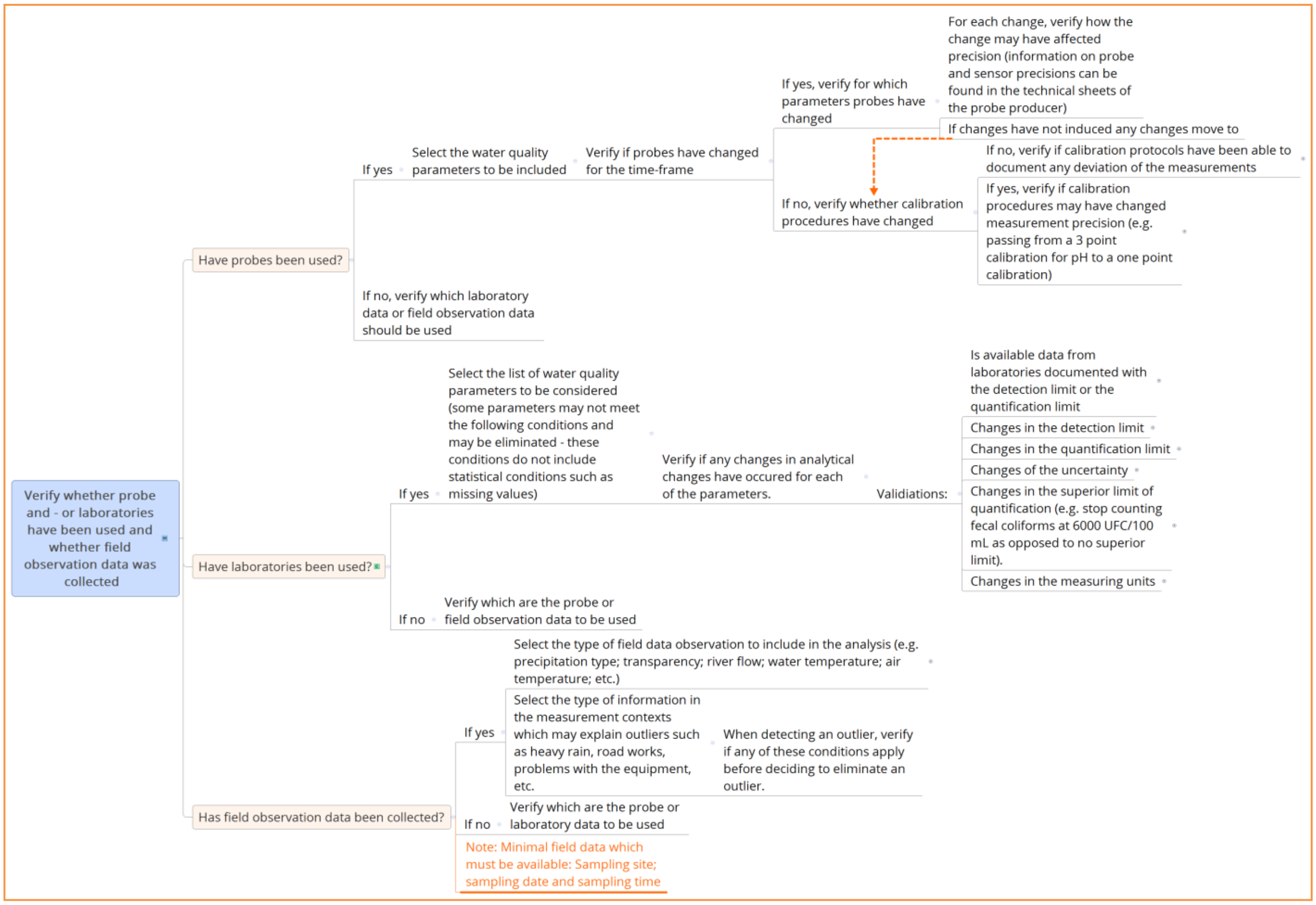

Figure 4. 8: Extraction of the decision-support questions on available data series to validate (and understand) integrity, comparability and outliers.

For W1, the optimization method which was applied can be consulted in Legendre and Gallagher (2001). For W2, the optimization method can be consulted in Beveridge et al. (2012) and in appendix C.

4.2.5. Decision support to complete the optimization procedure

The output from the statistical analysis provides a series of suggestions in line with the optimization objectives to optimize the WQMPs. Indeed, several authors have underlined the importance of bringing expert opinion into this step (Beveridge et al., 2012; Khalil and Ouarda, 2009; Pinto and Maheshwari, 2011). We thus propose that the WQMP managers be supported in this final step through questions which are integrated into the IDSS and which are based on expert knowledge (Behmel et al. submitted). The aim is to ensure consistency in the final decision-making and documentation of these decisions.

For each of the sampling sites suggested for scrutiny (removal, retention or stations considered as neutral) by the application of the statistical methods, the IDSS provides an additional series of questions to support the final decision to keep or remove a station. The same applies to suggestions on sampling frequency, adding or reducing water quality parameters, etc. A selection of questions from the decision-support trees for the final optimization of a river WQMP is listed below. If the question cannot be answered immediately, the system transforms it to an actionable task (Note that this is a non exhaustive list and the IF-THEN rules are not all shown).

A selection of questions for lakes:

- IF more than one station is visited in a lake, THEN verify the justification of the selection of each site in order to understand the rationale for each site (e.g., deepest sector of a lake; close to a major inflow; in a section of a lake with recurrent cyanobacteria blooms) (Thomas et al., 1996)
- For each station, verify the employed sampling strategy. These decisions can greatly affect the results: e.g., decisions taken on the profile (probe data every 0,5 m; 1 m etc.); decisions taken on sampling depth for laboratory parameters such as chlorophyll a; total phosporus; nitrogen compounds; cyanobacteria etc); decisions taken for the type of sampling method: e.g., horizontal bottle at a given depth; tube samplers for an integrative sample of the first n meters; etc).
- Validate whether the sampling strategy responds to the objectives and whether adding new parameters is in line with the existing sampling strategy and objectives.
- Verify whether a river WQMP is in place in order to observe changes in the watershed which may translate to the lake.

A selection of questions for rivers:

- Based on the results of the analysis provided for each station which suggest either the retention, removal or no specific action for a station, verify the following: IF a sampling site is suggested for removal, THEN verify the type of sampling site and the sampling site justification.
- IF the sampling site is an integrative station, THEN keep the sampling station
    - An integrative station is a station which is downstream from a subwatershed and represents the globality of the subwatershed.
- IF the sampling site is a section of a river, THEN verify whether a particular goal is pursued and justified for the station
    - A station of a section represents the water quality between two sampling sites and should be selected according to specific goals and pollution sources, and must be justified).
- IF the sampling site justification is a witness station, THEN verify if the sampling site still qualifies
    - A witness station is supposed to represent the natural water quality of a subwatershed – or, if it is not possible to have a witness station for every subwatershed, there should be a witness station for every sector representing the geology of the sectors of the WQMP. Therefore, it is necessary to

verify whether sufficient witness stations are available to be representative of every type of natural background in the territory subject to the WQMP.

- IF a specific goal is pursued, THEN verify whether the station is (1) still representative; (2) whether upstream and downstream stations contribute to achieving this goal – and, add, if necessary additional stations; (3) verify whether the station is still representative on the micro-level (mixing, accessibility, (new) local influences, whether water quality can be altered (improved – e.g., a waterfall – or degraded – e.g., a sewer overflow).
- Verify whether the water quality parameters taken at the station are contributive to attaining the goal (e.g., evaluate the influence of agriculture land use should include monitoring nitrogen-based compounds).
- Verify whether sufficient data were taken during wet weather conditions and, if not, adapt sampling calendar to a more flexible calendar.
- Verify whether new (additional) goals can be pursued at existing stations.
- Verify whether the sampling site justification is consistent with the stations' location and whether there must be another station implemented to be able to respond to the justification (e.g., if one wants to find out whether there is an influence of the inflow of a river at a station, there must be some information available on that river, and there must be a station upstream from this river inflow (triangle strategy).
- IF the sampling site justification is: upstream from a wastewater treatment plant (municipal or industrial), THEN there should be a station downstream from the treatment plant.

4.3. Results and discussion

In the first step, the challenge was to understand the initial WQMPs and to integrate the data into the database Enki™ connected to the IDSS.

The fact that the data were already entered in the prototype of Enki™ facilitated the process of integrating the data from W1. However, the purpose of the questions was to understand the rationale behind the selection of the lake sampling sites, the decisions taken on the sampling strategy at each site, as well as understand the sampling objectives which contributed greatly to documenting the rationale and making it transferable to WQMP managers and organizations that would like to increase the value of the data for other studies. This process also contributed to documenting the limitations of some sampling sites, such as shoreline sampling sites. This information is also crucial to optimize the network, as some of the deficits of the sampling site distribution might already be known and can be justified.

The data integration for W2 was more of a challenge, as the data had to be validated and completed from various sources. The choice of the sampling sites, their specific justification, especially for river sections, was not well documented at the outset and the information was retrieved from old paperwork. Also, changes in sampling frequency and problems in the data sets were a challenge for both the optimization of the data management and the application of the optimization approach. However, the onboarding (settings) steps and the retroactive integration of field observations, specifications on laboratories, sampling site justifications, etc. greatly contributed to obtaining a holistic view of the WQMP, as well as the specific rationale of decisions taken regarding the W2 WQMP. Data and metadata could now be efficiently consulted, visualized and retrieved. This contributed greatly to the choice of optimization methods: not only must they be based on specific optimization objectives (elicited by a participative approach), but also on the available data sets.

The data integration steps showed that the data management question is not always clearly addressed at the outset of a WQMP. This may be due to the fact that challenges related to data management are underestimated and are only addressed when the data needs to be analyzed. In addition, for lack of resources, solutions and knowledge on data management questions, data management is not always addressed adequately. For the W1 watershed this question had been addressed at the outset which led to a data management strategy which was adapted to the data management needs of a WQMP. W2 watershed managers have adopted the same strategy as W1 after this experience.

4.3.1. Optimization of the W1 WQMP – results and discussion

The step *Understand the rationale of the WQMP*, contributed greatly to providing a list of actionable tasks for the optimization of the W1 WQMP. The results from the statistical analysis for the optimization objective: evaluate whether a reduction in sampling frequency, sampling points and number of samples per sampling station (up to three at different depths) which would lead to a loss of information also contributed to the list of actionable tasks. As mentioned in Figure 4.2, one objective of this lake WQMP was to obtain a spatio-temporal portrait of cyanobacteria. However, the first and foremost objective was to obtain information on the evolution of the eutrophication of the lake. Therefore, at every station (C03; C08; C05; C04; C01 shown in Figure 4.9) visited at two-week intervals from the ice-free season (spring mixing) to fall mixing, a profile of physicochemical and biological parameters was taken at every 0.5 m with a YSI 6600 V2 probe (pH; specific conductivity; temperature; dissolved oxygen; phycocianine; chlorophyll a and turbidity). In addition, total phosporus (TP) nitrogen compounds and chloride were also taken at a depth of 1 m; in the meta-limnion and at 1 m from the bottom with a horizontal bottle (when depth permits). These stations were selected in a study conducted prior to the WQMP; the aim at this time was to continue with the same stations considered representative of the heterogenic zones of the lake. The objective of monitoring cyanobacteria was added afterwards. The objective was not only to know the distribution of cyanobacteria in the lake, but also to determine the locations onshore where they could be observed and sampled for the spatio-temporal portrait. The selection of these stations was first based on an equal spatial distribution around the lake, but was then very much influenced by accessibility and permissions to access the lake (SCx in Figure 4.9). The sampling strategy for cyanobacteria was one sample at the surface (all stations), at the peak of the phycocianine readings (lake stations) and at 1 m from the bottom (depth permitting – C0x). The sampling was done every two weeks with the other sampling campaign.

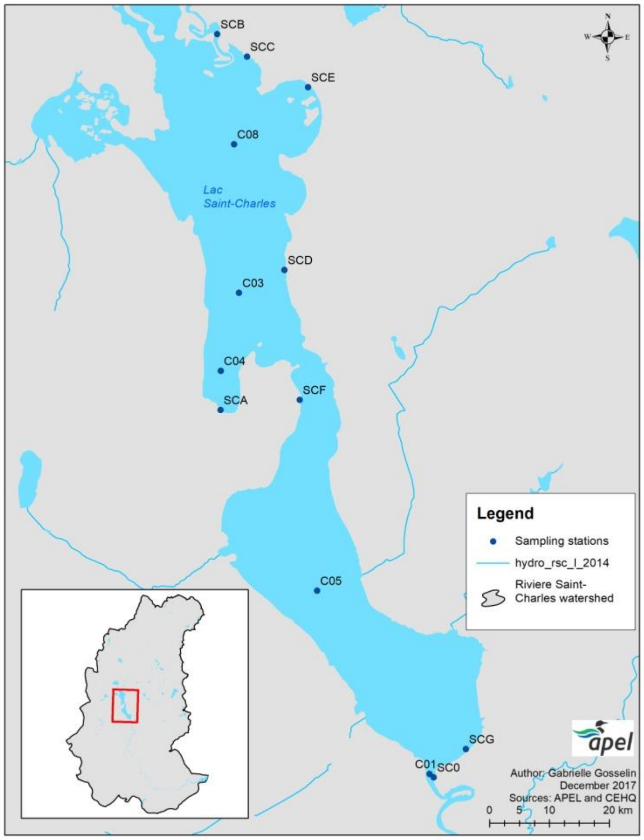

Figure 4. 9: Distribution of sampling stations on Lac Saint-Charles (lake). Maximum depth at each station: C03: 17 m; C08: 13 m; C04: 7.5 m; C05: 5 m and C01: 2 m).

The results of the analysis proposed by Legendre and Gallagher (2001), showed that there is a relative consistent factorial structure demonstrating that the distribution of the 29 cyanobacteria species is relatively constant throughout the year and between years. The results also show that there is a relatively consistent spatial distribution. For instance, *Planktothrix* sp. prefers the cold and deep hypolimnion of C08 and C03. Species such as *Anabaena* sp (now Dolichospermum). *Radiocystis* sp., *Microcystis* sp., *Aphanothece* sp. and *Aphanocapsa* sp consistently prefer the epilimnion at all stations, including the shore stations (surface and peak of phycocianine generally situated in the epilimnion) and *Planktolyngbya sp.* occupies the 4 m zone at station C05, as well as the hypolimnion at 12 m at C08. There is no difference between stations C01 and SC0, as they are very close to each other.

The conclusions of this analysis are that either station C01 or SCO could be abandoned and that the sampling frequency (every two weeks) could be significantly reduced. However, before taking a final decision, there are several actionable tasks to be followed which are summarized in Table 4.1. for the W1 WQMP.

Table 4. 1: Summary of the actionable tasks to take final decisions for the optimization of the W1 WQMP.

Actionable tasks	Verifications that must be made prior to the final decision
Verify whether changes in physicochemical parameters and other observations made in the river WQMP of this watershed can have an effect on the structure of the cyanobacteria community of Lake Saint-Charles	• The watershed of Lac Saint-Charles is exposed to multiple stressors. Data from the river WQMP show that specific conductivity is raising constantly in the main inflows of Lac Saint-Charles (APEL 2015; APEL 2016). Therefore, changes in the cyanobacteria community may occur rapidly and be an indicator of these changes. Further analysis is necessary to identify whether these changes can also be documented in Lac Saint-Charles before drastically reducing the sampling frequency. • IF there are no changes, the six years of intensive cyanobacteria monitoring can be taken as a reference, and the sampling frequency can be reduced (e.g., every 4 weeks). • IF changes in the lake occur, the sampling frequency can be increased again.
Verify sampling strategy	• Statistical analyses of links between the surface water communities and the epilimnion community may be challenging when TP and nitrogen compounds are not taken at the same depth. For economic reasons, the depth in lake stations for these analysis is at 1 m. IF the analysis for modeling cyanobacteria including these parameters is projected, then the sampling strategy should include these parameters at the same depth were the cyanobacteria are being sampled.
Verify which station can be retrieved between C01 and SC0	• Since no difference was observed between those two stations, select the station which requires less effort to be sampled. Since SC0 is accessible from the shore, this station should be kept and C01 eliminated.
Verify whether changes in the cyanobacteria monitoring affect other monitoring objectives	• During the process of understanding the rationale of the WQMP in the W1 watershed, many other monitoring objectives were identified for this lake. For any drastic change in the current strategy, the incidence on the other objectives must be evaluated. These objectives can be retrieved from the database, and the IDSS proposes the validation questions accordingly.

The WQMP revealed that it is possible to obtain a consistent spatio-temporal portrait of the cyanobacteria community with the proposed sampling strategy and sampling frequency and recurrence. In addition, sufficient data were collected to attribute the species to the trophic state of the lake. It is also possible to eliminate one station where generally two samples were taken (C01), for a total of 20 samples per year. In addition, it was shown that the sampling could be reduced to a four-week interval. However, the recommendations are to:

- ensure that changes in the water quality of the tributaries (in particular road salts) and the ensuing impact on Lac Saint-Charles are detected in order to reinstate the present cyanobacteria program and to observe changes which they may announce.

- verify whether other objectives followed within this WQMP are not compromised by these decisions.

4.3.2. Optimization of the W2 WQMP – results and discussion

After the data validation and integration process, it was much easier to gain an overview of the W2 WQMP datasets and make choices concerning the optimization processes. For this WQMP, from 2328 sample contexts (sampling outings) taken on 66 stations, a maximum of 14 water quality parameters could be observed and field observations would include precipitation classes and ambiant temperature. However, only for TSS, TP, FC and precipitation classes were sufficiently consistent data sets available for all these stations. The proportions of non-available data (NA) were only 6.4% (TSS), 7.2% (FC), and 18.4% (TP) respectively. The missing information on precipitation classes which could not be retraced represented 12.8%. Following validation with the WQMP managers, the optimization was conducted on these parameters and on all stations. The missing data were reconstructed with the package MissMDA with Software R – for further information consult Josse et al. (2012) and Josse and Husson (2016). The optimizations procedures proposed by Beveridge et al. (2012) and Levine et al. (2014) were then applied to these data sets.

For the W2 WQMP, the results on the optimization question - *Verify whether a reduction of the number of sampling sites is possible based on criteria such as redundancy of information between sampling sites* - are illustrated in Figure 4.10a. Figure 4.10b illustrates the sampling site network after having applied a first series of questions, as discussed in section 2.5. The results of this step suggest that four of the seven stations proposed for removal by the Kriging analysis could indeed be removed: stations 35, RDN121, 04010191, and 0401010192. For stations 21 and RDN121, information between the upstream and downstream stations was sufficient to obtain a picture on water quality, making these section stations unnecessary. Stations 04010191, and 0401010192 are tributaries to a lake and do not contribute any information to the river sampling site network. Other stations proposed for removal, such as M03 and 10, should be maintained as they are integrative stations. Station 04010258 should also be maintained as it is an important river section according to the justification provided (water quality downstream from the City of Lachute).. Stations suggested by Moran's analysis, 04010308 and 04010003 require further validation prior to removal. Stations such as 21 and 23 should be kept, as they are integrative stations. Stations 04010203 and 04010306 can effectively be removed as no justification is available. As for the stations to be suggested for conservation by both analysis types, some should indeed be kept, but some more actionable tasks for a final decision are necessary.

A total of five stations were suggested for a definitive removal. However, at least four stations (?1 , ?2, ?3 and 4?) should be added. Their location can be consulted in Figure 4.10.b. Station ?1 should be located on a tributary that drains an area where a ski resort and a golf course are located. Given the fact that sampling site 9 serves to verify these impacts, the outflow of this tributary should be known. Station ?2 should be added to determine water quality from Rivière du Nord upstream from this tributary. Station ?3 would be a station to be added to obtain information on the influence of Rivière Saint-Antoine. Ideally there should be a station downstream of the Rivière Saint-Antoine inflow (upstream from the wastewater treatment plant of the city of Saint-Jérôme) and downstream of the wastewater treatment plant (station ?4). A final station (?5) could be added, but accessibility and mixing are an issue. This station would be downstream of the Ruisseau St-André inflow, in order to obtain an integrative station for the Rivière du Nord river (station ?5).

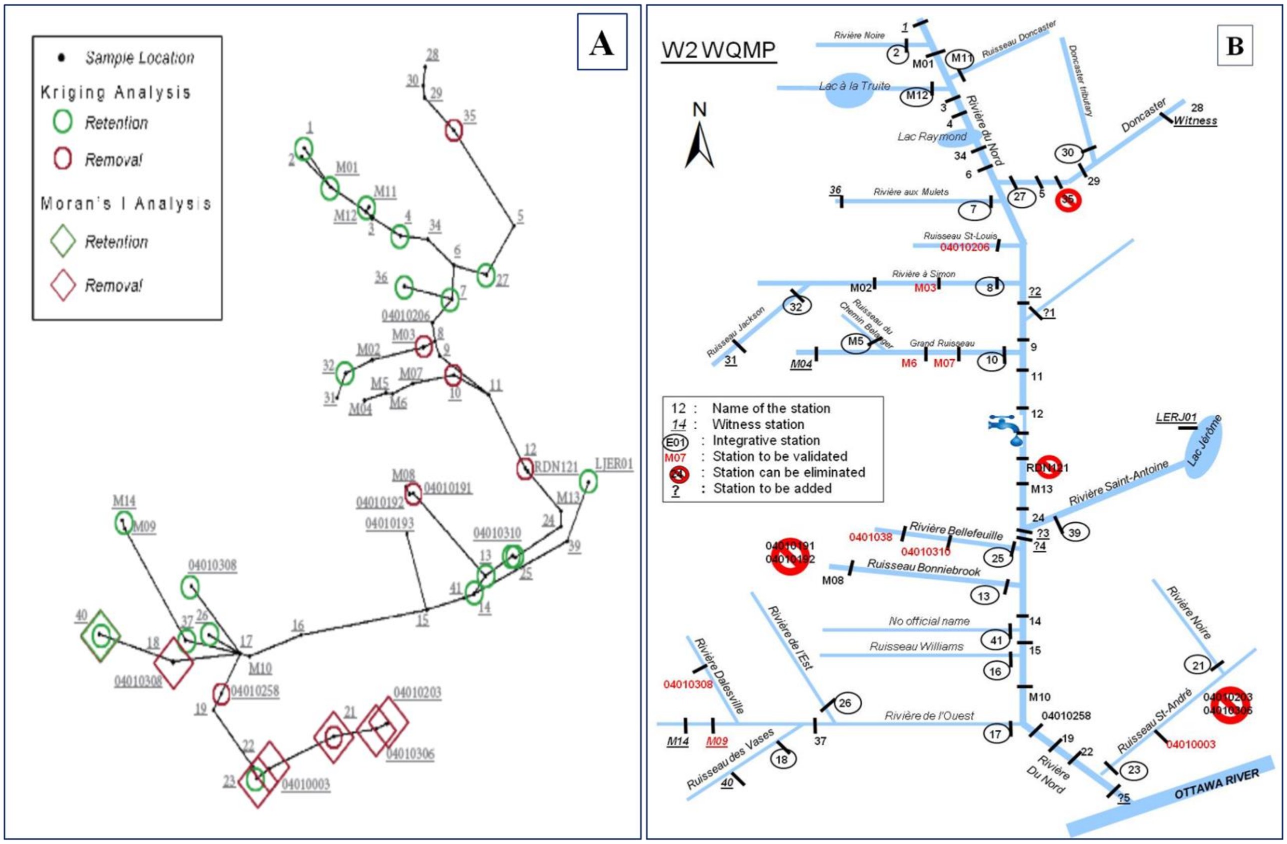

Figure 4. 10: A: illustrates the W2 sampling site network, the sampling site network and the sampling stations suggested for retention or removal following the Kriging and Moran analysis. Stations without any specifications are considered as neutral, as neither their retention nor their removal will have an effect on the model. B: Suggested sampling site network after a first series of validations (section 2.5).

Table 4.1 provides a summary of the actionable tasks still necessary for final decision making regarding the W2 WQMP. For instance, the verification whether sufficient data is available during rain events (already considered an optimization objective). This also applies to the actionable task: *Verify whether the sampling frequency was sufficient and whether a different type of sampling frequency should be adopted.* Several other tasks are proposed, such as verifying whether the stations are representative of the goals pursued and whether mixing is assured. Some of the tasks must be applied to all stations; others are specific to n stations. Table 4.1 is a summary of a detailed dashboard table of actionable tasks to be provided by the IDSS.

Table 4. 1: Summary of the actionable tasks to take final decisions to optimize the W2 WQMP

Actionable tasks	Stations submitted to the tasks (IDSS would lead to a specific series of options to comply with these tasks)
Verify whether sufficient data is available during rain events	All stations
Verify whether sampling frequency was sufficient and whether a different type of sampling frequency should be adopted	Ideally all stations, however the analysis is time consuming, therefore the following stations are suggested as being representative for different sections of W2: 1 – Witness station of the Rivière du Nord watershed. 12 – Station representing water quality upstream from the drinking water treatment plant of Saint-Jerôme. 14 – Station with the longest history. 22 – Station the furthest downstream on Rivière du Nord (close to an integrative station of the entire watershed). 23 – Integrative station of a watershed with mostly agricultural activities (representative of the downstream portion of W2). 17 – Integrative station of a watershed with mostly recreational activities (representative of the upstream portion of W2)
Verify mixing and representativity	• LJER01 – sampling site is situated on a lake shore. The site could be placed at the outflow of the lake – the goal of this site is to document the impact of downstream construction. • 12 – the goal of the sampling site is to document water quality upstream of the drinking water intake of Saint-Jérôme. A waterfall between this station and the intake probably contributes to oxygenation. Data from the raw water intake could be integrated into the WQMP. • All other stations on Rivière du Nord, due to the width of the river. Verify whether the precise sampling site represents the water quality of the entire river section (e.g., through validating mixing at different flow regimes with the help of a probe (representative parameters are specific conductivity, pH and temperature on several spots on the river section - if they are similar or identical mixing is provided. If not, another sampling site or strategy may be considered (e.g., composite sampling or taking several samples).
Verify whether additional water quality parameters should be taken according to the sampling site justification and new monitoring objectives	• All stations. • Stations M03 and 04010258 – can be removed unless more water quality parameters are monitored, such as specific conductivity (all stations) and road salts (on specific sections due to cost). These stations are downstream from Highway 15.
Verify whether additional stations should be added (or removed) (other than those presented in Figure 4.10b)	• Add a station upstream from station 16, Ruisseau Williams. • Verify whether other streams in the watershed are still orphans, such as the one represented by station ?1. • Add a station upstream from M08 (witness station for the watershed). • Station M09 was a witness station, but was replaced by M14 due to urban development upstream. Verify whether M09 can be kept as a section station to document the impact of this development.

The IDSS will provide further decision support for the actionable tasks. In the case of the two actionable tasks already identified as optimization objectives, the IDSS proposes analysis methods provided in the literature.

In order to answer the question as to whether sufficient data was available during rain events, it was necessary to verify under which rain event modality a difference in concentrations of the retained water quality parameters FC, PT and TSS could be detected. The results presented in Table 4.2. show that there is no difference between the concentrations of FC, PT and TSS between the rain modalities *1- rainfall the same day* and *2- rainfall 0-24 hours prior to sampling*. It may be assumed that the peak concentrations for each of these three water quality parameters are attained in rain event modality 3 *(rainfall 24-48 hours prior to sampling)*. The difference detected between modalities 2 and 3, as well as 3 and 4 supports this hypothesis. Therefore, rain events can be considered as defined in modality 3.

The number of samples necessary to capture such a rain event can be estimated through a Power test. This test provides an estimation of the number of n to obtain to observe a difference between rain event modalities (if there is one), with a defined threshold and a defined probability. The decision on the standard deviation, the probability and the time period for which the WQMP manager wishes to obtain the information on detecting effects of rain events must be supported by the IDSS. For instance, the decision on the standard deviation could be based on water quality classes for each observed parameter. An example would be fecal coliforms. The water quality classes provided by the Ministry of the Environment of Quebec have six classes for this parameter: ≤ 200 UFC/100 mL (good); 200 – 1000 UFC/100 mL (satisfactory); 1001 – 2000 UFC/100 mL (doubtful); 2001 – 3500 UFC/100 mL (bad); > 3500 UFC/100 mL (very bad) (Hébert, 1997). Therefore, a standard deviation, which one would want to observe, is one where classes are changed. This is not an easy decision to make, and could be considered as a biased decision, thus undermining the credibility of the WQMP. A suggested compromise would be to obtain an equal amount of samples for each modality of rain event for which differences were detected. This would result in the IDSS suggesting, as is the case here, to aim for 50% of modalities 0,1,2 and 4 and 50% of modality 3.

Table 4. 2: Summary of the results of the Kruskall-Wallis test for the three water quality parameters.

Water quality parameter	Rain event modalities	Number (n) of samples for each modality	Conclusions of the Kruskall – Wallis Test
Fecal coliform	*0 - no rain for 48 hours*	915	Differences were detected between all rain event modalities, except for differences between modality 0 and 1 and 2 and 4.
	1- rainfall the same day	199	
	2- rainfall 0-24 hours prior to sampling	429	
	3- rainfall 24-48 hours prior to sampling	126	
	4- rainfall 0-48 hours prior to sampling	295	
Total phosphorus	*0 - no rain for 48 hours*	918	Differences were detected between all rain event modalities except between modalities 0 and 1, 1 and 4, 2 and 4.
	1- rainfall the same day	204	
	2- rainfall 0-24 hours prior to sampling	421	
	3- rainfall 24-48 hours prior to sampling	122	
	4- rainfall 0-48 hours prior to sampling	301	
Total suspended solids	*0 - no rain for 48 hours*	840	Differences were detected between all rain event modalities, except for differences between modality 0 and 1 and 2 and 4.
	1- rainfall the same day	188	
	2- rainfall 0-24 hours prior to sampling	426	
	3- rainfall 24-48 hours prior to sampling	129	
	4- rainfall 0-48 hours prior to sampling	284	

The second actionable task (Table 4.1.): *Verify whether the sampling frequency was sufficient and whether a different type of sampling frequency should be adopted* leads to the application of a general linear regression with standard error test (Levine et al., 2014) for each variable at seven stations over the entire sampling period (2009-2016).

The results show that for all these stations and for all three water quality parameters, the sampling frequency (8 to 14 per year) should not be reduced. Stations 22 and 23 are visited more frequently than stations 1, 12, 17 and 21. An equal sampling frequency of all stations should be considered if the objective is to obtain a global picture.

The recommendations for the W2 WQMP are:

- Maintain the global WQMP of W2 according to the recommendations presented in Figure 4.10b;
- Collect samples in 50% of rain events (modality 3);
- Obtain at least 10 n for each of these stations per year;
- Respond to the actionable tasks in Table 4.2, with the priority of adding an integrative (and affordable) parameter such as specific conductivity to respond to the knowledge needs on road salts and other contaminations and identify other parameters that can be financed (the WQMP can still be pursued while these tasks are completed);
- Consider adding rotating WQMPs for the subwatersheds (more stations, more water quality parameters and a higher sampling frequency.

Through two different types of analysis (Kriging and Moran) proposed in the literature (Beveridge et al., 2012) to evaluate a river station network, it was possible to suggest stations to be retained or removed for the W2 WQMP. The IDSS was then solicited to submit the suggested stations to another series of questions on the sampling stations, such as sampling site justification, specific monitoring objectives for these sites, etc. Submitting the results of this analysis to further decision resulted in a final set of decisions to make, without consulting the manager of the WQMP.

Actually, the Kriging and Moran analysis requires quite some level of expertise in statistical analysis (Behmel et al 2016). When an expert in statistics is not available, the watershed manager who uses the IDSS could skip the analysis and be guided through a series of questions on the IDSS and still make a valid decision, even if not as well documented as the one made available through the process of using statistics.

The IDSS was based on expert input on the type of questions and decisions which have to be made during the planning, management and optimization of a WQMP. Regardless of the guideline, handbook or method based on geographical information systems, statistical analysis methods, etc. used, there is still a need for expert input. In order to standardize and capture the expert input, the type of expert input required for these decisions was integrated into the IDSS. The optimization of the two case-study WQMPs showed that expert input was required and that it was also possible to use the IDSS instead of this expert input, as it is not always certain that the knowledge on these issues could be adequately transferred within the organization or to these organizations. The advantage of using the IDSS is that there is some standardization and documentation possible for this expert input. As the system was designed to evolve, it is possible to add additional questions and decision problems to the system. The field of WQMPs is evolving rapidly and decisions must be made on new types of water quality analysis strategies (e.g., continuous monitoring devices and their challenges of positioning the apparatus, cleaning the data, etc.).

4.4. Conclusions

A major issue in WQMPs is ensuring that decisions related to planning, management and optimization follow some standard procedure and that decision making is guided by a set of questions that lead to a certain standardization or at least render the decision steps transparent to the people working for the WQMP. In this paper, we have strived to demonstrate how an IDSS connected to a database (Enki™) can significantly contribute to the challenge of optimizing WQMPs. We were able to show this for several steps of the optimization process:

- Understanding the initial WQMPs
    - The questions asked by the IDSS are crucial to understanding the rationale of the WQMPs. Having a firm set of questions and documented answers contributes to transferring the

information on the WQMP within an organization and communicating the information to the public, partners and decision makers.

- Decision support in data validation and integration (storage) process (quality assessment and storage)
  - The optimization of a WQMP is based on the data of the existing WQMP and the underlying decisions which led to the WQMP, as well as considerations such as possible changes that have occurred over time in the WQMP. All this information needs to be documented with the appropriate metadata for convenient retrieval when optimizing a WQMP.
  - The integration process of all the existing data of the case studies into the database Enki™ connected to the IDSS were key to understanding, documenting and relating information on sampling sites, sampling contexts, measured parameters and geographical information. The integration process also showed where changes in the WQMP were made, and why. In several cases, some of these changes can affect the continuity in the available data series and the conclusions to be drawn from the data sets. On the other hand, it was difficult to retrieve the information on why these changes were made, since the staff in charge were not always available. Therefore, there is a need for a system to be able to support and document these decisions.
- Selecting optimization procedures proposed in the literature
  - The IDSS proposes specific optimization procedures (methods) proposed in the literature that correspond to specific optimization objectives. The IDSS was constructed to propose these methods for specific optimization objectives and provide support in applying the optimization procedures.
- Contribution to applying the optimization procedures
  - In the course of the application procedures, specific questions arise concerning the data sets. The IDSS connected to the database is able to provide a quick answer to these questions, such as: variation in laboratories and data precision, changes in field protocols, changes in data series for a specific sampling site.
- Decision support (replacing experts) to finalize the optimization procedure
  - This step provides very crucial additional decision support. Indeed, in all optimization methods proposed in the literature, expert input is necessary to take final decisions regarding sampling. The IDSS was designed for this task and can be used, whether or not a statistical optimization method has been used. However, it was shown that the results of an optimization method provide a very good starting point for these questions and support the justification of the choices made.

- Data-driven decision support to redesign WQMPs
    - We were able to show that the database Enki™, the onboarding process and the decision support provided by the IDSS were instrumental in redesigning the WQMPs of our two case studies. A solid data and metadata management system are crucial to the IDSS, and cannot be separated without losing efficiency and accuracy in the process.

To conclude, in this study we demonstrated that every WQMP needs a solid database for data management and decision making. In addition, an IDSS is necessary to take and document any type of decision during the planning, management and optimization phases in order to gain a clear idea of when and why changes are made and obtain actionable tasks in the optimization process that are documented and monitored by dashboards.

Several of the features of the IDSS were already implemented, and other can now be implemented since the decision-support trees were tested through the case studies. The next steps are to continue the implementation to respond to the other optimization objectives set through the participative approach (see Behmel et al. submitted).

4.5. Acknowledgements

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GENERAL CONCLUSIONS

At the onset of this thesis, the hypothesis was advanced that water quality monitoring programs (WQMPs) are rarely based on the concerns of a broad spectrum of citizens and organizations within a watershed. Therefore, the information provided by the WQMPs is not necessarily representative of actual knowledge needs. This lack of representativeness may eventually limit the acceptability of best management practices to protect and restore water resources. It was also stated that existing approaches contributing to planning, managing and optimizing WQMPs do not address all the aspects of WQMPs. Also, the available information to plan, manage and optimize WQMPs is very fragmented, making it difficult to establish a workflow. In addition, many decisions concerning WQMPs remain undocumented and are not transferred. Given the fact that every decision can have an impact on the information on water quality obtained through a WQMP, this is a crucial element to be considered. Planning, managing and optimizing WQMPs must be based on precise monitoring objectives. Every decision concerning the WQMP must be based on these monitoring objectives. Decisions concerning the WQMPs must also be guided by explicit knowledge on WQMPs (handbooks, guidelines and scientific papers), as well as by tacit knowledge from subject matter experts. In order to channel the decisions, a general framework is required based on tacit and explicit knowledge. Finally, the underlying decisions related to a WQMP must be made transparent and transferable through time and space.

Therefore, it was proposed to develop a participative approach to elicit knowledge needs and concerns regarding water-related issues from all types of stakeholders within a given watershed and the human catchment area of the watershed. The participative approach was designed to yield new monitoring objectives and optimization objectives for WQMPs. It was also designed to gain an understanding of respondents' preferred modes of communication and their concerns regarding communication modes (and messages) on water-related issues.

It was also proposed to develop a holistic, intelligent decision-support system (IDSS) to address all aspects of WQMP planning, management and optimization, while integrating explicit knowledge from the literature, optimization methods from the literature and tacit knowledge from subject matter experts. In addition, the system was designed to document all the decisions made concerning the WQMP. The IDSS was connected to a previously developed database, Enki™. The database was developed to store and contextualize all types of data and information related to WQMPs (Behmel, 2010).

Finally, both the participative approach and the IDSS were tested on two case studies situated in the province of Quebec, Canada, the Saint-Charles river watershed north of Quebec City (W1) and the Rivière du Nord river watershed northeast from the city of Montreal (W2). These watersheds differ significantly in size, land use and population dynamics. The WQMPs of the case studies also follow very different monitoring objectives and have very different human, financial and technical resources at their disposal. Finally, the organizations in charge of the WQMPs operate under different missions: one is a grassroots organization (W1), the other is a watershed organization set up by the Government of Quebec in 2002 (W2). Thus, the development and testing of the participative approach and the IDSS involved two different realities.

From the participative approach it was possible to conclude that:

- Based on both case studies, both the citizens and ROS expressed a clear desire to be consulted on water-related issues and informed regarding restorative and protective measures of water resources.
- The participative approach developed and tested yielded new monitoring and optimization objectives representative of the knowledge needs and concerns regarding water resources in the area subject to the participative approach.
- Participative approaches must consider and be applied to a variety of scales, such as the watershed scale with the delimitations proposed by a government, the human catchment areas, the groundwater catchment (aquifers) and local homogenous zones (e.g., municipal level; catchment of small individual lakes; areas with the same type of land use).
- In order for IWRM to be successful, it must be adapted to these zones and take them into consideration; in other words, IWRM cannot be limited to a watershed scale to be successful.
- Information produced by the WQMPs must be communicated through a diversification of communication modes (e.g., interactive maps; reports; newspapers; notice boards; scientific papers; social media).
- Communication modes must be adapted to the different scales (e.g., watershed scale, local homogenous areas, human catchment area).
- Communication modes must be adapted to different types of public.
- Data and knowledge on water-related issues must be made transparent and accessible.
- Citizens and ROS question the credibility of some communication modes because of the way the message is conveyed. Sensationalism, negativism and lack of background knowledge were pinpointed in particular.
- Citizens and ROS question the credibility of information due to a lack of transparency and accessibility to the underlying data.
- Media and political decision makers must be specifically trained to understand water-related issues in order to be able to communicate them in a trustworthy manner. This will make the implementation of restorative or protective measures more acceptable to the stakeholders in general.
- Restorative and protective measures must be communicated through the same variety of communication modes and scales as the information produced by the WQMPs.

Through the development and testing of the IDSS it was possible to conclude that:

- The IDSS, with its integration to Enki™, was able to

    - integrate all the data and metadata from the existing WQMPs of the case studies;
    - render the underlying rationale of these WQMPs transparent and transferable;
    - provide a selection of optimization methods from the literature for the specific optimization objectives of the WQMPs (elicited through the participative approach);
    - provide decision support to apply the optimization methods;
    - provide decision support to finalize the optimization methods and produce acceptable WQMPs for both case studies;
    - provide a series of actionable tasks for the WQMP managers to pursue their optimization process.
- Sound data management, including metadata management, is essential to understand the underlying rationale, document changes in WQMPs and facilitate reporting and optimization.
- The planning and optimization of WQMPs must be guided through very specific monitoring objectives that must be elicited through an inclusive participative approach.
- The IDSS can integrate both explicit and tacit knowledge to provide decision support for the WQMP manager tasked with planning, managing and optimizing WQMPs.
- The IDSS can be adapted to the regulatory, scientific and historic requirements of specific regions and specific WQMPs.
- The IDSS can document these decisions and render them transferable and transparent.
- The IDSS can be updated to new knowledge needs and new scientific findings on WQMPs.
- The IDSS can be used as a tool to pool knowledge (tacit and explicit) on WQMPs.

Based on these conclusions, it is possible to state that existing approaches to develop WQMPs are inadequate for real-world contexts of IWRM and do not sufficiently address all the issues related to planning, managing and optimizing WQMPs. For example, the onboarding process of the data from the existing WQMPs (which served as our case studies) and the decision support to understand the underlying rationale revealed aspects not considered during the planning, management and optimization phases. Decisions taken had to be reconstructed from a variety of documents and interviews with the current WQMP managers. Closing the knowledge gaps on the existing WQMPs was a lengthy task. However, it was possible to integrate this information into the database connected to the IDSS, as were the questions asked to close these gaps. Thus, using an IDSS containing explicit and tacit knowledge connected to a database leads to WQMPs with more transparent decision-making processes where knowledge (from both the literature and subject matter experts) and decisions become transferable over time and space.

The participative approach to prompt stakeholders within the watersheds to state their knowledge needs in terms of water quality and quantity served to identify monitoring objectives more representative of these issues than those proposed in the literature and obtained through the collaboration of experts alone. Indeed, it was possible to show some differences in, and even discrepancies between, citizens and ROS knowledge needs and concerns regarding water-related issues. The objectives of the ROS were more in line with those proposed in the literature. In addition, it was possible to show that ROS added additional monitoring objectives after having been confronted with the preoccupations and lack of preoccupation of the citizens. Therefore, the participative approach yielded new monitoring and optimization objectives not only representative of citizens and ROS concerns, but which will also contribute to closing knowledge gaps (e.g., lack of concerns) identified through this approach.

The participative approach yielded very specific optimization objectives for the two case studies. Some were selected to test the capacity of the IDSS to accompany the WQMP managers in understanding the underlying rationale of the existing WQMP; integrate all the data into the database while providing a quality assessment decision support; select among optimization methods proposed in the literature; accompany the user in the application of these optimization procedures; and support final decisions. It was possible to show that the use of an IDSS, driven by specific optimization objectives obtained through the participative approach, facilitated the planning and optimization of WQMPs in line with local or regional needs, available resources and WQMP planning issues.

Finally, the proposed WQMPs are more representative of local and regional needs, resources and WQMP optimizing issues than a standard optimizing method, particularly since no standardized information is available for their application and final decision making related to the conservation, removal or addition of sampling sites. In addition, it was possible to show how an understanding of the initial WQMP is crucial to taking decisions. Since it was possible to document the initial WQMPs' rationale and make decisions relating to them transparent over the years, it was possible to take this information into account in the decisions for the optimization process.

I. Recommendations

At the present time, knowledge needs on water quality and quantity are evolving much faster than the solutions and tools provided to assess water quality, model water quality and quantity, and provide planning and management decision support to restore and protect the resource. Therefore, a recommendation is that protective and restorative measures be based on past and contemporary examples and experiences of success and failure, as well as on common sense and the principles of precaution. The modern paradigm of having to understand all aspects before acting to protect or restore the resource is not realistic – we are constantly introducing new changes to the hydrologic cycle (construction of dams, modification of wetlands, deforestation, etc.) and new substances into the system (drugs, pesticides, herbicides, construction materials, etc.) before having even understood the impact of doing so. Thus, there is a constant knowledge gap on which we base decisions and new impacts on water quality and quantity (for which we do not seem to need all that knowledge). Of course, water and environmental impact assessment studies strive to do exactly that. However, there are many human-induced changes for which impact studies on the environment are not mandatory (e.g., introduction of new drugs, pesticides, herbicides, personal care products, construction materials, etc.) and for which scientists are trying to find ways to measure them and measure their cumulative impacts on the environment (Brack et al., 2015). In addition, climate change adds another complex factor to the already severely modified natural hydrological cycle. In this context, modelers and water quality specialists are working hard to try to predict local, regional and global changes and provide additional information on the local water cycles and their impact on source waters (Navarro-Ortega et al., 2015; Vrzel et al., 2018; Williams et al., 2016).

There is a need to close the gap between the rapid human-induced changes and the ability of science to keep pace measuring and monitoring them. In order to close this gap, it is important to consider changes in policies, rules and regulations that must be based on the principle of precaution. There is enough knowledge, without it necessarily being specific to a local area, to take some measures based on this principle.

There is also a crucial need to educate people and communicate issues on water quality and quantity. The impact of declining water quality and quantity must be communicated to every level of society and at every scale. The communication modes must be as diversified as possible in order to raise awareness and encourage individual and collective measures to protect water resources. It is particularly important to make water a trans-disciplinary issue and a topic of the curriculum.

As for knowledge acquisition processes and management decision-support systems, a recommendation is that the time and effort invested in these processes should be pooled and tested by international committees that include scientists, decision makers, organizations and citizens. The aim is to make the processes transferable and acceptable to all parties. Much time is wasted prior to the implementation of protective and restorative measures because monitoring and management decision-support systems are constantly being challenged by the parties most impacted by the protective and restorative measures. The IDSS and the participative approach proposed in this thesis aim to mitigate some of these disputes. The first pools knowledge on WQMPs and provide a decision-support system that makes decisions surrounding WQMPs more transparent and transferable. The second provides a participative approach to include all types of stakeholders (on a variety of scales) for the purpose of obtaining monitoring objectives representative of the area subject to the WQMP. It is strongly recommended that a participative approach be used to plan and optimize WQMPs. Information produced by WQMPs which take these considerations into account will possibly render restorative and protective measures (based on the information yielded by the WQMP) more acceptable.

II. Originality and strengths of the thesis

The main originality of this thesis is to have approached the question of planning, managing and optimizing WQMPs in a holistic manner. The holistic approach involves developing a participative approach to identify knowledge needs on water quality and quantity to feed an IDSS which assists WQMP managers in every aspect of planning, managing and optimizing WQMPs.

More specifically, it was possible to develop an IDSS that integrates subject matter expert knowledge on WQMPs from North America and Europe, knowledge from the scientific and practical literature and optimization methodologies proposed in the literature. According to the literature review, such an integration had never before been tried. To a certain extent, the demonstration was made that it is possible to pool information on knowledge acquisition processes into an adaptable and evolvable system that provides a general framework to make decision processes for WQMPs more transparent and transferable. The framework is important because it allows future updating to integrate new planning, management and optimization methods, new water quality parameters and new assessment tools into the system. Finally, this system ensures that all the knowledge can be perennialized, to a certain extent.

Knowledge acquisition must be based on realistic and real knowledge needs and WQMPs must be fed by specific monitoring objectives that reflect these local and regional needs. In order to provide means to elicit these specific objectives, a participative approach was proposed that includes citizens and ROS within a watershed and the human catchment area of the watershed. According to the literature reviewed on participative approaches and to the best of our knowledge, this is the first time that a participative approach involving a wide variety of stakeholders has been proposed to determine knowledge needs on water-related issues. In addition, the methodology proposed includes steps of preparation, communication, analysis and validation of the results that are transferable and adaptable to different scales. In addition, the tools used to apply the participative approach (Survey Monkey® and the public participation geographical information system (PPGIS) implemented into the IDSS/Enki™) are accessible and user friendly.

Finally, both the participative approach and the IDSS were tested on two real, yet very different, watershed case studies. The feasibility and acceptability of the participative approach which yielded precise monitoring objectives for the WQMPs of these case studies was also shown. These monitoring objectives are more representative of the knowledge needs initially identified for these watersheds. The participative approach also allowed illustrating the complexity of the information layers consulted and sought by stakeholders. Furthermore, it was possible to feed the IDSS with some of these monitoring objectives and test the IDSS on the data of these WQMPs. Proposals of optimized WQMPs were devised for each case study that reflect the optimization objectives. The proposals of these WQMPs were also rendered transferable and transparent as to their underlying rationale to the present and future managers of the WQMPs, citizens and ROS.

III. Limitations of the thesis

One limitation of the IDSS developed in this thesis is that the expert input on WQMPs is concentrated on the realities of North America and Europe. The IDSS would most probably have benefitted from experiences of WQMP managers from very different backgrounds, with different regulations, policies and resources (E.g. Australia, Asia, Africa and South America). However, since that the IDSS's settings can be adapted to different realities, we believe that this drawback can be overcome. Especially considering the fact that the general and specific use-cases which were identified remain the same, no matter which the specific realities are on which decision support is being provided.

A very specific limitation of the current IDSS lies in the difficulty to automate, even partially, existing statistical methods into the IDSS in order to reduce the degree of difficulty of their application. This would take a lot of effort, while new, and maybe more sophisticated optimization methods are being constantly developed. Thus, just the integration (updating) of these methods into the system, without even having to automate them, is already a challenge.

Another limit of the IDSS is that, while it provides decision support to plan, manage and optimize WQMPs of surface waters (lakes and rivers), it does not provide the support to coordinate surface water monitoring with groundwater monitoring. Finally, there is still a lot of work ahead to implement all the elements of the IDSS to make it a fully functional software.

The participative approach that we developed is very dependent on the involvement, and willingness of involvement of the respondents to the survey and the workshops. While we were able to provide a reproducible methodology with very accessibly and easy to use tools such as Survey Monkey® and the PPGIS implemented into the IDSS/Enki™, there is a considerable amount of case to case adaption necessary for the local application of the methodology. Also, the results, which are the optimization objectives, are representative of the respondents and not of the entire population of the area subject to the participative approach. While there was a clear message that participative practices are welcome, there was also a clear message that these must be adapted and applied to localized areas of common interest and common problems in order to receive a number of answers which could be considered as representative – if it is put against the number of population and organisations of the area. Thus, the question of scale on applying participative approaches remains fundamental.

IV. Future research and work

Based on the findings and experience of the work completed in this thesis, some development work on the IDSS should be pursued and more research be carried out to improve some methodological aspects presented in this study. Future development work on the IDSS could focus on:

- Evaluating the costs and benefits of the proposed IDSS.
- Fully implementing the IDSS and testing it on the remaining optimization and new monitoring objectives of the two case studies.
- Completing the settings of the system for the different WQMP contexts identified in this research, such as the monitoring guidelines of the European Water Framework Directive and the United States Environmental Protection Agency (Directive, 2000/60/EC; USEPA, 2001).
- Following up on ongoing research on WQMPs to integrate new optimization methods into the system (e.g., Alilou et al., 2018; Pérez et al., 2017; Villas-Boas et al., 2017).
- Following up on subject matter expert knowledge on WQMPs in order to incorporate this knowledge into the IDSS.
- Including subject matter expert knowledge from geographical areas not yet considered (Asia, Australia, Africa, South America).
- Evaluating the possibility of automating some of the most common and proven optimization methods (e.g., principal component analysis and regression analysis), while overcoming the shortcomings of these methods identified in the literature with adequate decision support provided by the IDSS.

Follow-up work concerning the participative approach should include:

- Communicating the results of the participative approach to the respondents of the participative approach, as well as to all citizens and ROS of the concerned watersheds and human catchment areas.
- Communicating the underlying rationale of the optimized WQMPs and the monitoring objectives to the citizens and ROS of the concerned watersheds and human catchment areas of the two case studies.
- Adapting the communication strategies of the two WQMPs to the findings of the participative approach.

Future research could focus on:

- Adapting the scope of the IDSS to integrate other environmental issues such as groundwater monitoring, air quality monitoring and municipal distribution system monitoring.
- Evaluating the extent to which an IDSS as proposed would be adopted by the intended users and, accordingly, develop adapted strategies to increase the capacity of users to apply it.
- Providing more transferable management decision-support systems and models based (and adaptable) on
    - a consensus of scientists, citizens, decision makers and organizations;

    - data needs to feed the management decision-support systems and models;
    - data and metadata produced through WQMPs (which respond to data needs from all these parties).

  Note: Two examples where efforts were made to integrate models, data and knowledge at the national level to provide management decision support are: The Netherlands Hydrological Instrument (De Lange et al., 2014) and the Danish National Water Resources Model (Højberg et al., 2013)).
- Testing whether the proposed participative approach can be adapted to contribute to the development of criteria for specific areas on which models, management and decision support tools are based.
- Further developing knowledge and data management systems that can feed these management support systems, models and the IDSS and which are based on common criteria of the data and metadata.
- Evaluating the applicability of the participative approach in different socio-economic and political contexts.
- Developing methods to evaluate the long-term costs and benefits of applying the proposed participative approach.

The development of this thesis served to identify some more general research issues that could contribute to advances in IWRM, such as:

- Studying how governance structures could be adapted and improved to contribute to IWRM, regardless of the scale.
- Further investigating how communication strategies could yield the best results in raising awareness on water issues and creating social acceptability of restorative and protective measures.
- Further studying why there is often more acceptability (or less resistance) to implement major infrastructure projects to regulate water than to implement infrastructure to protect and restore the resource (for further reading: de Bruijn et al., 2015; Warner and van Buuren, 2011).
- Studying how historic knowledge and success and failures regarding water resource management can be integrated into the mindset of engineers, city planners and politicians in order to avoid mistakes in water resource management.

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Appendixes

Appendix A

The appendix A contains the use-case models for each of the twelve main use-cases identified in the Global use-case model of the intelligent decision support system (IDSS).

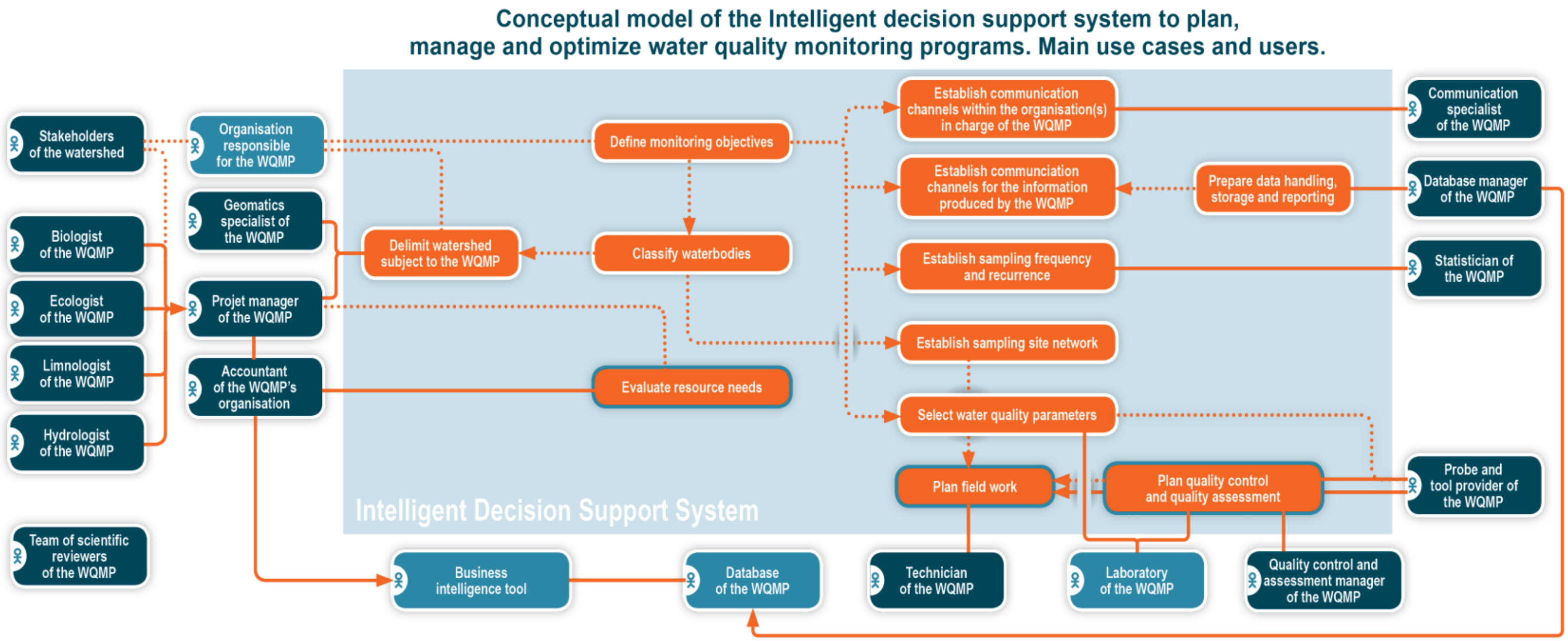

Figure *1* and chapter 3). It has to be noted that the IDSS is intrinsically connected to the database Enki™. For each of the use-case models user-stories are presented in order to illustrate some of the features of the system. To further illustrate each of the use-case models one example of the system is provided. Such an example can be an excerpt of a decision support tree, a ladder of refined use-case slices or a screen shot of the system.

Conceptual model of the Intelligent decision support system to plan, manage and optimize water quality monitoring programs. Main use cases and users.

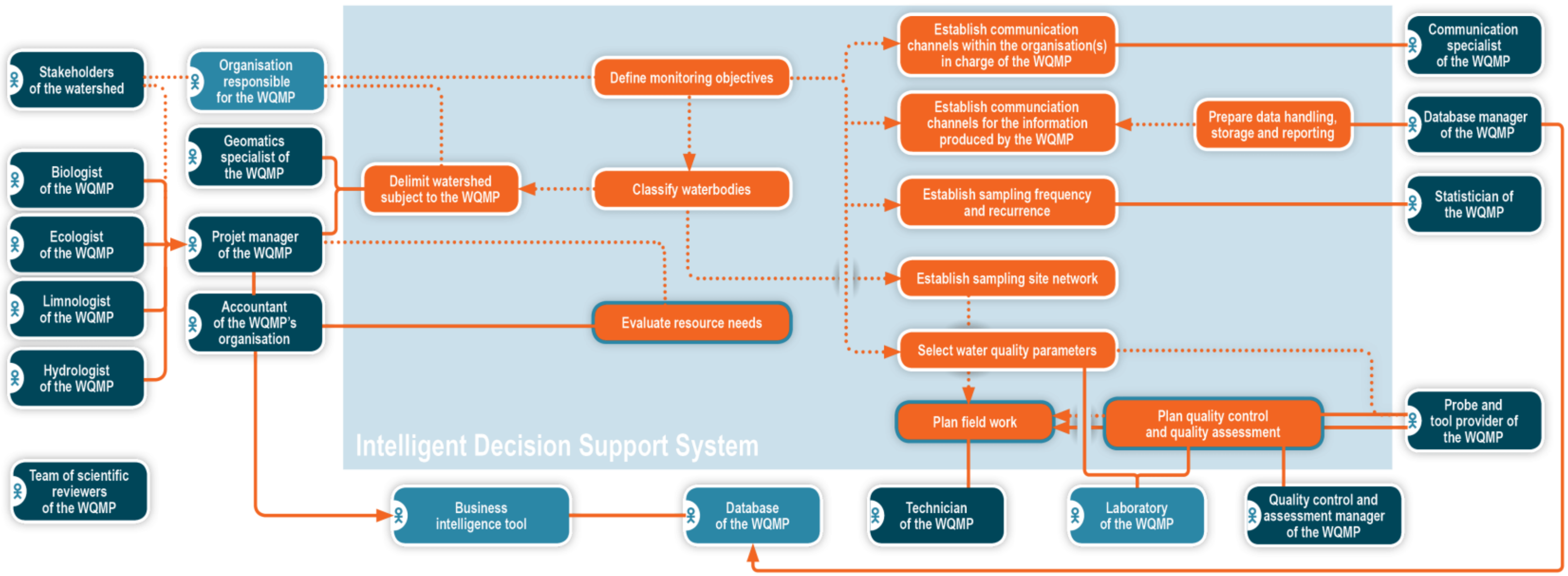

Figure 1: User stories of IDSS and connectivity to the database Enki™ and to business intelligence modules.

Note: The listed user stories or illustrations are not exhaustive, nor do they represent the prioritization of the implementation of functionalities. To illustrate the entire system would be out of the scope of the paper version of the thesis.

A.1. Use case model: *Delimit a watershed (territory) subject to the WQMP*

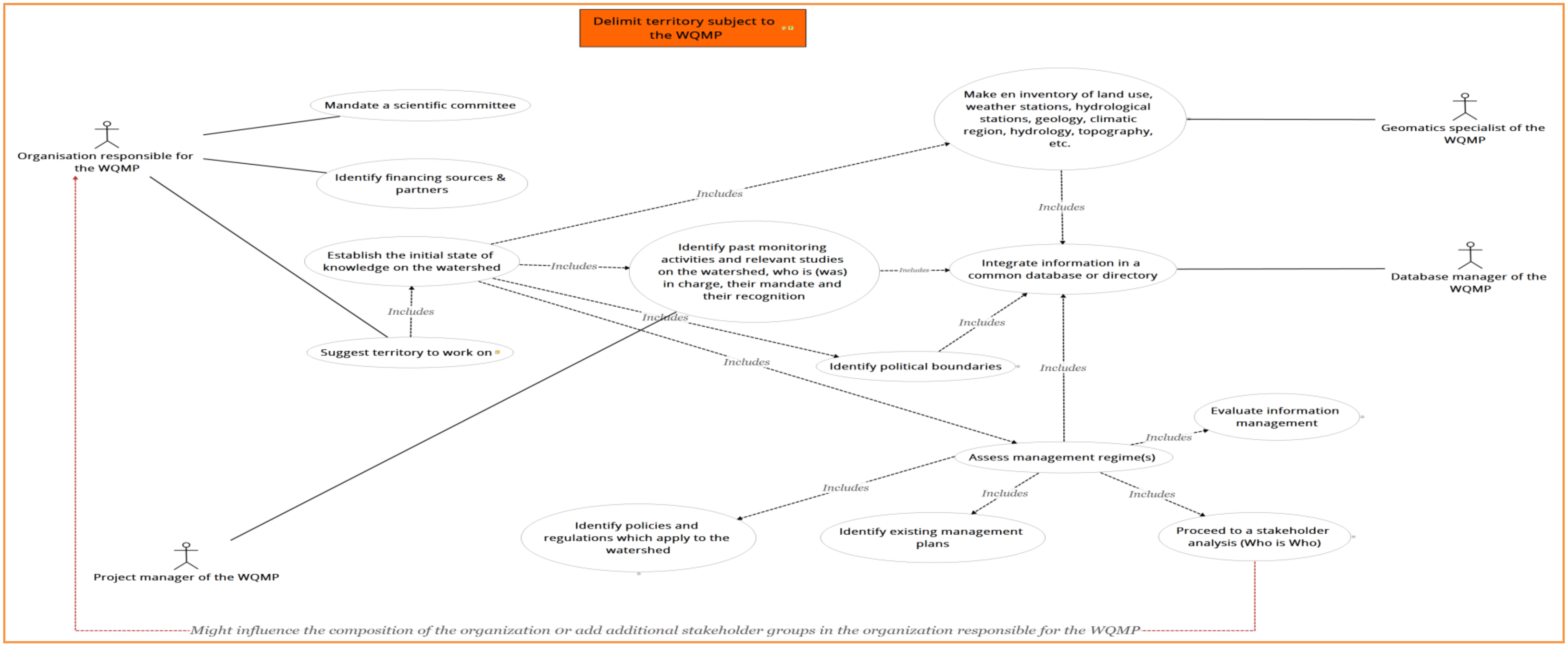

Figure 2: Use-case model for the use case: Delimit a watershed (territory) subject to the WQMP.

User story: Suggest territory to work on
A user can suggest a territory to work on and will then be guided through the use-cases: Establish the initial state of knowledge on the watershed(territory); assess management regimes; identify political boundaries; identify past monitoring activities, etc. The user will then be able to evaluate whether the chosen territory is appropriate for the WQMPs' objectives.

User story: Establish the initial state of knowledge on the watershed (territory)
A user is guided through the necessary reflections on identifying the necessary information to implement, manage or optimize a WQMP. This user story includes the user stories: Identify past monitoring activities and relevant studies on the watershed (territory); identify who is (and was) in charge; assess their mandate and their recognition; assess management regimes; identify political boundaries; make an inventory on land use, etc.

User story: Identify political boundaries
A user is guided through the process of identifying all political boundaries within the territory subject to the WQMP. The results contribute to the use-cases: Assess management regimes; identify stakeholders; identify financing sources and partners; identify rules and regulations, etc.

User story: Proceed to a stakeholder analysis
A user is guided through the necessary steps to a stakeholder analysis, that is identifying the who's who within the territory. This may influence the composition of the organisation in charge of the WQMP, influence the monitoring objectives, influence the communication channels, etc.

User story: Identify financing sources & partners
A user is guided through the reflections necessary to identify financing sources and partners for the activities of the WQMP. These reflections may include: Identify all the governmental entities within the territory and their potential financing sources which can be made available for the type of organisation which is piloting the WQMP. The reflections can include: Identify pros and cons of addressing potential financing resources (these can be effort - benefice analysis, how the financing source can be perceived by other partners or stakeholders within a watershed, etc.).

User story: Identify existing management plans
A user is guided through the process of identifying existing management plans once the management regime has been assessed and the stakeholder analysis has been completed. Note: The information on the management plans will influence the WQMP as there might be actions which need to be monitored, and there might be recommendations of past monitoring activities which are being implemented on which one may want to keep track on. **NOTE: A module to follow up on action plans prepared by APEL is going to updated and integrated into the IDSS.**

User story: Evaluate information management
A user is guided through the necessary steps to identify present communication flows (formal and informal) and to identify information sources, availability of information, level of democratization of the information, available data management tools, etc. This will be helpful to making an inventory necessary to implement the WQMP, to identify information gaps and gaps in the flow of information. It will also help to propose a communication plan (Go to use case model: Establish communication channels and production guidelines for the information produced by the WQMP.

User story: Mandate a scientific committee
A user is guided through the reflections of choosing a scientific committee to review the WQMP, the reports issued by the WQMP and to assist n communication activities on the results. These reflections may include: Cover the necessary expertise; assess availability; assess general credibility; assess whether the persons are willing to work together; evaluate communication skills; assess independency (perceived or real); etc.

User story: Identify past monitoring activities and relevant studies
A user is guided through the process of identifying (and updating) all past monitoring activities and relevant studies in order to avoid duplication. This use case is related to Integrate existing data and studies into the database; identify monitoring objectives; assess whether pas monitoring objectives were attained.

User story: Identify policies and regulations which apply to the watershed
A user is guided through the necessary steps to identify policies and regulations which apply to the watershed after having assessed management regimes. This use case will help the user identify rules and regulations which should be reinforced and why.

User story: Make an inventory of land use, weather stations, hydrological stations, geology, climatic regions, etc.
A user is guided through the reflections of which is the necessary (mandatory) information and information precision to be able to implement the WQMP, how to validate this information through mandatory metadata, and how to integrate this information in a common database or directory – in this case Enki.

Figure 3: User stories for the use-case model: Delimit a watershed (territory) subject to the WQMP.

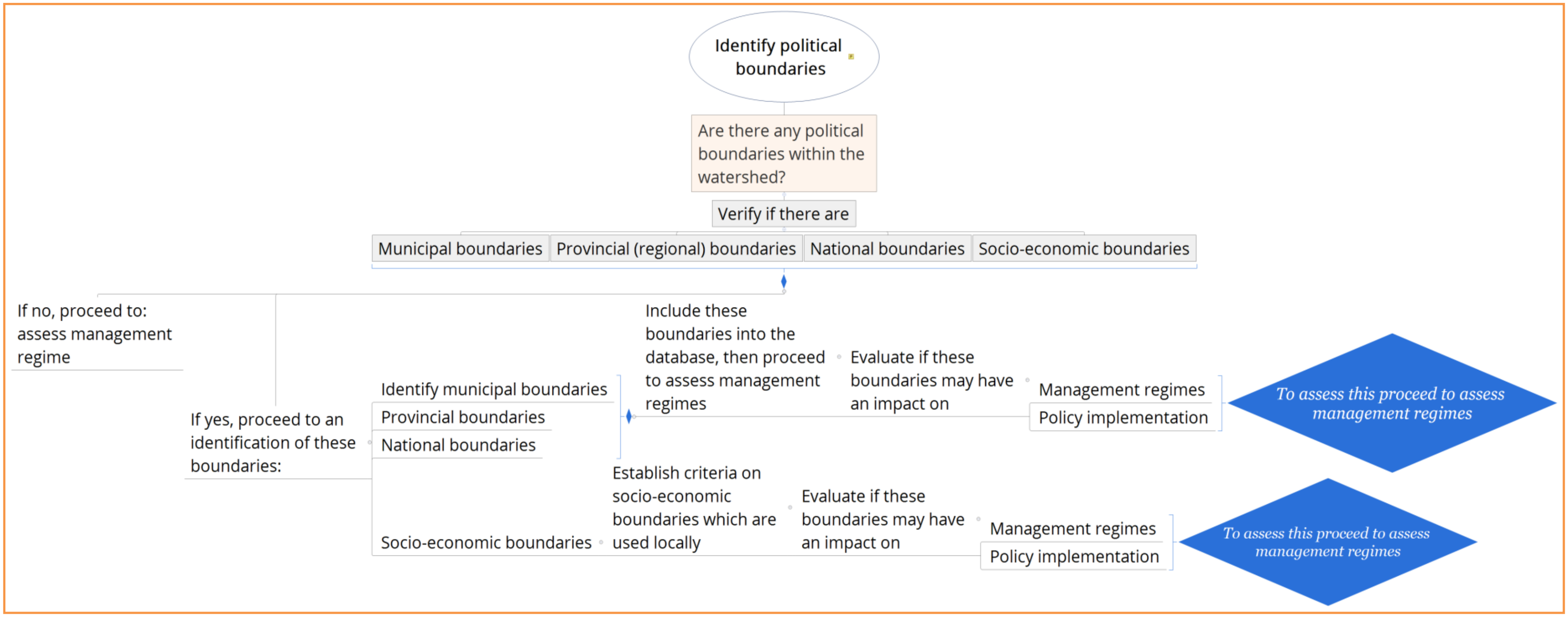

Figure 4: Excerpt of the decision support tree for the use-case slice: Identify political boundaries.

A.2. Use-case model: *Define monitoring objectives*

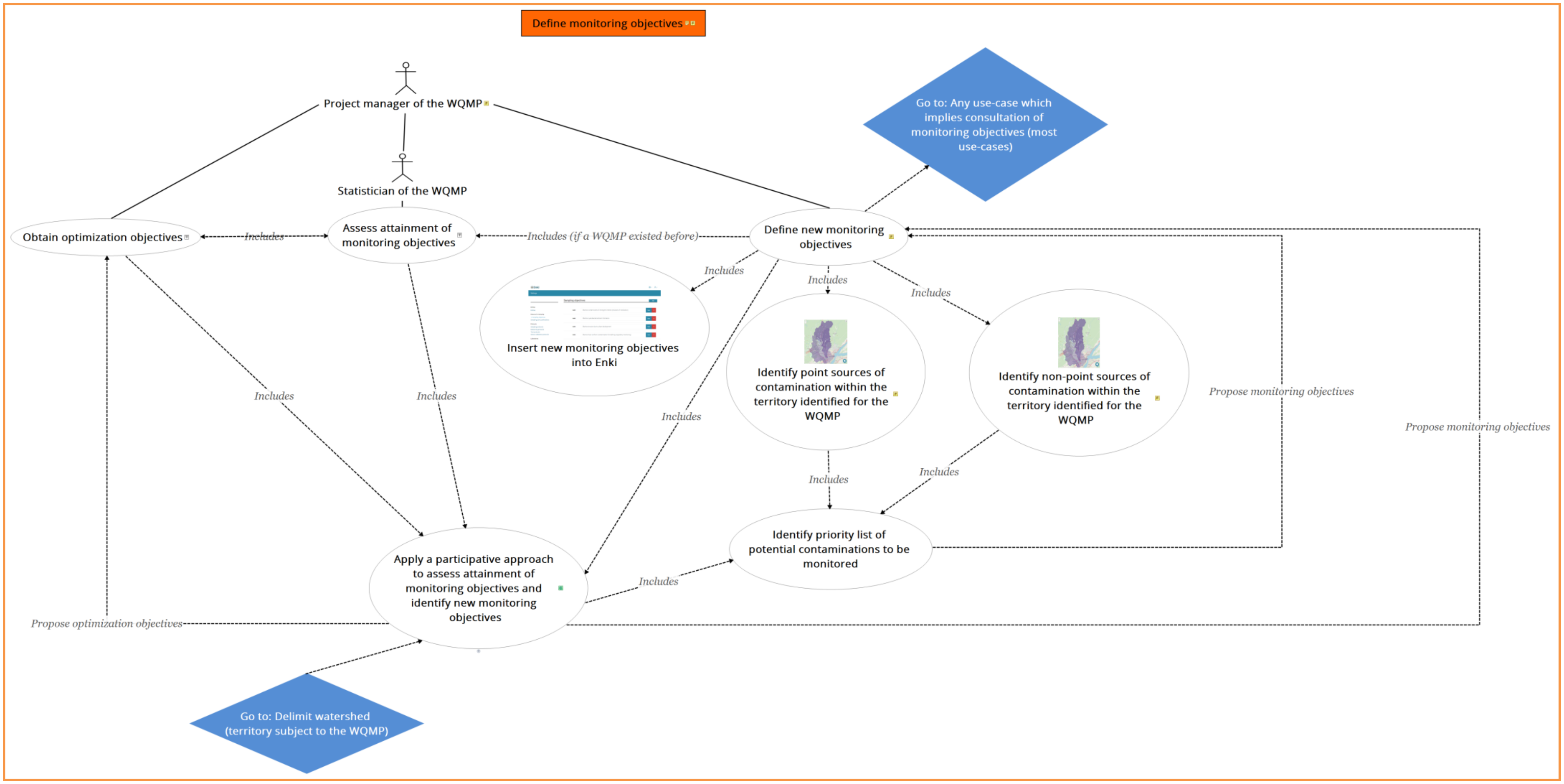

Figure 5: Use-case model for the use case: Define monitoring objectives.

User story: Extract past monitoring objectives
A user can extract past monitoring objectives from the database Enki.

User story: Extract data related to past monitoring objectives
A user can extract data (to assess attainment of existing monitoring objectives) through a filter **Extract data** related to 1 – n monitoring objectives (other filters: time frame based, project based; watershed based; waterbody based; laboratory based; probe based; context based; etc.).

User story: Identify assessment objectives
A user can select from a list of elements on which he wishes to assess attainment of monitoring objectives (e.g.: was the spatial coverage adequate (redundancy or lack of information between sampling stations; whether the acquired data could be kept comparable (e.g. : have changes in probes, laboratories ,field protocols, sampling frequency, etc. had an impact on data series); other sampling activities could be coordinated; information was produced in a timely and adequate manner. Etc.).

User story: Apply a participative approach to assess attainment of monitoring objectives and identify new monitoring objectives
A user can consult the system on the application of a participative approach to assess attainment of monitoring objectives and can identify new monitoring objectives (See chapter 2).

User story: Identify stakeholders
A user can select stakeholders according to the land use of the area subject to the WQMP (e.g. If agriculture is predominant of an area, the agricultural sector needs to be considered).

User story: Evaluate a sampling site network
A user is directed to the use case: Evaluate a sampling site network

User story: Find past monitoring objectives
A user can search for monitoring objectives by key words (e.g. Nutrient loads, eutrophic state, erosion, compliance monitoring, ecological integrity, etc.).

User story: Identify means of assessing attainment of past monitoring objectives
A user is provided with means of assessing the attainment of monitoring objectives depending on the element which was selected in the use case: Identify assessment objectives. Statistical or participative approaches are suggested depending on assessment objectives. Metadata is provided to assess whether acquired data could be kept comparable. Etc.

User story: Characterize stakeholders
A user can characterize stakeholders according to their role, interest, mission, vision, objectives, use of the resource, geographical zone of influence, political zone of influence, etc.

User story: Map stakeholders
A user can consult the list of stakeholders to be included in a participative approach through the mode stakeholder mapping . This mode includes options such as: area of consultation, political boundaries, organisations identified within theses boundaries, etc..

User story: Follow-up on action plan
A user is connected to the action plan follow-up data base in order to be able to assess whether actions have been put into place and whether this may have had an impact on water quality and quantity.

User story: Consult events which may have altered water quality and quantity
A user is connected to the event management data base in order to be able to consult whether events may have altered water quality and quantity (events may be changes in land use, construction sites, spills, etc.).

User story: Prepare participative approach survey questions
A user can choose from a list of proposed questions to identify sampling objectives for the participative approach (e.g. Is there a public health problem, what is the use of the waterbodies of the territory, is there a goal to attain for 1 or n waterbodies as to water quality or quantity (quantification of monitoring objectives), etc.). This interface must be made available to users in discussion tables preparing the participative approach.

User story: Prepare a public participation geographical information system (PPGIS)
A user can select (or delimit) a territory (area) for which he wishes to obtain local knowledge. A user can propose a list of observations for which he would like to obtain local knowledge. A user can create an URL to send to specific stakeholders, websites, etc. and provide access to the personalised PPGIS. A user can visualize the observations on a map and can extract the responses for statistical analysis. A user (respondent to the PPGIS) can upload pictures and add specific notes on observations **(see chapter 2 and Figure 6).**

Figure 6: User stories for the use-case model: Define monitoring objectives

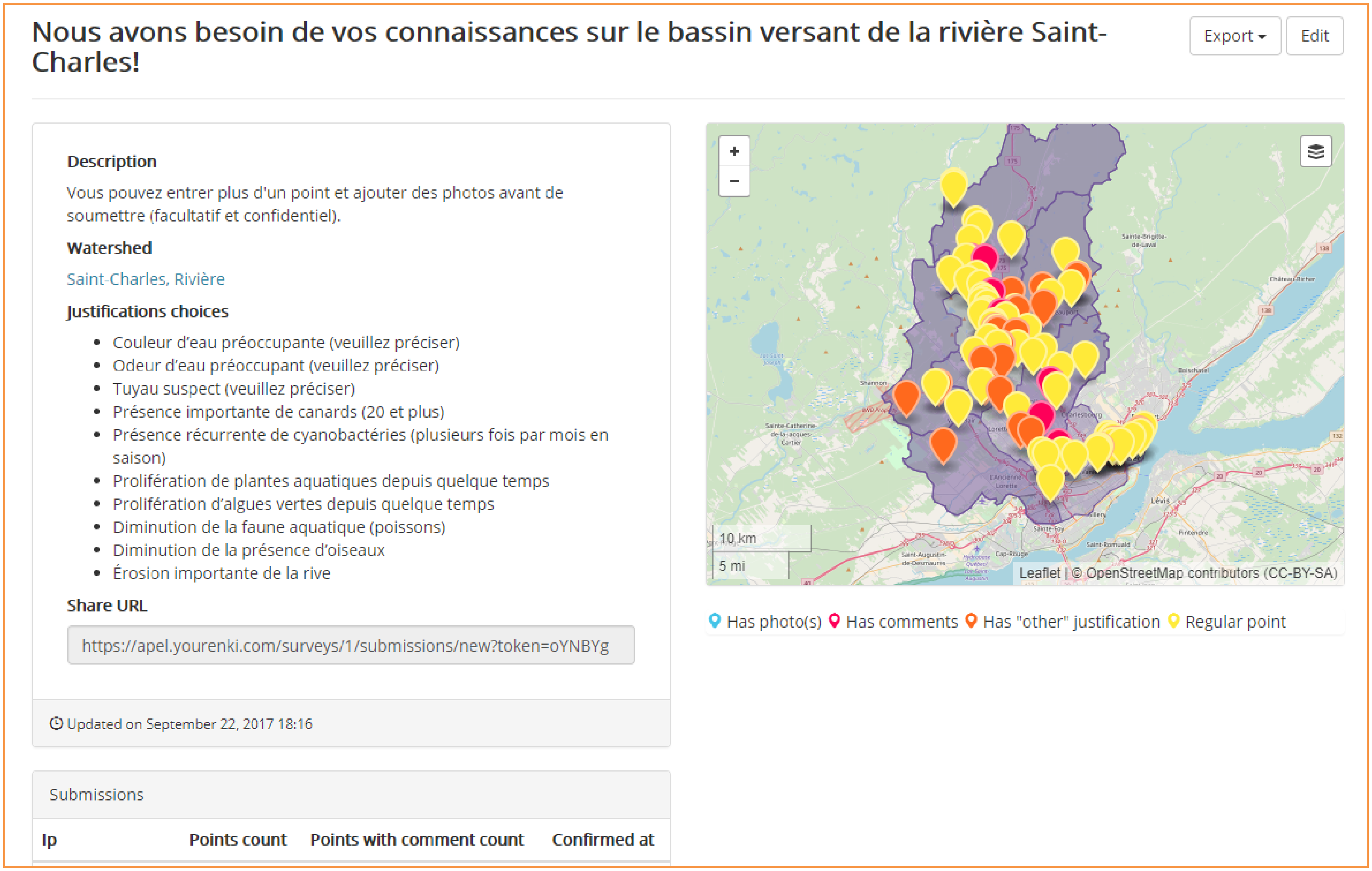

Figure 7: Screen shot of the functionality of the use-case slice: Prepare a public participation geographical information system (see chapter 2).

A.3. Use-case model: *Establish communication channels within the organisation(s) in charge of the WQMP*

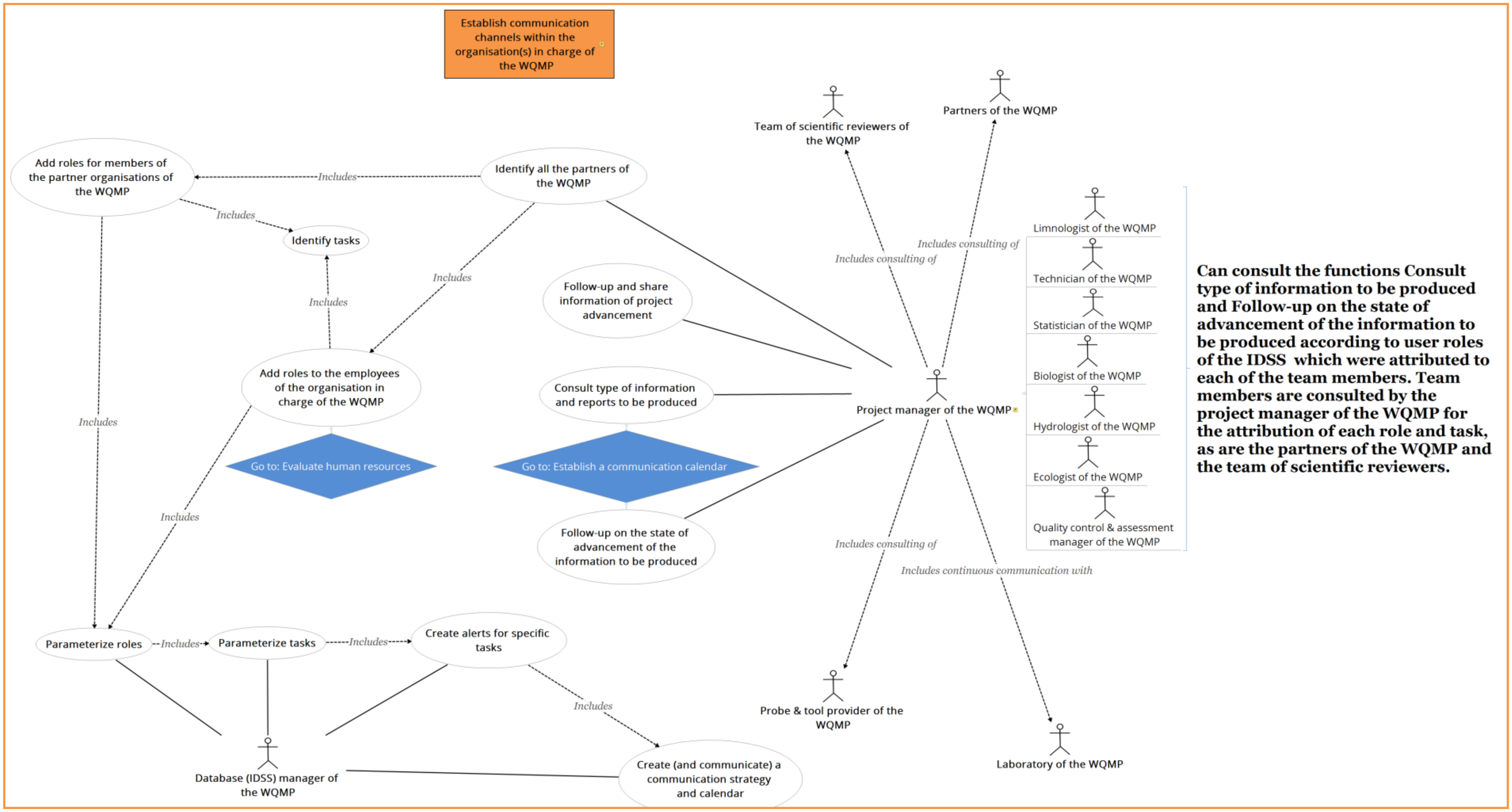

Figure 8: Use-case model for the use case: Establish communication channels within the organisation in charge of the WQMP.

User story: Identify all the partners of the WQMP
A user can parameterize (and update) the system with all the organisations which are contributors to the WQMP according to their role (e.g. Laboratories, Scientific partners, financial partners, probe providers, stakeholders (e.g. Users or contributors of the data and information produced within the WQMP). A user can include information on these organisations such as contact information for specific members and laboratory accreditation.

User story: Follow-up on the state of advancement of the information and reports to be produced
A user can inform himself on the type of information and reports to be produced for 1 or n projects, as well as on the state of advancement of the reports (e.g. Draft completed, final version for internal review completed, final version for linguistic review, final version authorized for public release, places published, etc.).

User story: Consult type of information and reports to be produced
A user can inform himself on the type of information and reports to be produced for 1 or n projects, as well as on the state of advancement of the reports (e.g. Draft completed, final version for internal review completed, final version for linguistic review, final version authorized for public release, places published, etc.).

User story: Add roles for members of the partner organisations of the WQMP
A user can parameterize (and update) the system in order to attribute members to each organisation and add information according to their role within the organisation and their role in relationship to the WQMP.

User story: Parameterize tasks
A user can parameterize (and update) the system in order to add tasks which can be attributed to 1 or n partners, members and or employees of the WQMP. These tasks could be: Calibration of probes (identify probes for which a person or organisation is in charge); order calibration liquids, preparation of field material for a project X, reservation of field material for a field campaign for a project X, order bottles from the laboratory, planning of field campaign, handling of probes for the field campaign for a project X, filling of bottles for the field campaign of a project X, in charge of taking the measurement contexts for the field campaign for a project X, in charge of data extraction of a probe X, in charge of data validation of a probe X, in charge of data import into the database, in charge of communication with a partner X, in charge of the scientific review of a subject, etc.).

User story: Create alerts for specific tasks
A user can program alerts he wishes members of organisations and employees to receive according to attributed tasks.

User story: Add roles to the employees of the organisation in charge of the WQMP
A user can parameterize (and update) the system in order to create employees of the organisation in charge of the WQMP. A user can add attributes for these employees such as contact information, role within the organisation, competences, curriculum vitae, attributed tasks, salary, etc..

User story: Follow-up and share information of project advancement
A user can share the state of advancement of 1 or n projects with 1 or n partners of the WQMP and or employees of the WQMP. This advancement can include specific information one wants to share (e.g. Number of sampling campaigns (e.g.: 5 of 10 completed), precipitation types observed during the campaign (with checklist of the type of sampling campaign – e.g. River sampling, lake sampling,), time spend on the field, advancement of data validated and entered into the database (e.g. Field observations, field measurements, probe and or laboratory data imported) etc..

User story: Create and communicate a communication strategy and calendar
A user can, according to the tasks, roles, sampling calendar, information communication calendar and members' preferences, prepare a communication plan which takes the modes and effectiveness of communication modes and importance of results into account **(see figure 10)**.

Figure 9: User stories for the use-case model: Establish communication channels within the organisation in charge of the WQMP.

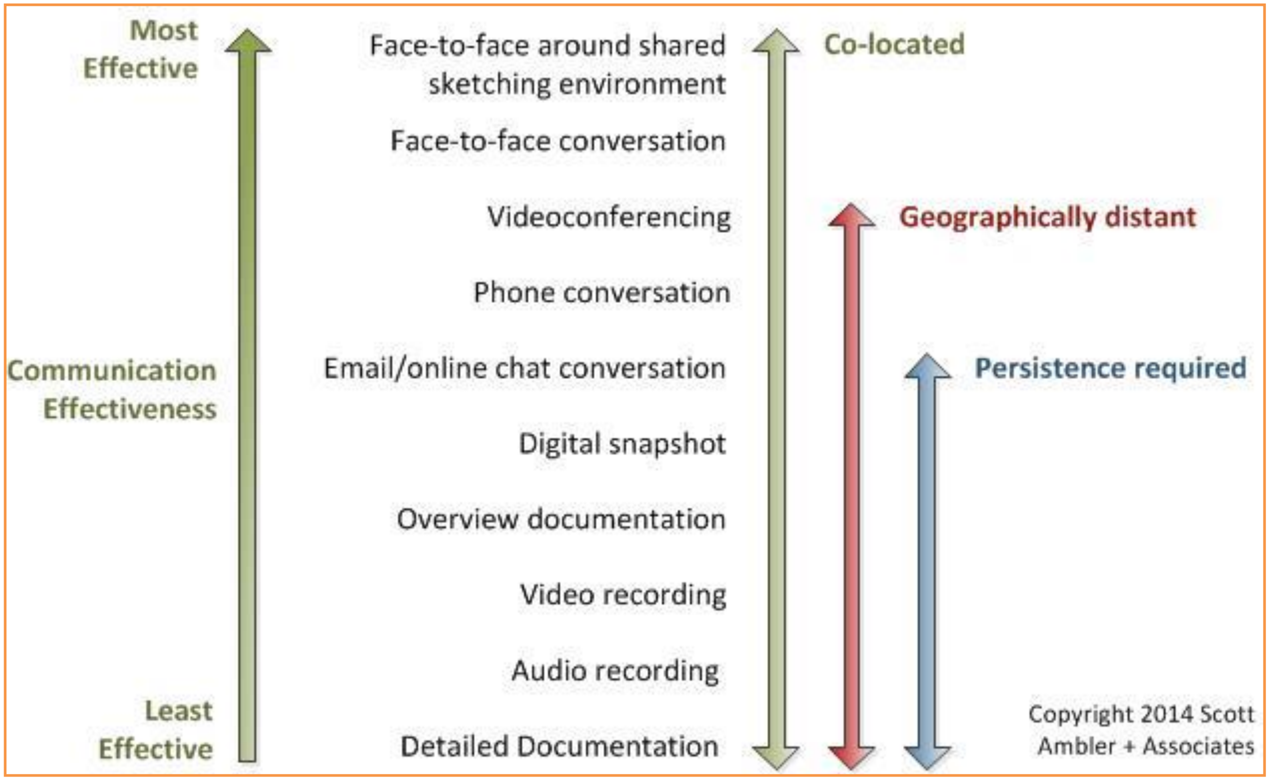

Figure 10: The figure shows considerations which need to be taken into account for the use-case: Create and communicate a communication strategy and calendar within the organisation in charge of the WQMP. Face-to-face meetings with shared sketching environments are the most effective, while detailed (paper) documentations are the least effective. The figure also shows that there is more persistence (follow-ups) required when communication is not direct. Therefore, the communication strategy within the organisation and the partners of the organisation should take these realities into account to plan the internal and external communication strategy. Also see chapter 2 for communication modes (Retrieved online [09-10-2017]: http://agilemodeling.com/essays/communication.htm)

A.4. Use-case model: *Establish communication channels for the information produced by the WQMP*

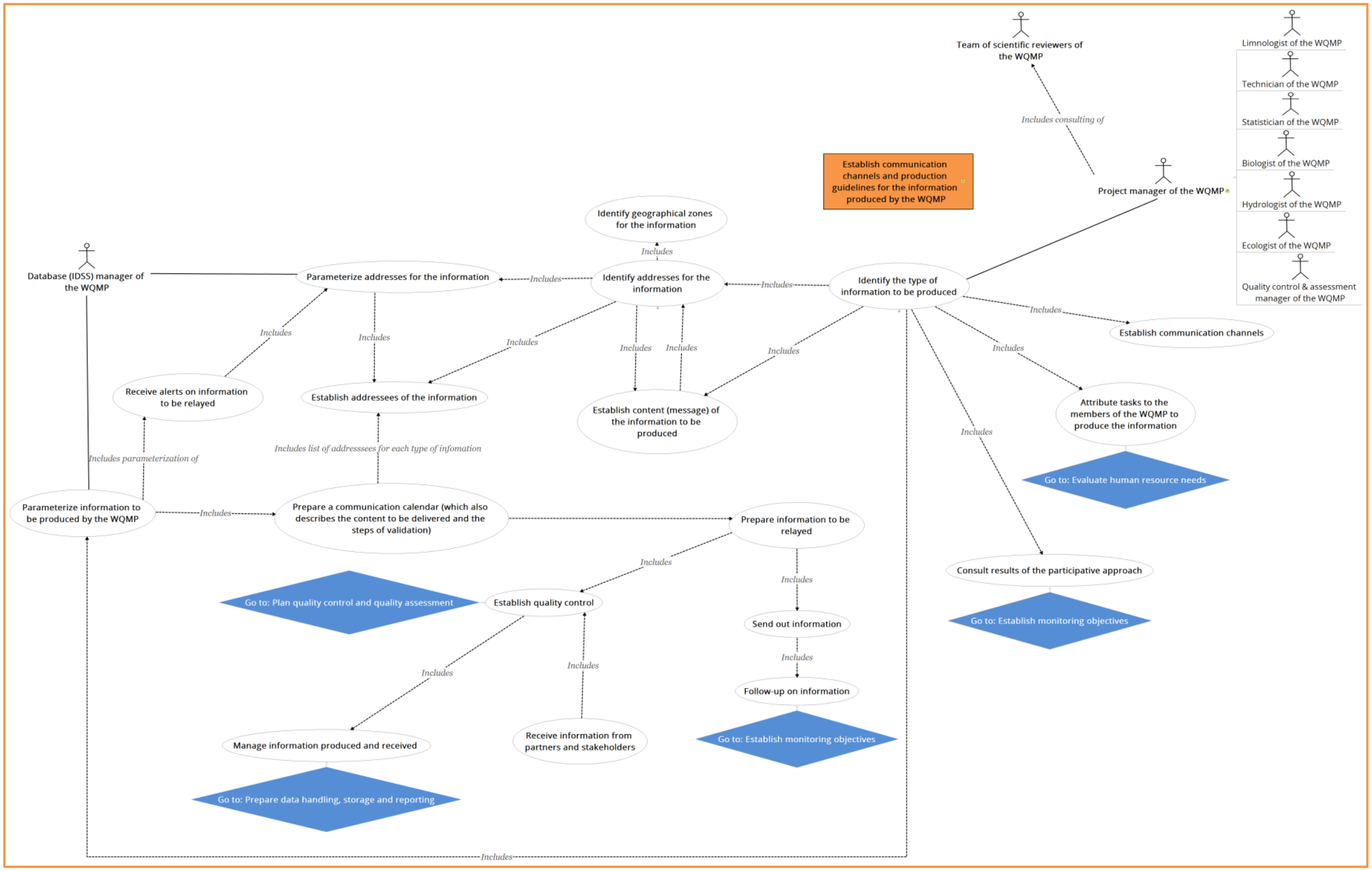

Figure 11: Use-case model for the use case: Establish communication channels for the information produced by the WQMP.

User story: Establish addressees of the information
A user can establish a list of addressees of information produced by the WQMP.

User story: Establish communication channels
A user can establish communication channels of the information by selecting 1 or n addressees to be communicated 1 or n types of information.

User story: Establish a communication calendar
A user can establish a communication calendar by selecting a date or a time-frame for which 1 or n types of information should be communicated for 1 or n types of communication channels.

User story: Receive information from partners and stakeholders
A user can create specific PPGISs' for specific areas, subjects and stakeholders in order to receive information on specific events within the study area (event detection). These type of events could be sewer overflow events, road works, new residential development, etc. The user is directed to the use case: Establish a PPGIS.

User story: Parameterize addressees for the information
A user can parameterize addressees of information produced by the WQMP according to a list of attributes (e.g.: type of information to receive, timing for the information, stakeholders, geographical areas, reason to receive information (e.g. Alert on specific events or observations during a field campaign – this can be a blue green algae bloom observation or an oil spill - which must be send to 1 or n addressees,)

User story: Establish content (message) of the information to be produced)
A user can establish a list (and pieces) of content which need to be included in 1 or n type of information (e.g. In order to communicate a blue green algae bloom a minimal number of information needs to be completed before sending it to the addressees; in order to send out raw data to 1 or n addressees for a specific project or sampling objectives the minimal information to be included can be identified).

User story: Receive alerts on events within the watershed
A user can receive alerts on events within the watershed which are communicated through the PPGIS, according to established emergency criteria.

User story: Parameterize information to be produced by the WQMP
A user can parameterize the type of information to be produced by the WQMP (e.g. Information to produce water quality indicators, information to produce alerts, narrative information (reports, summary of the results for Websites, press releases, etc.), statistical information, visual information (e.g. Videos, interactive maps), numeric information (e.g. Raw data) (This parameterization is done according to monitoring objectives, knowledge needs, preferred communication channels identified through the participative approach (see chapter 2) and addressees of the information).

User story: Establish quality control
A user is directed to the use-case quality control of the information produced by the WQMP before sending it out.

User story: Manage knowledge
A user can receive information from universities or other partners on research, monitoring or studies which are either related to the knowledge needs of the WQMP or the study area.

User story: Receive alerts on information to be relayed
A user can receive an alert on information to be communicated according to the information which is entered in the field observation context (e.g. When the users enters the sampling objective: follow up on blue green algae blooms, he will receive a list of additional information to enter in the sampling context, such as: have you observed any scum? If the user says yes, the scope of the bloom is assessed and depending on the scope the user is informed that he needs to relay the completed information report to 1 or n number of addressees (including the contact information).

Figure 12: User stories for the use-case model: Establish communication channels and production guidelines for the information produced by the WQMP.

Monitoring objectives	Type of information	Form of information transmission	Person(s) in charge of the information production	Person(s) in charge for the quality control (in order)	Transmission timing	Addressees
Monitor cyanobacteria blooms in lake Saint-Charles	Field observations' report	No action if no bloom can be reported Phone call to the ministry of environment in case of bloom observation Bloom report can be generated automatically	Field technician in charge of the field work	Limnology project manager and director general of the organisation	Same day as the bloom was observed, as soon as all the necessary information on the field was documented and the report validated	Persons in charge of the drinking water facility production manager@city.com operator@city.com etc. Persons in charge of communication at the city communication@city.com etc.
Obtain a global picture on water quality of all main rivers of the watershed every second year	IQBP Box-plots	Interactive map Report with results and interpretation after each sampling season. Consult report example:	Limnology project manager	Linguistic reviewer Director general of the organisation Member of the team of scientific reviewers – *Tom Hanks* Organisation(s) who use the information to implement best management practices	Every other year, unless some alerts have been produced on specific events during the sampling campaign	Citizens Organisation(s) who use the information to implement best management practices (Watershed organisations, municipalities, NGO's) (addresses would be included in the output)

Figure 13: Example output of the Use-case model: Establish communication channels for the information produced by the WQMP. This output can be numerical (modifiable and integratable in an electronic agenda) or produced as a print out.

A.5. Use-case model: *Establish sampling frequency and recurrence*

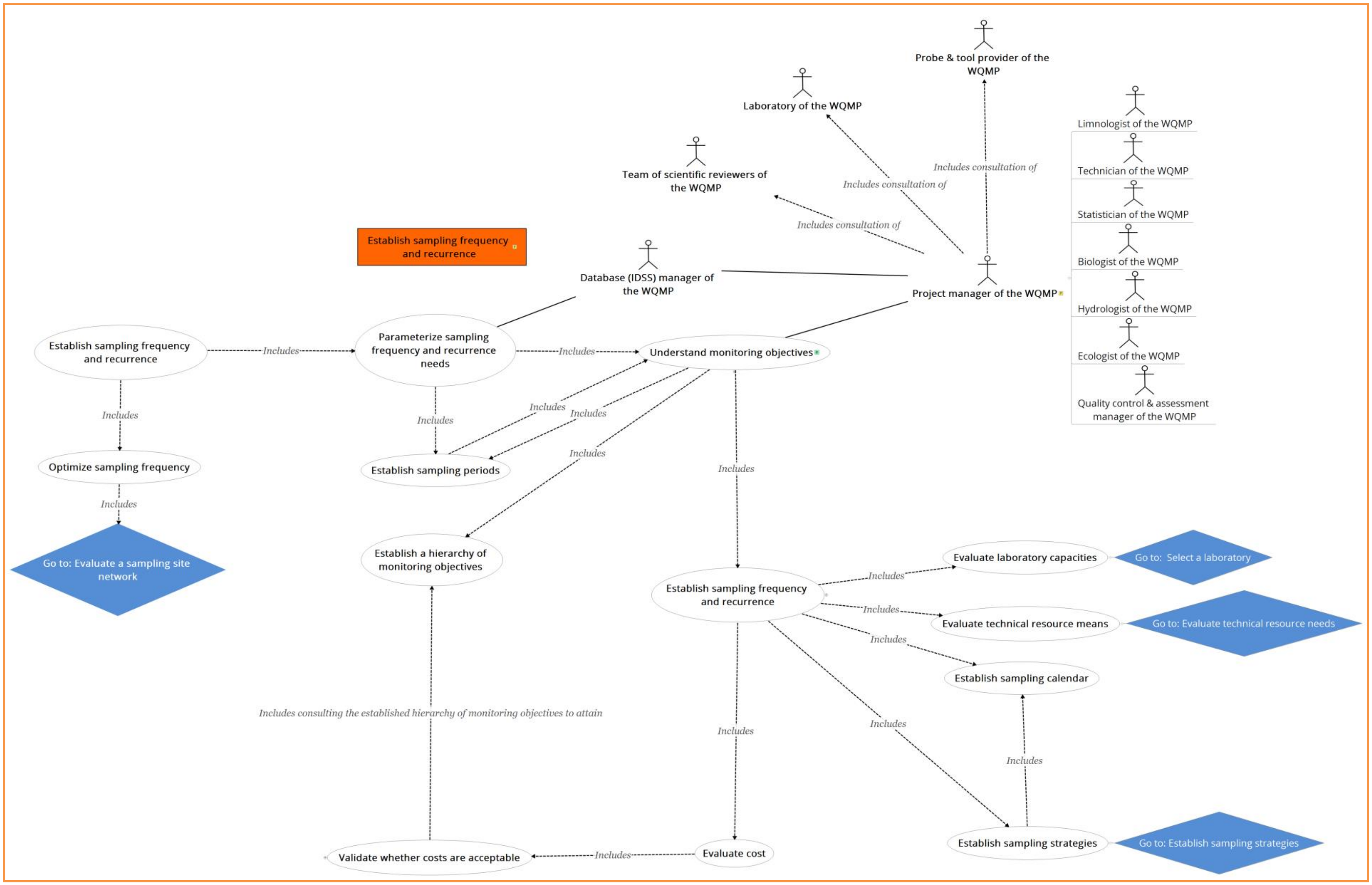

Figure 14: Use-case model for the use case: Establish sampling frequency and recurrence.

User story: Consult information on sampling calendar decisions
A user can consult information on advantages and disadvantages of fixed versus flexible sampling calendars.

User story: Select sampling frequency according to statistical analysis needs
A user is provided with a number of n to obtain according to the type of statistical information, water quality indices, etc. which need to be produced (the user is redirected to consult the use case: establish communication channels for the information channels and production guidelines for the information produced by the WQMP).

User story: Select sampling frequency based on cost
A user cam calculate sampling frequency scenarios based on cost for laboratory analysis, probe availability, human resource needs, transportation costs, data treatment capacities etc.. The user is redirected to the use-case: Evaluate resource needs.

User story: Establish sampling frequency in accordance with specific sampling strategies
A user is redirected to the use case: Establish sampling strategies.

User story: Establish sampling periods according to specific monitoring objectives
A user can establish sampling periods according to specific event monitoring objectives (e.g. E.g. Manure spreading (agriculture), pesticide spreading (agriculture and golf resorts), application of nitrogen (ski resorts) etc.).

User story: Select sampling frequency according to technical , financial and human resource availability and monitoring objectives
A user cam evaluate whether spot sampling, high frequency sampling (continuously deployed probes), automated grab sampling are more or less adapted to monitoring objectives, technical and human resource availability.

User story: Establish sampling calendar (time of the day, time of the year, frequency, and recurrence)
A user can obtain a proposition of a sampling calendar for each type of monitoring in accordance with the monitoring objectives, sampling strategies, statistical analysis needs, and other criteria which have been taken into account in the previous steps.

User story: Select sampling frequency according to regulations and policies
A user is provided with a number of n and periods of sampling according to local, regional and transnational regulations (e.g. Water framework directive).

User story: Parameterize sampling frequency and recurrence needs
A user cam parameterize sampling frequency and recurrence for each parameter according to rules and regulations.

User story: Select sampling frequency according to specific monitoring objectives
A user is provided with a number of n to obtain according to rules of thumb proposed in the literature for lake and river monitoring (e.g. Establish trophic status – for each type of parameter or set of parameters a frequency is provided).

User story: Optimize sampling frequency
A user is redirected to the use-case: Evaluate a river station network.

Figure 15: User stories for the use-case model: Establish sampling frequency and recurrence.

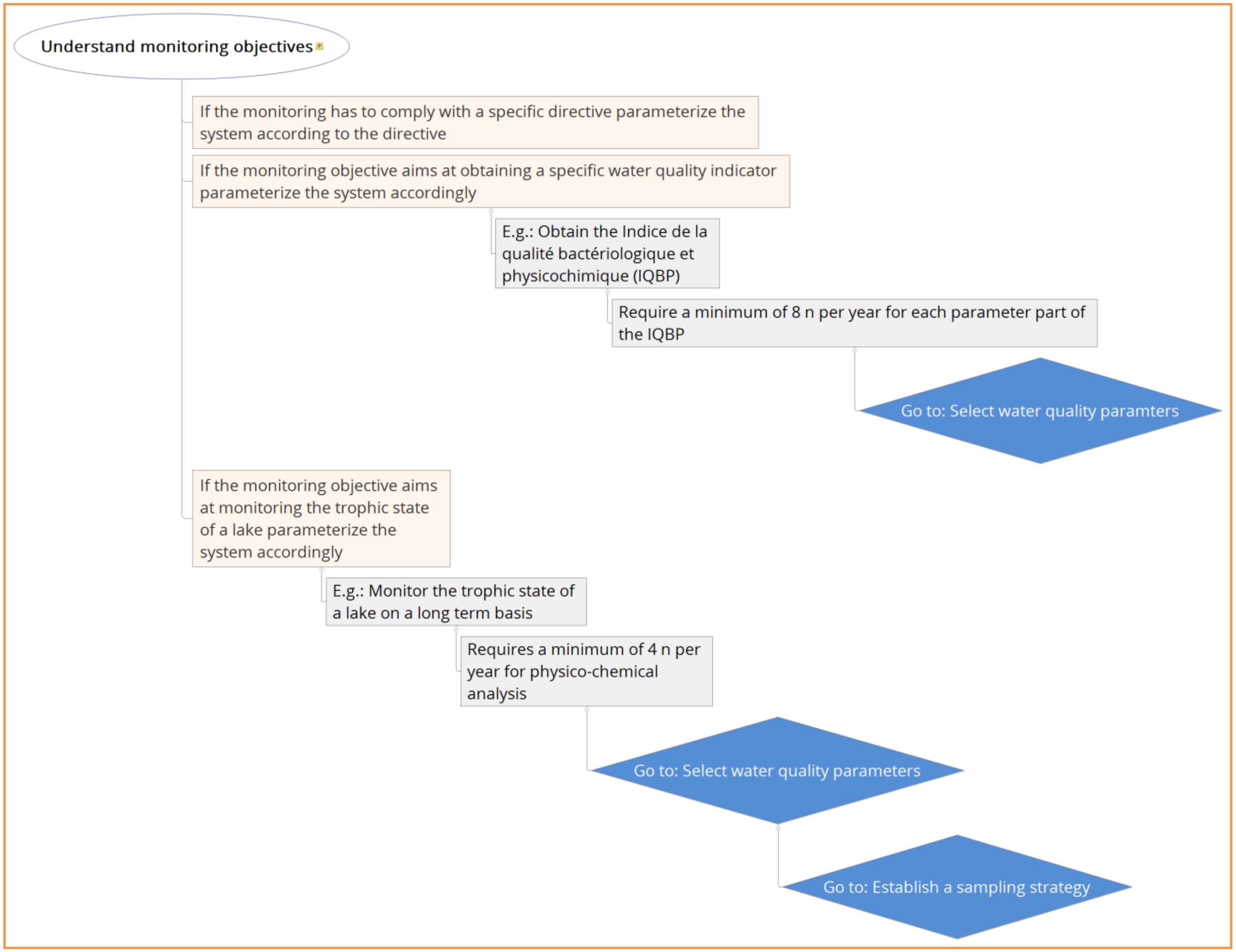

Figure 16: Example of reflections for the use-case slice: Understand monitoring objectives.

A.6. Use-case model: *Prepare data handling, storage and reporting*

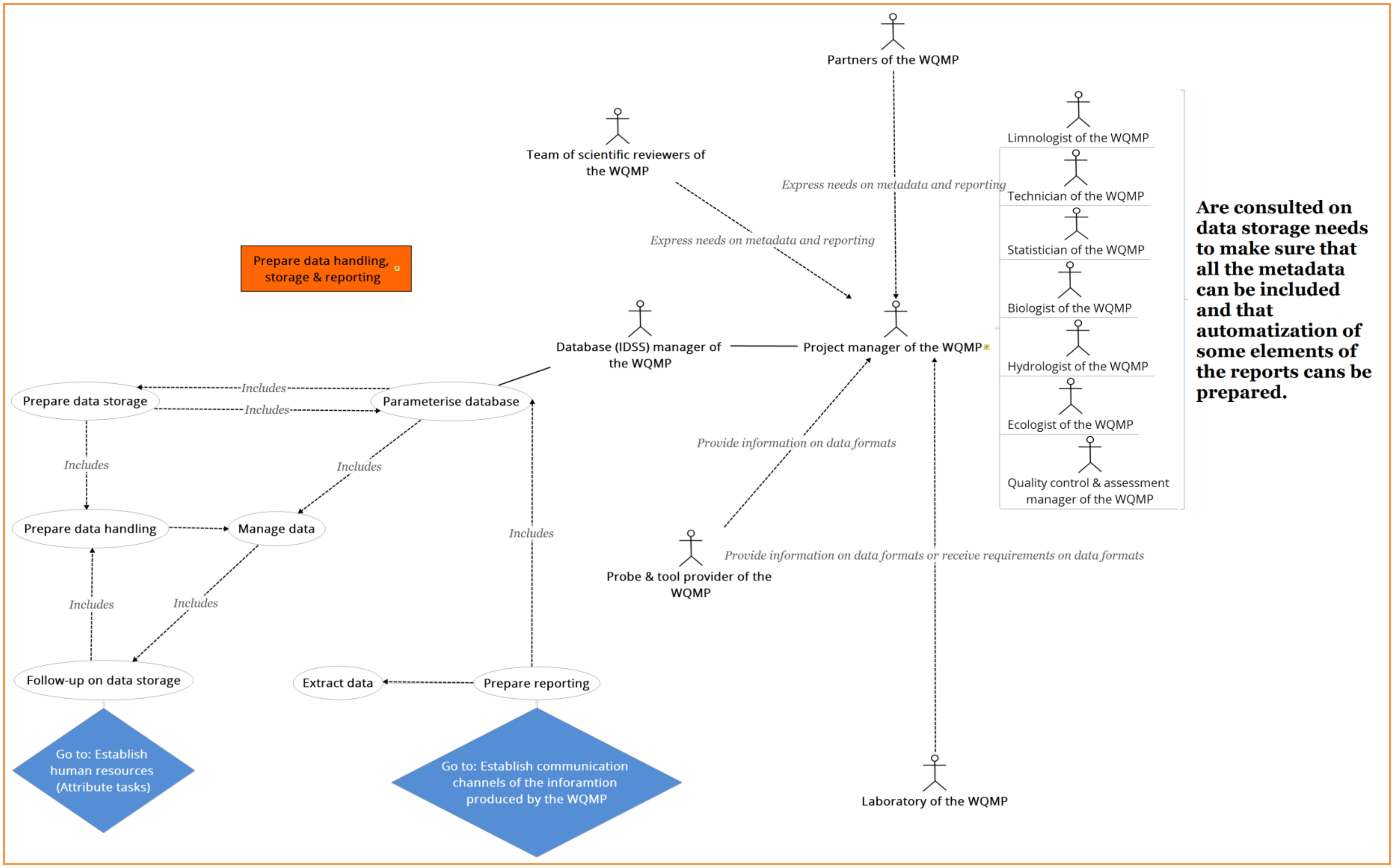

Figure 17: Use-case model for the use case: Prepare data handling, storage and reporting.

User story: Prepare data handling

A user can consult a list of relevant data handling considerations for field observations (contexts), for probes, field measurements and laboratory data. These considerations include for field observations: prepare field note books (write in the rain paper or electronic devices, according to field conditions ,observations to be taken on the field, minimum requirements of the data base, ensuring integration of the information in the data base. These considerations include for probes: parameterize the probes' logging system according to the order in which the stations are being visited, parameterize the probe to the previously established measuring units and data formats, ensure that probe calibration was done, export data from the probe, validate data from the probe, import data into the data base. The considerations for laboratory data include: Ensuring that laboratory registry forms are in accordance with the sampling campaign (e.g. sampling station names, parameters to be analyzed), ensuring that the laboratory results are provided in the necessary formats for easy data import into the database ((see figure 19 for an illustration of the data base).

User story: Prepare data storage

A user can follow an onboarding procedure to the data base Enki™ to prepare for data storage. Some of the onboarding procedure was generally already part of the use-cases Select an area subject to the WQMP, Establish a sampling site network. These have included the creation of watersheds, waterbodies and sampling sites and parameterize sampling site justifications, monitoring objectives, probes, tools, laboratories, protocols, mandatory and optional field observations, parameters and measuring units. An important last step is to ensure that data formats from the probes and laboratories can be supported by the system, and, if not, program the system to be able to support the data formats.

User story: Parameterize database

A user can parameterize the database according to the retained water quality parameters, measuring units, laboratory and probe data formats to be supported , field observations to be included, tools and protocols which are used, etc.

User story: Prepare data reporting

A user is directed to the use case: Establish communication channels and production guidelines for the information produced by the WQMP.

User story: Extract data

A user can extract data from the database from an extraction pane with a variety of possible filters (select data for a project, timeframe, sampling station(s), according to sampling objectives, for a watershed, waterbody, sampling site justification, sampling tool, probe, laboratory, field personal etc.).

User story: Follow-up on data storage

A user can follow-up on data storage through a dashboard showing whether sampling contexts have been entered according the sampling calendar, whether probe data has been entered according to the type of probes which have been used for 1 or n sampling contexts, idem for laboratory data.

Figure 18: User stories for the use-case model: Prepare data handling and reporting.

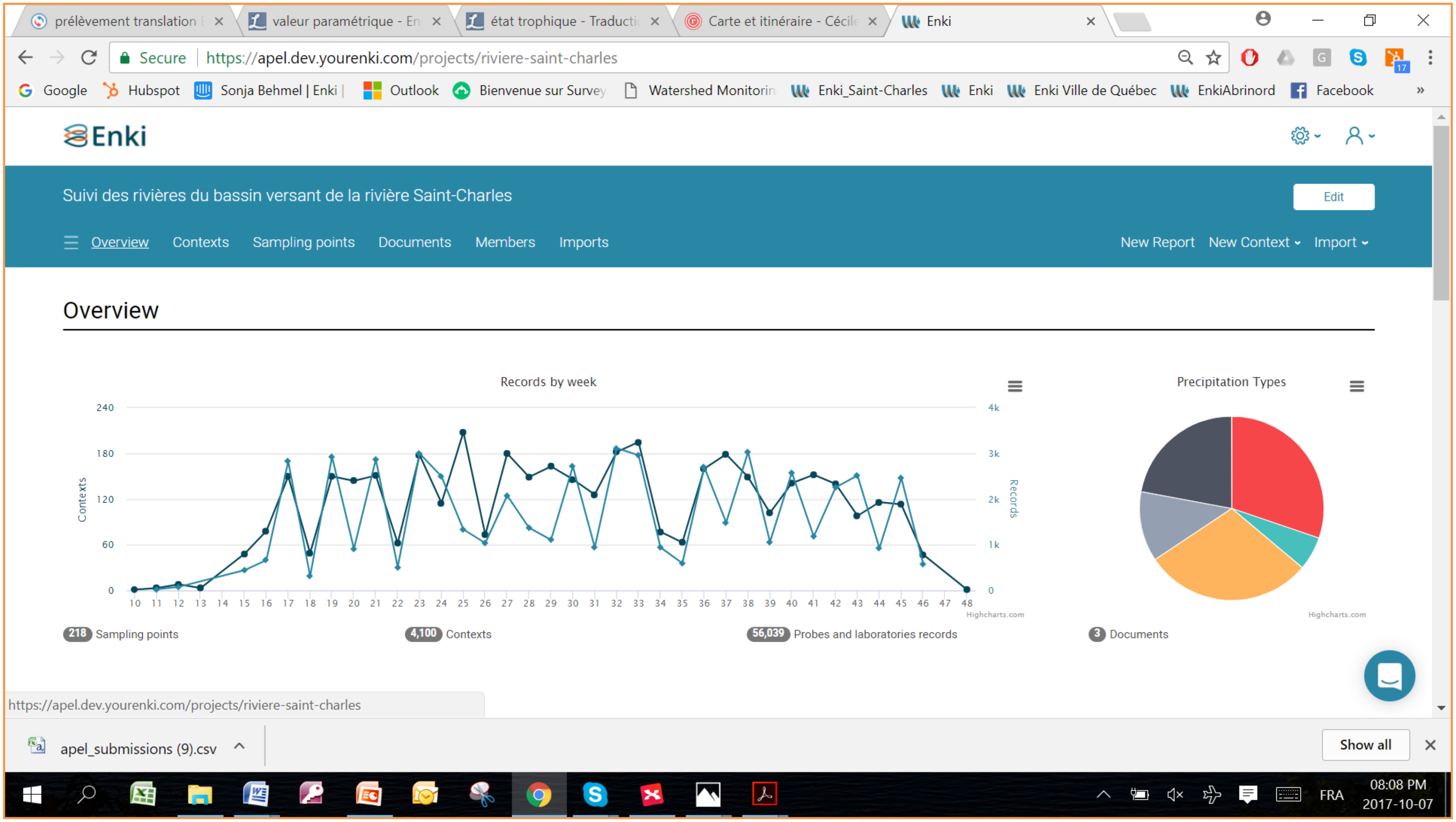

Figure 19: Excerpt of the data base Enki™ which shows the main dashboard for data storing and reporting for the monitoring of rivers of the Saint-Charles river case study: Project overview including number of sampling contexts, sampling points, probe and laboratory records, project related documentation, project members, imports (related to data import from probes and laboratories.

A.7. Use-case model: *Classify waterbodies*

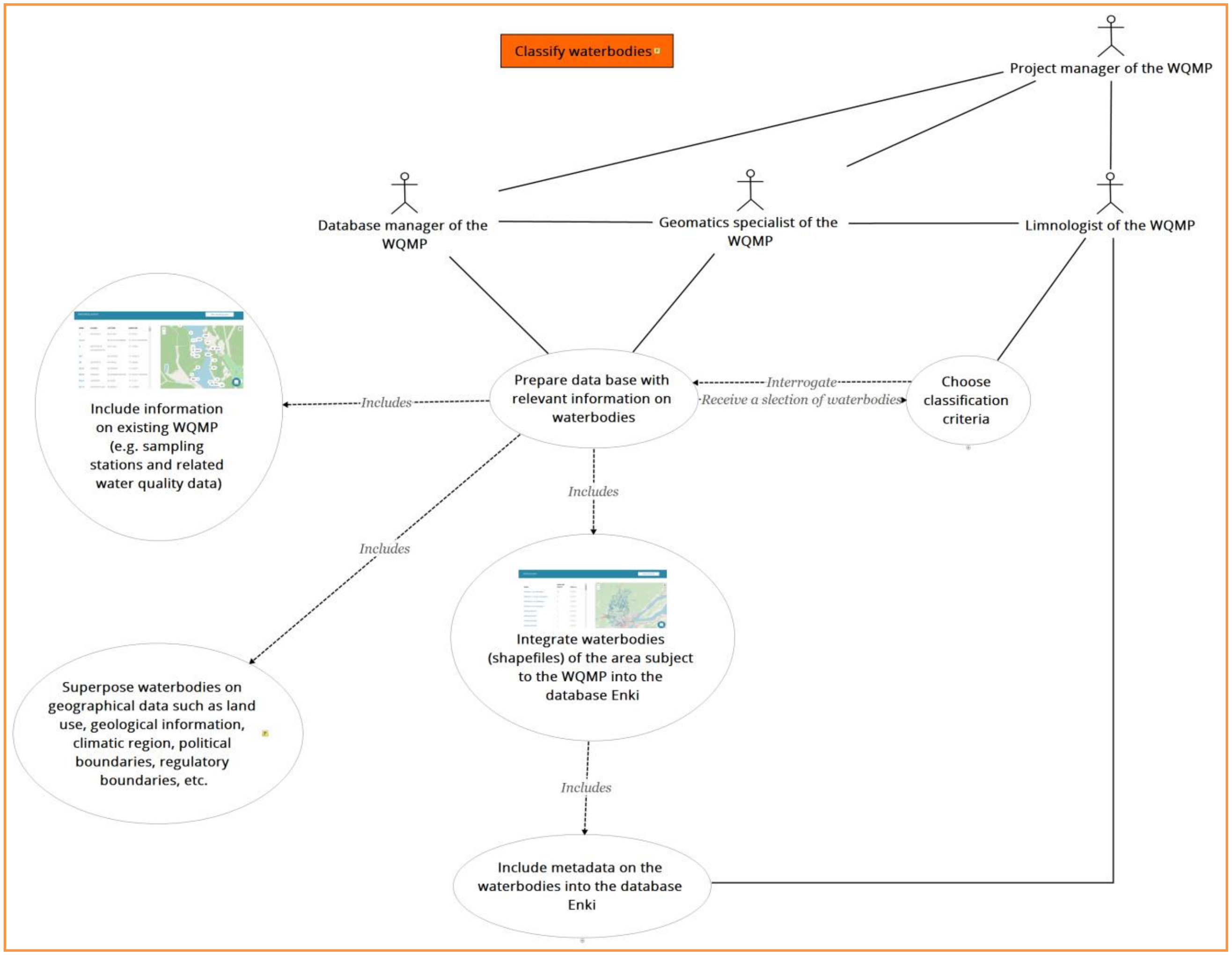

Figure 20: Use-case model for the use case: Classify waterbodies.

User story: Integrate waterbodies of the area subject to the WQMP into the database Enki.
A user can enter waterbodies into the database including a selection of additional information to the basics (e.g.: name, aliases), attributes and metadata on the waterbodies (e.g. For lakes: area, volume, perimeter, fetch, bathymetry, year of bathymetry, source of bathymetry, inflows, outflows, dams, type of dams, operator of dams, available studies, etc.).

User story: Obtain information on waterbodies
A user can obtain information on waterbodies according to a number of first queries (e.g. Name, alias, watershed, monitoring objective, etc.) which will then provide the user with the available information in the database.

User story: Choose classification criteria
A user can select from a list of classification criteria (which is (1) provided according to policy or regulatory requirements), (2) can be parameterized to the type of classification needs of the user (see use case: Parameterize classification criteria of waterbodies) in order to obtain a checklist of minimal information which needs to be included when entering the waterbodies in the database in order to enable the system to classify the waterbodies.

User story: Include information on existing WQMP
A user can include (and consult) information on existing monitoring efforts on the waterbodies (e.g. Sampling stations, sampling site justification, sampling objectives, related data and information etc.).

User story: Parametrize classification criteria
A user can enter classification criteria other than "official" classification criteria provided in the use case: Choose classification criteria. These criteria could include criteria such as destined use of waterbody, known impacts on waterbody, association with watershed(s), associations with other waterbodies(s) (e.g. Inflow of, outflow of), economic value (tourism, water sports, fishing, etc.), ecological value, cultural value (e.g. First Nations heritage), etc.). (NOTE: in order to achieve a valuation of a waterbody, a multi-criteria decision process using a participative approach could be proposed).

User story: Classify waterbodies
A user can classify waterbodies according to regulatory or policy requirements or according to monitoring or study objectives.

Figure 21: User stories for the use-case model: Classify waterbodies.

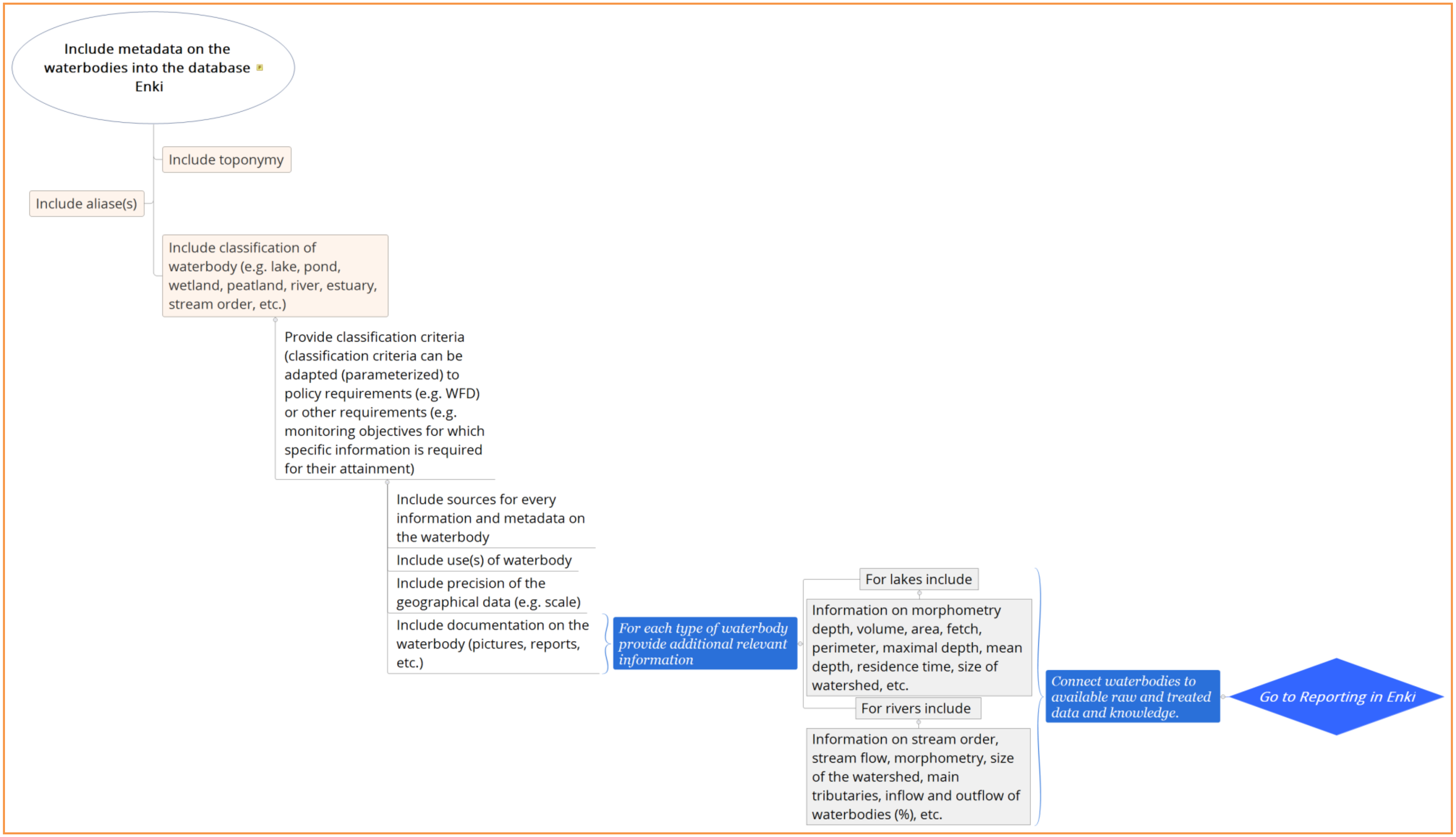

Figure 22: Excerpt of the decision support tree for the use-case slice: Include metadata on the waterbodies integrated into the database Enki.

A.9. Use-case model: *Select water quality parameters*

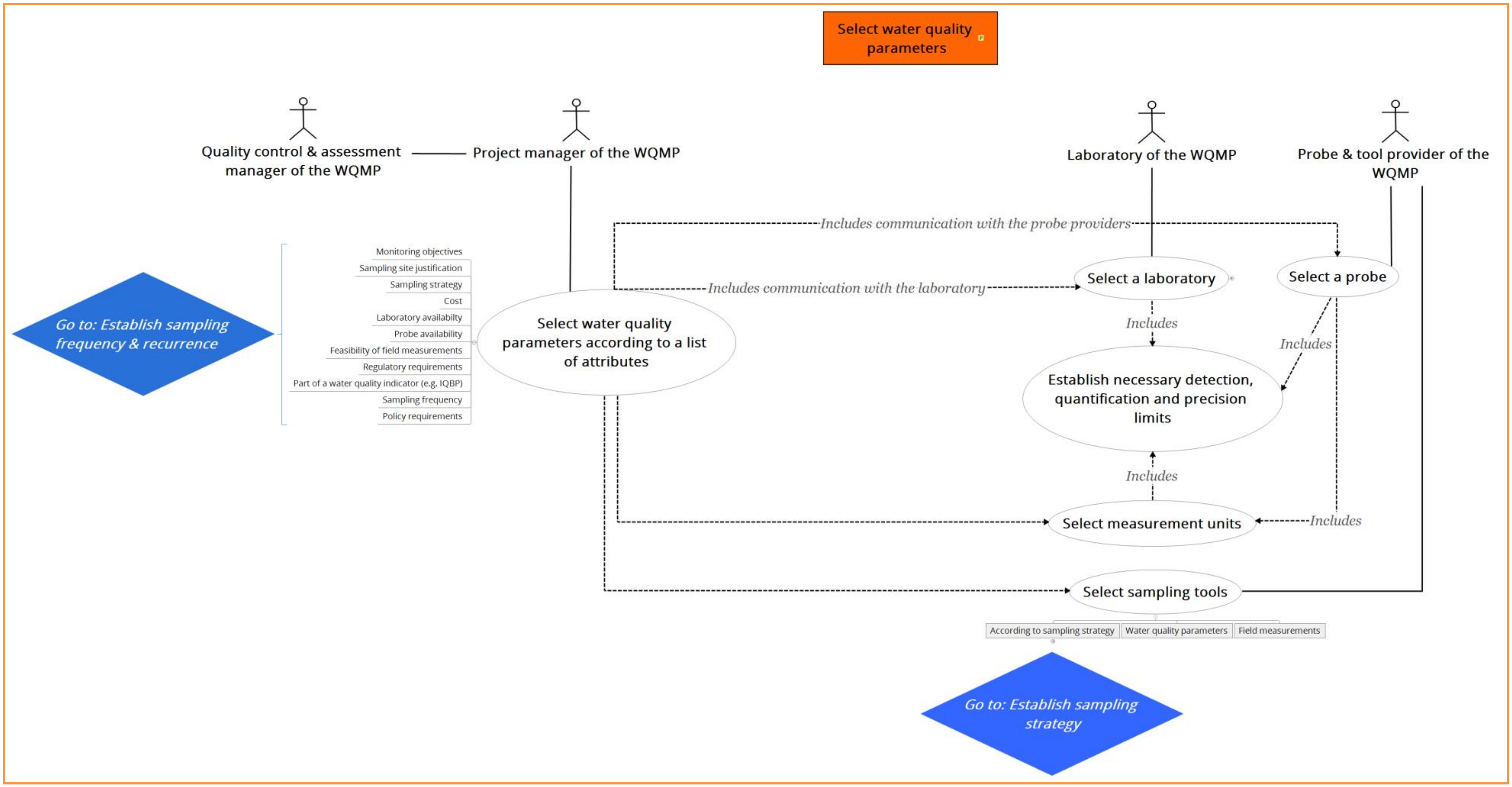

Figure 23: Use-case model for the use case Select water quality parameters.

User story: Select measurement units
A user can select from a set of measurement units he wishes to work with in order to homogenise results, facilitate communication and be in accordance with measurement units used for reporting (e.g. use for water quality indices or regulatory limits).

User story: Identify parameter precision (performance characteristics)
A user can identify parameter precision according to a list of questions : if you chose this parameter, the detection limit should be at least X, the quantification limit Y , the certainty W, etc. These specifications can be related and adapted to regulatory obligations, need of precision according to sampling objectives, use for indices, or for water quality criteria.

User story: Establish field manipulation
A user can establish which type of field manipulation is necessary for each parameter (e.g. filtration, titration, conservation) in order to plan for time and materials (The user can be directed to the use-case: Plan field work.

User story: Assess capacity of staff to interpret results
A user can verify in the data base of the staff and scientific support team whether the expertise to interpret results from the selected water quality parameters is available. If not, he can make a note of finding the expertise, for instance.

User story: Select a laboratory
A user can follow a list of criteria and guidelines on the choice of a laboratory **(see decision support tree in figure 25)**

User story: Select water quality parameters
A user can selected water quality parameters according to grouping which is provided according to monitoring objectives (e.g.: monitor the trophic state of a lake – if the territory subject to the WQMP is the province of Quebec, the minimal requirements to establish this state are provided : transparency, total phosphorous, chlorophyll a. Other water quality parameters will be suggested : total dissolved oxygen, temperature, aquatic plant identification, etc.). For each of the proposed parameters, a sampling strategy is suggested .

User story: Understand water quality parameters
A user can visualize information on water quality parameters (under the form of a dictionary which also briefly explains the type of information a parameter can provide during the analysis phase).

User story: Identify matrix
A user can identify the matrix to be analyzed (water, sediment, particulates according to regulatory or policy requirements or type of parameter).

User story: Select sampling frequency and recurrence
A user is directed to the use-case establish sampling frequency and recurrence.

User story: Select a probe
A user can follow basic criteria and guidelines on the choice of a probe.

User story: Select sampling tools
A user can select from a list of sampling tools according to the type of water quality parameter which was retained.

User story: Select sampling strategy
A user is directed to the use-case: Establish a sampling strategy.

User story: Establish conservation requirements
A user can, according to the list of water quality parameters which were retained for the field campaign, identify conservation requirements (the latter were part of the attributes of each water quality parameter).

User story: Select protocols
A user can select from a list of field sampling protocols and field tools according to the retained water quality parameters (e.g. Transparency in a lake– Secchi Disk – Secchi Disk protocol).

User story: Choose between a laboratory and a probe for specific parameters
A user can verify whether specific parameters can be measured at the laboratory and/or with a probe and is provided with a list of decisions to make in favor of one or another (e.g. Cost, precision, precision needs, regulatory requirements, rapidity of obtaining results, monitoring objectives).

User story: Parameterize attributes of water quality parameters
A user can parameterize attributes of water quality parameters which he needs in addition to the minimum attributes already in the system to effectuate a choice (minimum attributes: measurement unit, label). Type of attributes the user can choose from and add information to: cost per parameter, being part of 1 or n water quality indicators, being part of 1 or n regulatory obligations, type of parameter (biological, chemical, physical, transformation product, pesticide, etc.), dependency on sampling time (e.g. Diurnal and seasonal changes in oxygen and temperature can have an impact on the sampling time and rigor of keeping up a same sampling timing between campaigns), impact of sampling strategies on variation (e.g.. Chlorophyll a concentrations in lakes are very variable according to seasonal and diurnal variations, as well as to transparency (this will impact the sampling strategy and is thus a very important information for the use-case establish a sampling strategy).

Figure 24: User stories for the use-case model: Select water quality parameters.

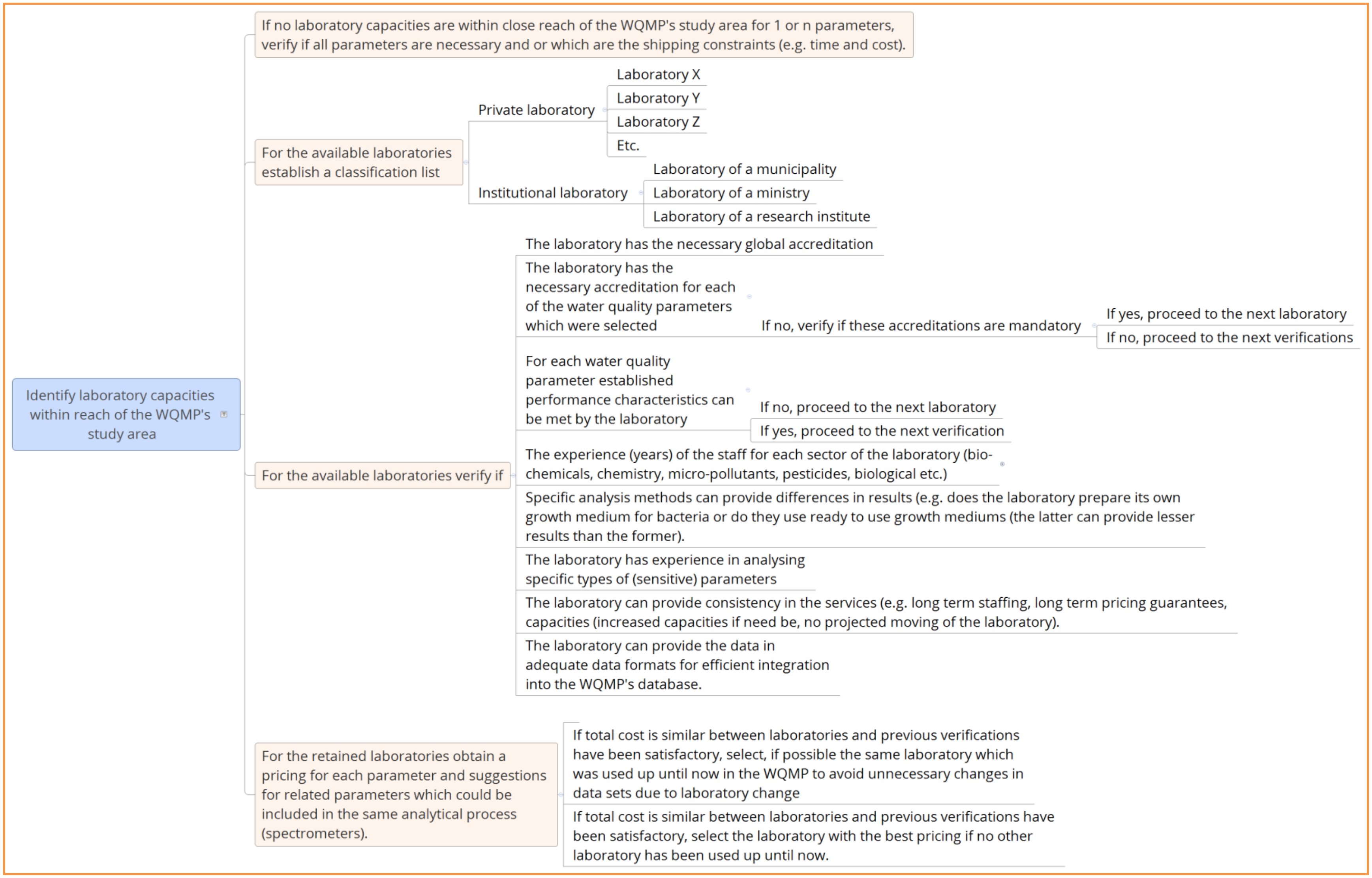

Figure 25: Excerpt of the decision support tree attributed to the user story: Select a laboratory.

A.10. Use-case model: *Establish a sampling site network*

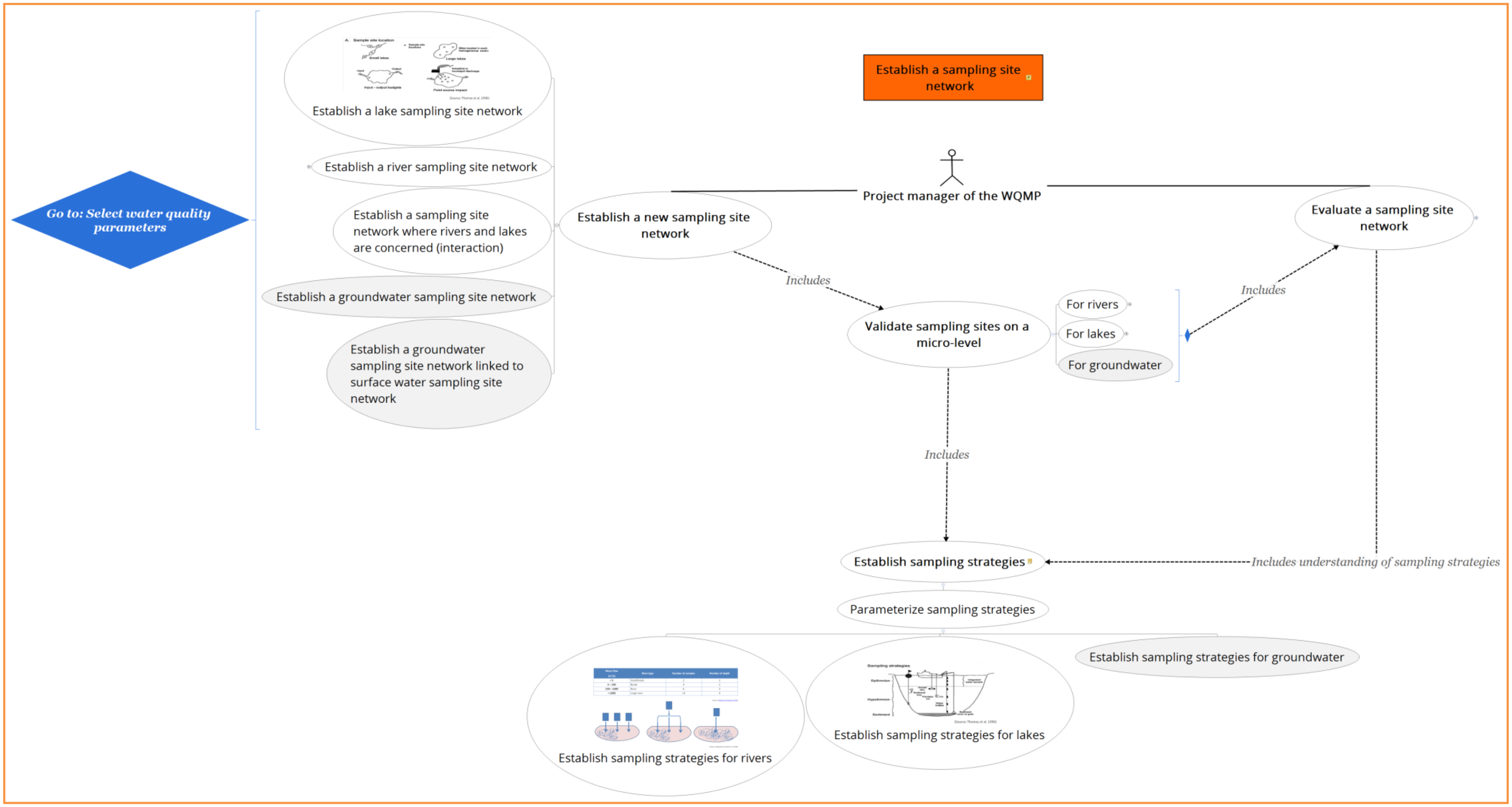

Figure 26: Use-case model for the use case: Establish a sampling site network (Note: in order to illustrate that the system is eventually expandable to groundwater monitoring, the ellipses for groundwater were included).

User story: Establish addressees of the information
A user can establish a list of addressees of information produced by the WQMP.

User story: Establish communication channels
A user can establish communication channels of the information by selecting 1 or n addressees to be communicated 1 or n types of information.

User story: Establish a communication calendar
A user can establish a communication calendar by selecting a date or a time-frame for which 1 or n types of information should be communicated for 1 or n types of communication channels.

User story: Receive information from partners and stakeholders
A user can create specific PPGISs' for specific areas, subjects and stakeholders in order to receive information on specific events within the study area (event detection). These type of events could be sewer overflow events, road works, new residential development, etc. The user is directed to the use case: Establish a PPGIS.

User story: Parameterize addressees for the information
A user can parameterize addressees of information produced by the WQMP according to a list of attributes (e.g.: type of information to receive, timing for the information, stakeholders, geographical areas, reason to receive information (e.g. Alert on specific events or observations during a field campaign – this can be a blue green algae bloom observation or an oil spill - which must be send to 1 or n addressees,)

User story: Establish content (message) of the information to be produced)
A user can establish a list (and pieces) of content which need to be included in 1 or n type of information (e.g. In order to communicate a blue green algae bloom a minimal number of information needs to be completed before sending it to the addressees; in order to send out raw data to 1 or n addressees for a specific project or sampling objectives the minimal information to be included can be identified).

User story: Receive alerts on events within the watershed
A user can receive alerts on events within the watershed which are communicated through the PPGIS, according to established emergency criteria.

User story: Parameterize information to be produced by the WQMP
A user can parameterize the type of information to be produced by the WQMP (e.g. Information to produce water quality indicators, information to produce alerts, narrative information (reports, summary of the results for Websites, press releases, etc.), statistical information, visual information (e.g. Videos, interactive maps), numeric information (e.g. Raw data) (This parameterization is done according to monitoring objectives, knowledge needs, preferred communication channels identified through the participative approach (see chapter 2) and addressees of the information).

User story: Establish quality control
A user is directed to the use-case quality control of the information produced by the WQMP before sending it out.

User story: Manage knowledge
A user can receive information from universities or other partners on research, monitoring or studies which are either related to the knowledge needs of the WQMP or the study area.

User story: Receive alerts on information to be relayed
A user can receive an alert on information to be communicated according to the information which is entered in the field observation context (e.g. When the users enters the sampling objective: follow up on blue green algae blooms, he will receive a list of additional information to enter in the sampling context, such as: have you observed any scum? If the user says yes, the scope of the bloom is assessed and depending on the scope the user is informed that he needs to relay the completed information report to 1 or n number of addressees (including the contact information).

Figure 27: User stories for the use-case model: Establish a sampling site network.

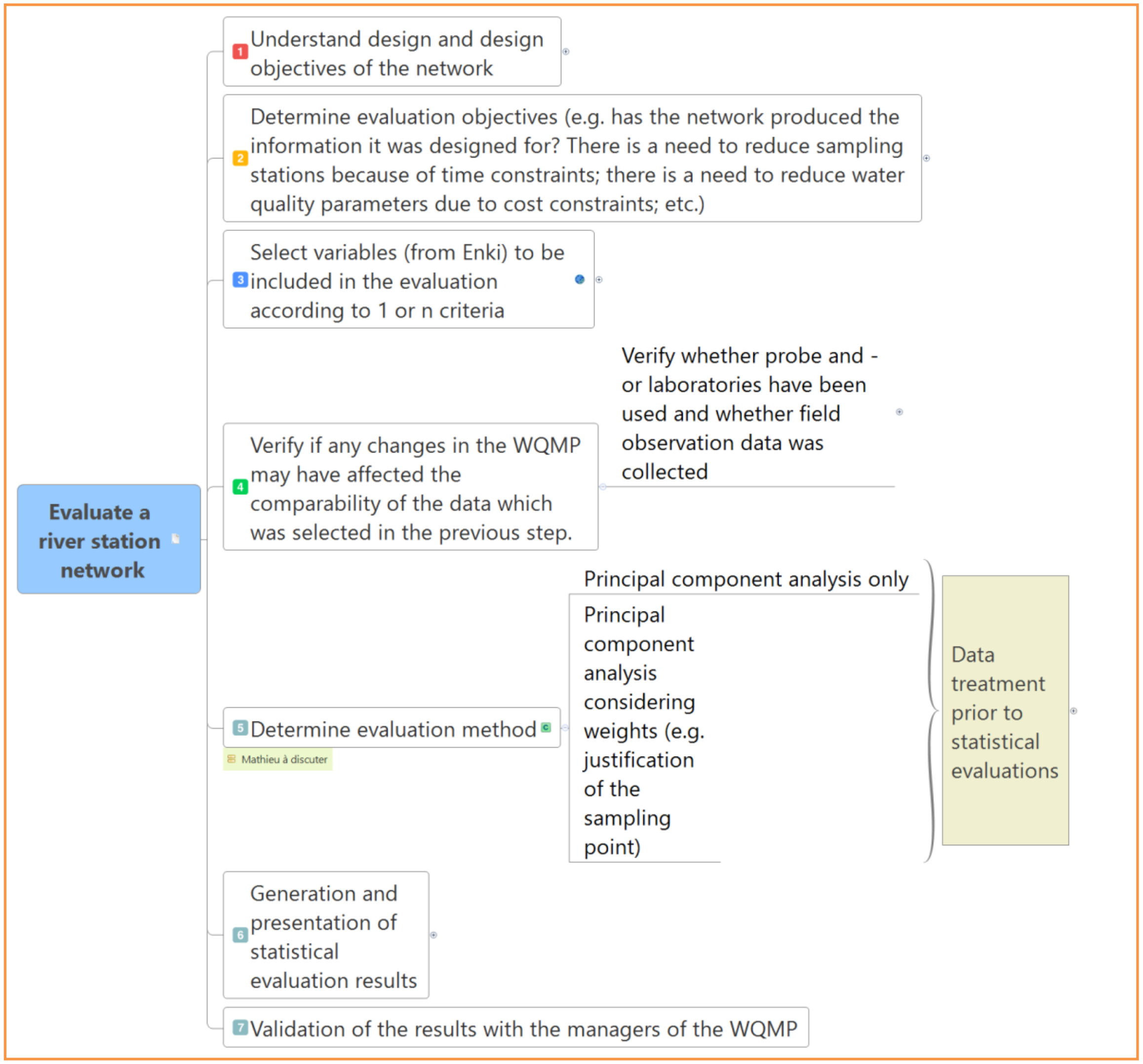

Figure 28: Excerpt of the decision support tree for the use-case slice Evaluate a river station network. This decision support tree aims at helping the user understand the existing WQMP before proceeding to its evaluation (see chapter 4).

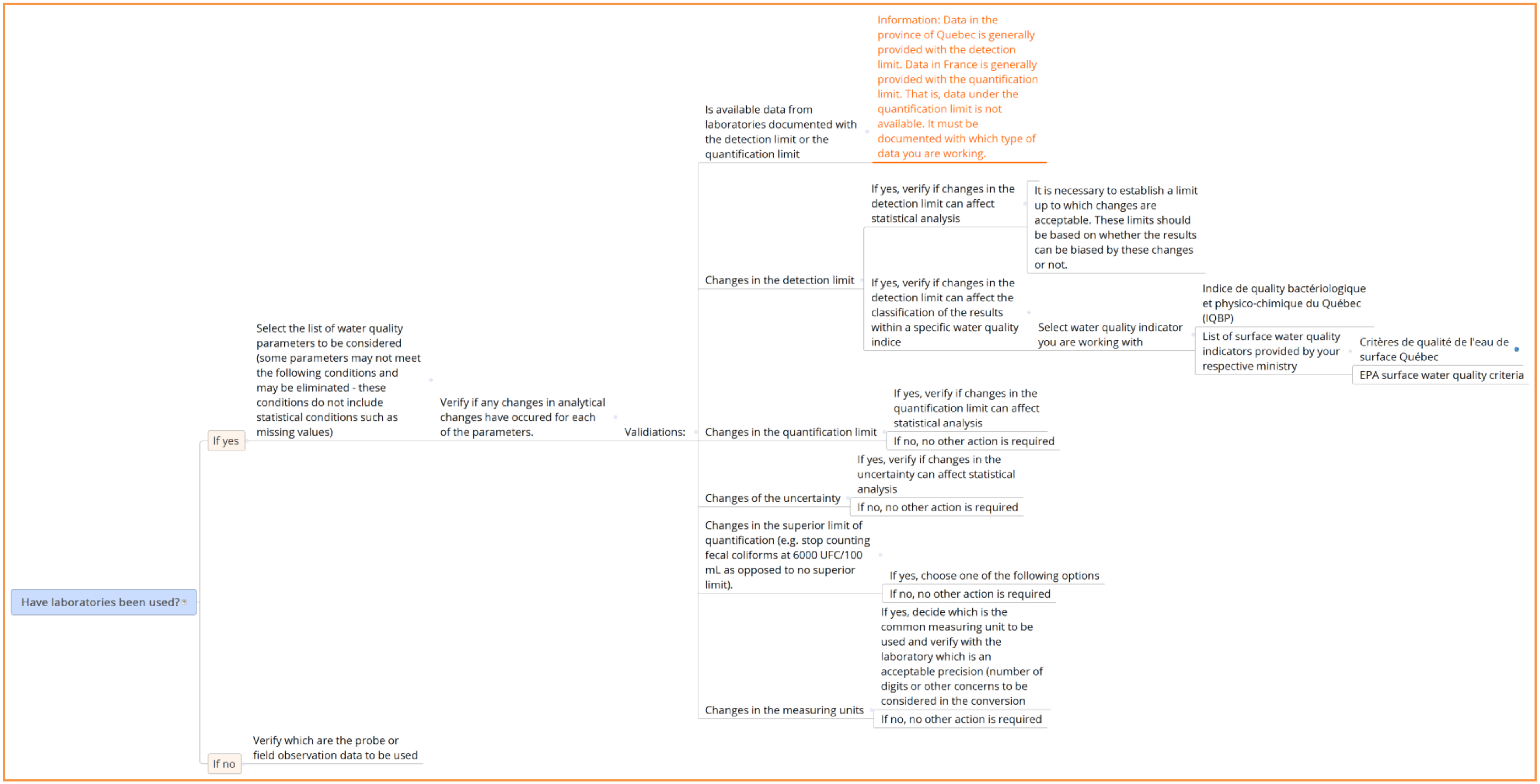

Figure 29: Small excerpt of the decision support tree: Evaluate a river station network. This excerpt aims at making the user aware of changes and specificities of the data which was analyzed in laboratories before proceeding to the statistical optimisation options.

A.11. Use-case model: *Plan field work*

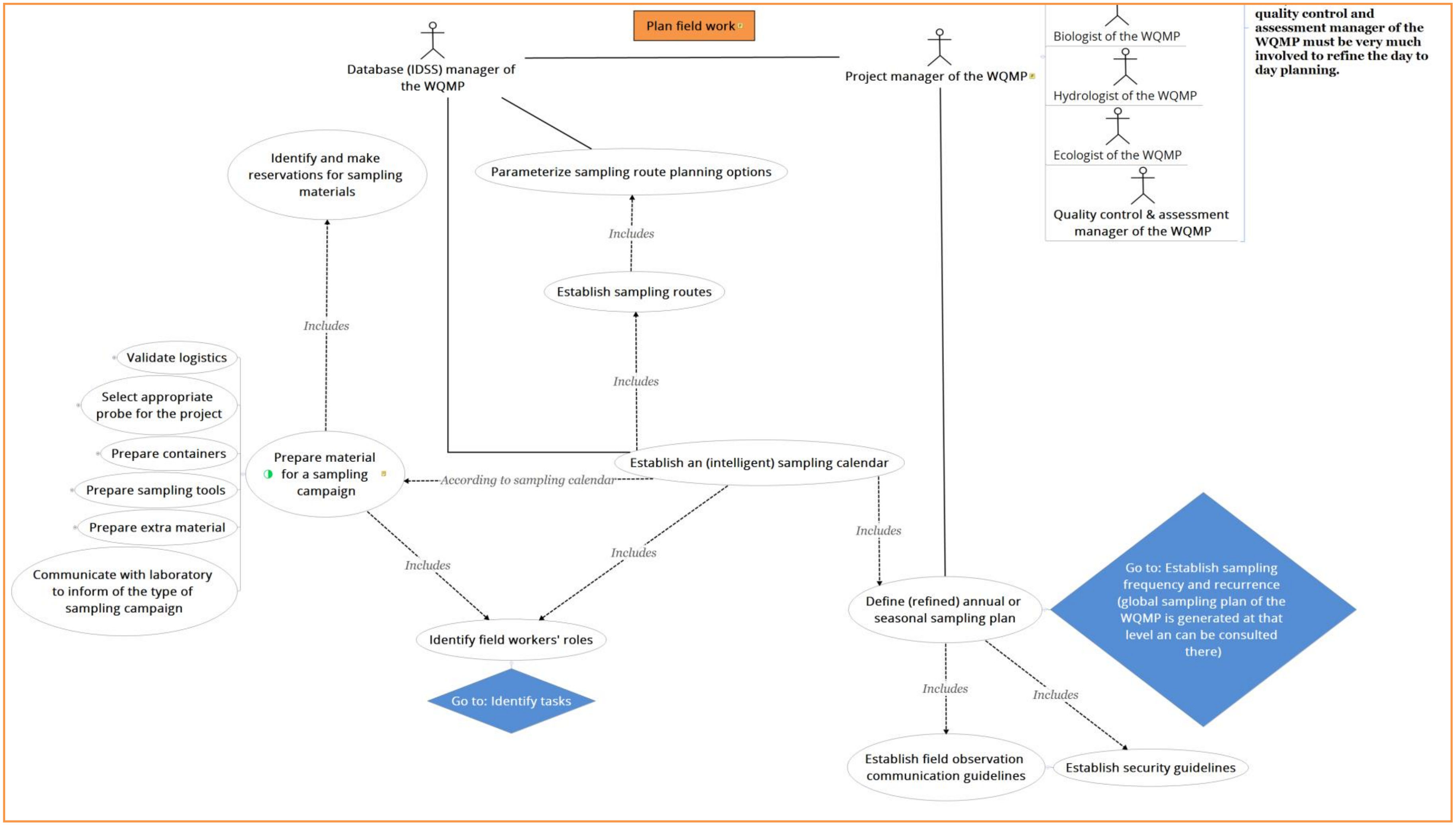

Figure 30: Use-case model for the use case: Plan field work.

User story: Define sampling plan
A user can define the annual (or seasonal) sampling plan of a WQMP according to the global plan of the WQMP before each season. The sampling plan contains information such as project name, project objectives, sampling stations, justification of the sampling stations, parameters to be sampled, sampling means (laboratory, probe, field measurements), project number of outings, period (e.g. Ice-free season, spring), days of the week were the sampling can be effectuated (e.g. If the laboratories do not accept bottles on Fridays, the sampling plan must restrict the time window to deliver to the laboratory), whether the sampling calendar will be flexible or static.

User story: Define sampling calendar
A user can define a sampling calendar according to information such as sampling frequency per project, number of stations to be visited, projected time for each station, number of personal for the campaign (1 or n persons), requirement such as: all stations for one waterbody should be visited on the same day, all stations for one watershed should be visited on the same day.

User story: Provide support for field staff
A user can consult the sampling routes which were established. The sampling routes include: Sampling route, name, position and detailed description of the sampling stations, precise positioning where the samples need to be taken, information on parking facilities, bottles to be filled at each site, material needed for each site, security issues, etc. (See figure 32).

User story: Identify and make reservations for materials
A user can identify needs for materials according to the sampling calendar and sampling routes, make reservations for the needed material and communicate with the laboratory.

User story: Establish an intelligent sampling calendar
A user can link the sampling calendar to weather predictions for the area subject to sampling and receive alerts on weather conditions which are either sought for (e.g. Rain for river monitoring, sun and calm conditions for lake monitoring) in order to change plans on the short term.

User story: Establish sampling routes
A user can establish sampling routes according the sampling calendar and additional information such as transport time between stations, requirements on the order of stations (up-stream to downstream, downstream to upstream), time onsite (according to the tasks to fulfill and number of staff to do the work), position at the outset of the sampling campaign, position at the end of the campaign, stops which need to be calculated in between (e.g. Toilet, pauses, etc.). The system can provide the user with alerts on traffic conditions.

User story: Establish emergency guidelines
A user can verify which are the emergency guidelines for a specific project, waterbody or study area.

User story: Establish security guidelines
A user can verify whether a field technician has specific health issues which need to be considered in case of emergency.

User story: Establish field observation communication guidelines
A user can verify which are the communication guidelines to follow in case of field observations which may impact water quality and quantity (first contact, organisation in charge of a specific area, organisation in charge of a specific type of problem, etc.).

User story: Identify roles of the field personal
A user can identify specific roles for the field personal (e.g. Probe manipulation, taking field notes, filling water bottles, preparing bottles, ordering bottles, delivery to the laboratory, cleaning of the materials).

User story: Parameterize sampling route planning options
A user can parameterize sampling route planning options in order to feed the system with considerations which are important for 1 or n specific projects from which the sampling route planner can be fed (e.g.: laboratory sample reception hours, earliest hour for field personal to be available, selections on preferences (sampling route per watershed, per waterbody, per project, per objective, etc.).

Figure 31: User stories for the use-case model: Plan field work.

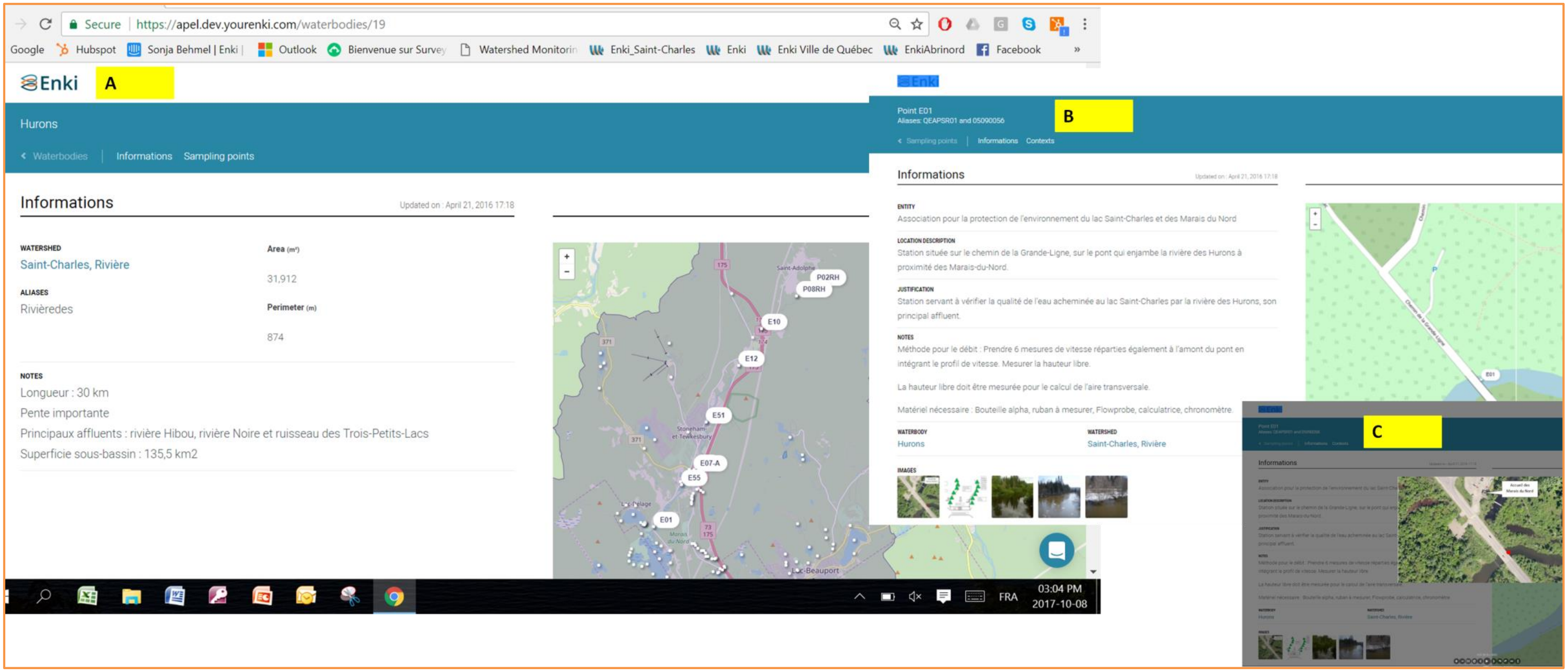

Figure 32: Figure A shows the use-case: Select sampling stations and plan a sampling route for a field campaign for a watershed. Figure B shows the specifications of a sampling station (e.g.; justification and material to use). Figure C shows where exactly the samples have to be taken and which are the accommodations in the vicinity (parking, toilets, etc.). When the selection is completed it is possible to print out (or save for access via a tablet) all the information as to the sampling route to follow for 1 or n specific days (https://apel.dev.yourenki.com/users/sign_in - with the kind permission of APEL).

A.12. Use-case model: *Plan quality control and quality assessment*

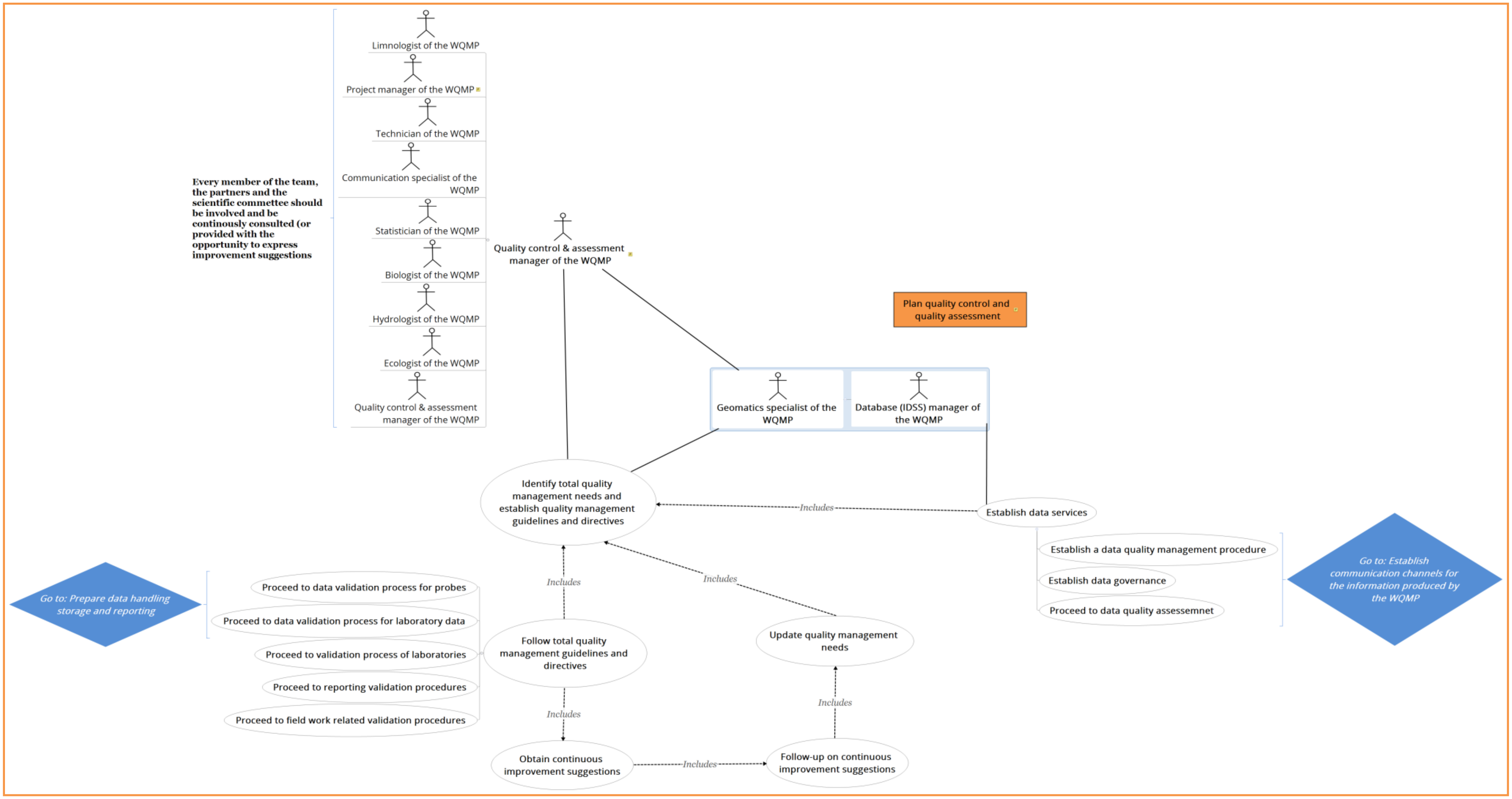

Figure 33: Use-case model for the use case: Plan quality control and assessment.

User story: Proceed to data quality assessment
A user can evaluate produced data in order to determine whether the data responds to the monitoring objectives (See use-case: Evaluate a river station network and chapter 4)

User story: Identify total quality management needs and establish quality management guidelines and directives
A user can identify quality management and assessment guidelines for every aspect of the WQMP by selecting the subject (e.g.: Data validation process for probes; data validation process for laboratories; quality assessment procedures for field work; material maintenance; report validation process; laboratory validation process (e.g.; if the laboratory is independent of the organisation of the WQMP, follow up procedures on potential changes in the laboratories' production line are proposed), etc.).

User story: Follow up on continuous improvement suggestions
A user can organize the improvement suggestions according to different levels of implementation: evaluation of the suggestion, priority of the suggestion, acceptance of implementing the suggestion, rejecting of the suggestion (with a justification), state of implementation, implementation completed.

User story: Establish a data quality management procedure
A user can establish a data quality management procedure for data management by attributing roles and responsibilities to the team members (e.g. Data extraction from probes, probe data validation, probe data import, work with the IT personal to improve the data management system). Note: Enki provides a series of .data quality management requirements to support the user in data quality management **(See figure 35).**

User story: Establish data services
A user can establish the type of data and access to the repository of data for the partners of the WQMP (the user is redirected to the use-cases: Proceed to data quality assessment (before integrating the data into the final database and Establish data governance for access to this data).

User story: Obtain continuous improvement suggestions
A user can provide a platform to team members (and partners of the WQMP) were they can communicate, by subject suggestions on improvements which could be made (e.g. Data validation procedures, field work, team management, communication, communication modes, reporting, etc.).

User story: Establish data governance
A user can attribute access roles to the database of the organisation, these roles can be: administrator, visitor, visitor with extraction and contributor . A user can limit or provide access to 1 or n projects, 1 or n type of datasets, 1 or n types of features of the system (e.g. Access only to the feature Implement a survey for the implementation of a PPGIS). **(See figure 35).**

User story: Follow total quality management guidelines and directives
A user can follow total quality management guidelines for the selected aspect and check whether the required procedures were fulfilled. A user receives reminders for tasks which have not been completed, or which have to be repeated (e.g. Probe calibration, data extraction from the probes, data import from probes, entry of measurement contexts pending according to the samplind calendar, etc.).

Note:
Part of the quality control and quality assessment is intrinsically part of the data base Enki which requires mandatory validation information and metadata on all types of data which is being entered into Enki.

Figure 34: User stories for the use-case model: Plan quality control and quality assessment.

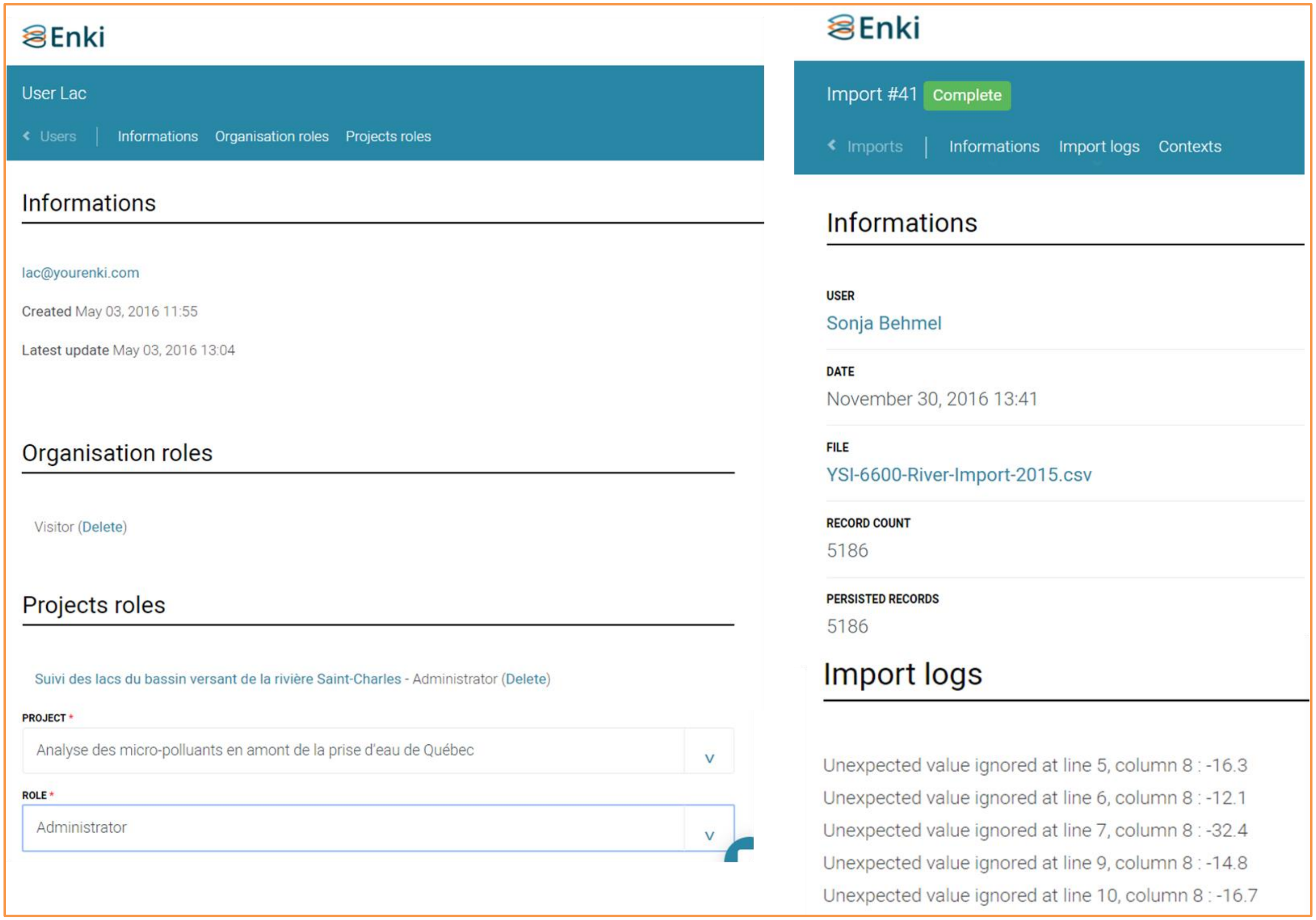

Figure 35 Excerpt of the data base EnkiTM for the use cases Establish data governance (left) and Establish a data quality management procedure (right). On the left, the screen shot shows the different roles which can be attributed to a user, that is, member of the WQMP's organisation or partners. On the right, the screen shot shows an excerpt of a data import log which specifies which type of data was not imported due to unexpected values, while providing information on the data which needs to be reviewed.

A.13. Use-case model: *Evaluate resource needs*

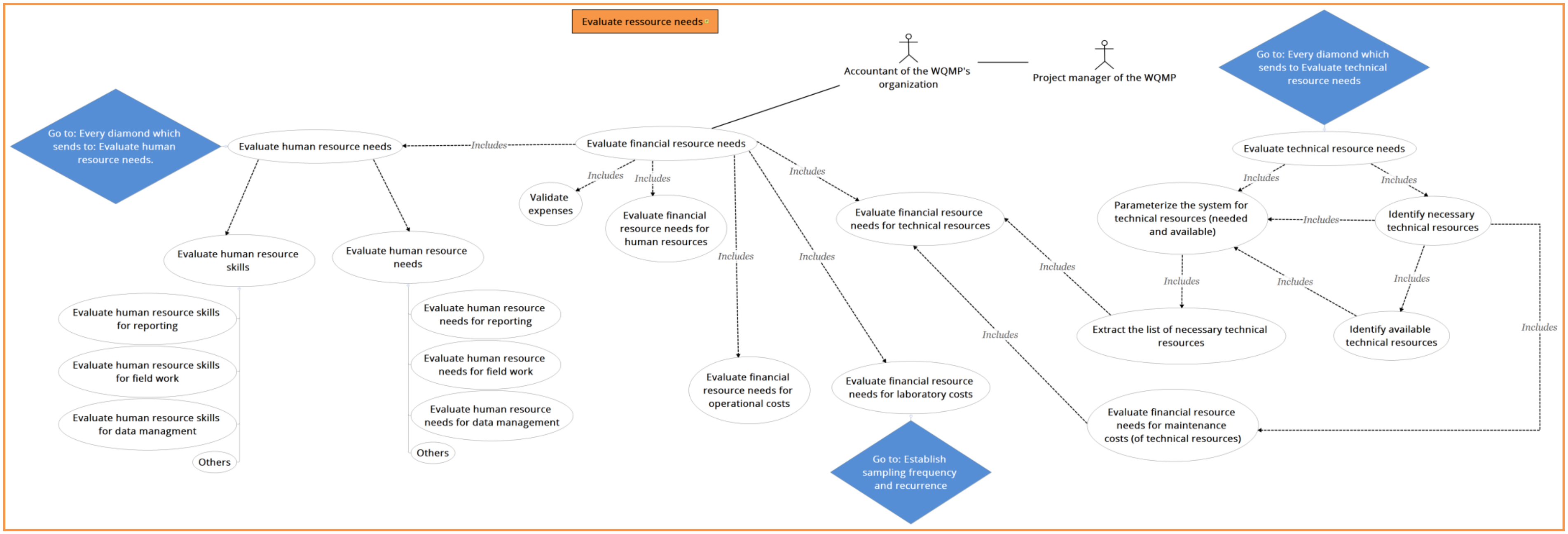

Figure 36: Use-case model for the use case: Evaluate resource needs.

User story: Define sampling plan
A user can define the annual (or seasonal) sampling plan of a WQMP according to the global plan of the WQMP before each season. The sampling plan contains information such as project name, project objectives, sampling stations, justification of the sampling stations, parameters to be sampled, sampling means (laboratory, probe, field measurements), project number of outings, period (e.g. Ice-free season, spring), days of the week were the sampling can be effectuated (e.g. If the laboratories do not accept bottles on Fridays, the sampling plan must restrict the time window to deliver to the laboratory), whether the sampling calendar will be flexible or static.

User story: Define sampling calendar
A user can define a sampling calendar according to information such as sampling frequency per project, number of stations to be visited, projected time for each station, number of personal for the campaign (1 or n persons), requirement such as: all stations for one waterbody should be visited on the same day, all stations for one watershed should be visited on the same day.

User story: Provide support for field staff
A user can consult the sampling routes which were established. The sampling routes include: Sampling route, name, position and detailed description of the sampling stations, precise positioning where the samples need to be taken, information on parking facilities, bottles to be filled at each site, material needed for each site, security issues, etc. (See figure 32).

User story: Identify and make reservations for materials
A user can identify needs for materials according to the sampling calendar and sampling routes, make reservations for the needed material and communicate with the laboratory.

User story: Establish an intelligent sampling calendar
A user can link the sampling calendar to weather predictions for the area subject to sampling and receive alerts on weather conditions which are either sought for (e.g. Rain for river monitoring, sun and calm conditions for lake monitoring) in order to change plans on the short term.

User story: Establish sampling routes
A user can establish sampling routes according the sampling calendar and additional information such as transport time between stations, requirements on the order of stations (up-stream to downstream, downstream to upstream), time onsite (according to the tasks to fulfill and number of staff to do the work), position at the outset of the sampling campaign, position at the end of the campaign, stops which need to be calculated in between (e.g. Toilet, pauses, etc.). The system can provide the user with alerts on traffic conditions.

User story: Establish emergency guidelines
A user can verify which are the emergency guidelines for a specific project, waterbody or study area.

User story: Establish security guidelines
A user can verify whether a field technician has specific health issues which need to be considered in case of emergency.

User story: Establish field observation communication guidelines
A user can verify which are the communication guidelines to follow in case of field observations which may impact water quality and quantity (first contact, organisation in charge of a specific area, organisation in charge of a specific type of problem, etc.).

User story: Identify roles of the field personal
A user can identify specific roles for the field personal (e.g. Probe manipulation, taking field notes, filling water bottles, preparing bottles, ordering bottles, delivery to the laboratory, cleaning of the materials).

User story: Parameterize sampling route planning options
A user can parameterize sampling route planning options in order to feed the system with considerations which are important for 1 or n specific projects from which the sampling route planner can be fed (e.g.: laboratory sample reception hours, earliest hour for field personal to be available, selections on preferences (sampling route per watershed, per waterbody, per project, per objective, etc.).

Figure 37: User stories for the use-case model: Evaluate resource needs.

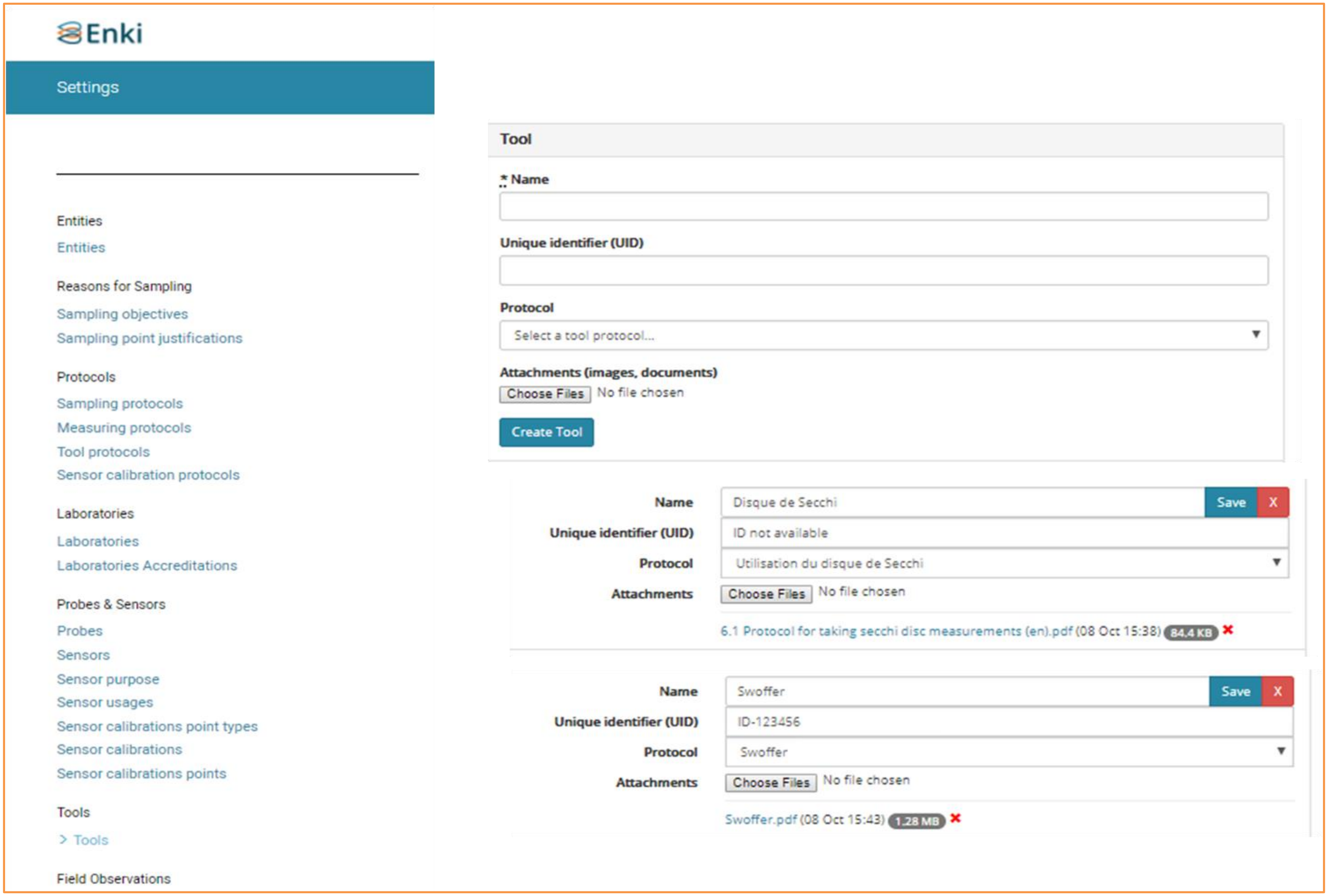

Figure 38: Screenshot of the use case: Parameterize the system for technical resources.

Appendix B

This appendix contains the survey questionnaire (in French) which was submitted to the citizens and representatives of organized stakeholders (ROS) of the two case studies. We are aware that the resolution is not optimal. The survey pages are inserted from PDF documents extracted from Survey Monkey.

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L'eau, ça nous concerne tous!

1. Bienvenue dans le sondage: L'eau, ça nous concerne tous!

L'eau en qualité et en quantité suffisante est essentielle à la vie, à la santé publique, au développement économique et à tout ce qui est lié aux sports nautiques et à la villégiature. Pour cette raison, il est essentiel de bien connaître la qualité de l'eau dans le but de prendre des actions communes pour protéger la ressource.

Vous êtes cordialement invités à participer à ce court sondage de 15 à 20 minutes pour connaître vos préoccupations sur la qualité de l'eau des lacs et rivières du bassin versant de la rivière Saint-Charles. Cette information servira ensuite à l'élaboration d'un nouveau programme de suivi de la qualité de l'eau dans le bassin versant de la rivière Saint-Charles qui tient compte de ces préoccupations.

La participation de tous les acteurs de la société au sondage est essentielle afin d'identifier l'ensemble des préoccupations et des besoins de connaissances concernant la qualité de l'eau. Ce sondage s'adresse à vous, peu importe si vous viviez dans ce bassin versant ou non.

Ce sondage est réalisé dans le cadre d'un projet de doctorat en Aménagement du territoire et développement régional en partenariat avec la Chaire de recherche en eau potable de l'Université Laval, Québec et la Ludwig Maximilians Université de Munich, Allemagne.

Vos réponses seront traitées de façon anonyme. Pour toute question, il est possible de communiquer avec madame Sonja Behmel, étudiante au doctorat responsable du sondage (418 255-9477 ou sonja.behmel.1@ulaval.ca).

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2. Renseignements généraux

*** 1. Veuillez indiquer si vous répondez en tant que citoyen ou en tant que membre d'une organisation**

- ◯ Je réponds en tant que citoyen
- ◯ Je réponds en tant que membre d'une organisation

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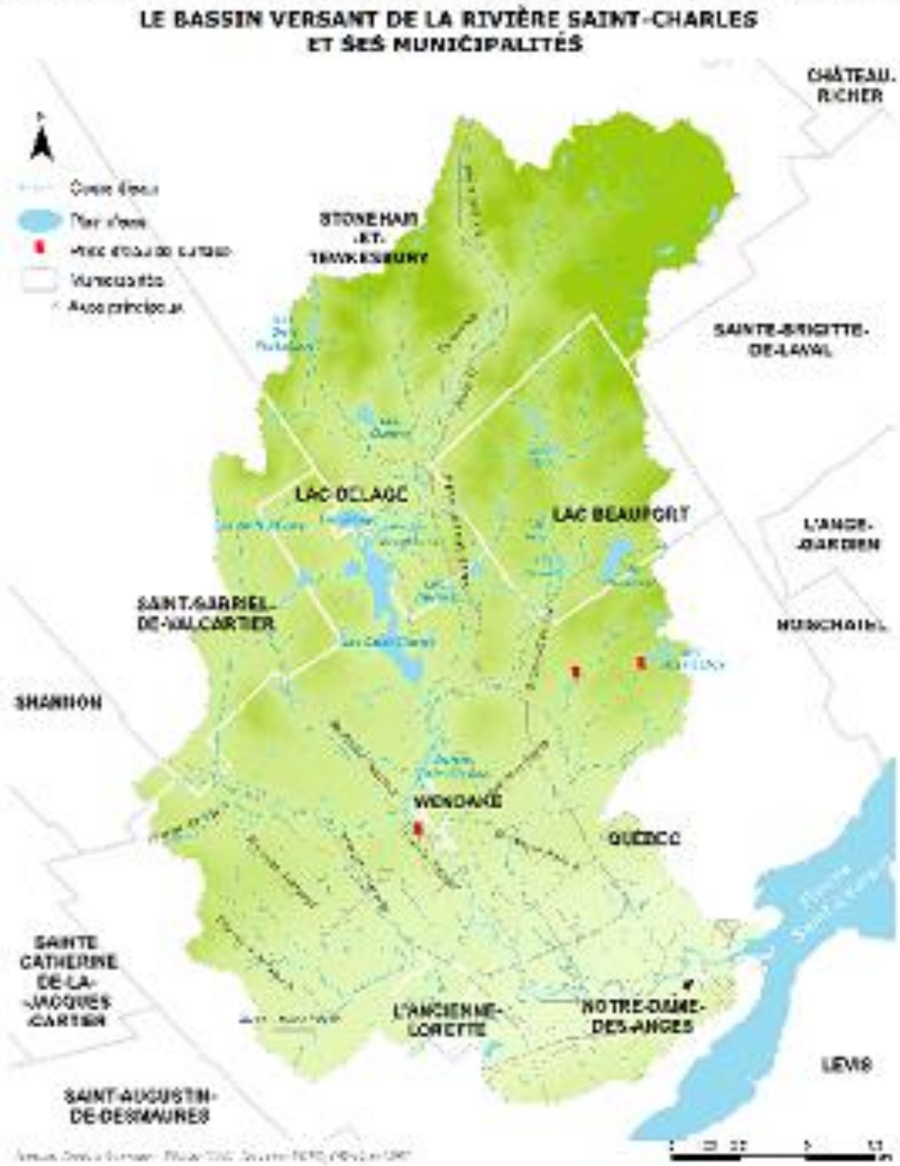
3. Renseignements généraux

2. Dans quelle municipalité vivez-vous actuellement ?

- ◯ Ville de Québec
- ◯ Ville de Lac-Delage
- ◯ Municipalité de Lac-Beauport
- ◯ Municipalité des Cantons unis de Stoneham-et-Tewkesbury
- ◯ Saint-Gabriel de Valcartier
- ◯ Sainte-Brigitte-de-Laval
- ◯ Wendake
- ◯ Ville de L'Ancienne-Lorette

Autre (veuillez préciser)

3. Vivez-vous dans le bassin versant de la rivière Saint-Charles? (Le bassin versant est le territoire en vert sur la carte)



- ◯ Oui - résidence principale
- ◯ Oui - résidence secondaire
- ◯ Non - veuillez tout de même répondre au questionnaire
- ◯ Je ne sais pas

Autre (veuillez préciser)

4. Origine de l'eau pour mon usage quotidien

- ◯ Je consomme l'eau en provenance du bassin versant de la rivière Saint-Charles (Usine de traitement de l'eau de Québec)
- ◯ Je consomme l'eau en provenance du fleuve Saint-Laurent (Usine de traitement de l'eau de Sainte-Foy)
- ◯ Je consomme l'eau en provenance de la rivière Montmorency (Usine de traitement de l'eau de Beauport)
- ◯ Je consomme l'eau en provenance de la rivière des Sept Ponts et le lac des Roches (Usine de traitement de Charlesbourg)
- ◯ Je consomme l'eau en provenance d'un puits municipal
- ◯ Je consomme l'eau en provenance de mon puits personnel
- ◯ Je consomme l'eau en provenance d'un puit commun
- ◯ Je ne sais pas

Autre (veuillez préciser toute autre source d'eau pour votre consommation)

5. Utilisation des lacs et des rivières

- ☐ Je pratique des activités nautiques sur un lac dans le bassin versant de la rivière Saint-Charles
- ☐ Je pratique des activités nautiques sur une rivière dans le bassin versant de la rivière Saint-Charles
- ☐ Je pratique des activités nautiques sur un lac ailleurs que dans le bassin versant de la rivière Saint-Charles
- ☐ Je pratique des activités nautiques sur une rivière ailleurs que dans le bassin versant de la rivière Saint-Charles
- ☐ J'aime prendre des marches sur le bord d'un lac ou d'une rivière
- ☐ J'aime pratiquer des activités en bordure de lac ou de rivière (marche, détente, observation de la faune/flore)
- ☐ Je ne pratique aucune activité nautique

Autre (veuillez préciser le(s) nom(s) du lac ou de la rivière où vous pratiquez des sports nautiques

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4. Les usages de l'eau

*** 6. Veuillez énumérer vos usages de l'eau et leur fréquence**

	Quotidiennement	Fréquemment (2-3 fois par semaine en saison)	Parfois (en saison)	Jamais	Ne s'applique pas
Arrosage et entretien extérieur en saison avec **l'eau du robinet** (pelouse, jardin, piscine, lavage voiture, etc.)	◯	◯	◯	◯	◯
Arrosage et entretien extérieur en saison avec **l'eau pluviale récupérée** (pelouse, jardin, piscine, lavage voiture, etc.)	◯	◯	◯	◯	◯
Baignade dans les lacs ou cours d'eau en saison	◯	◯	◯	◯	◯
Baignade dans une piscine	◯	◯	◯	◯	◯
Pratique activité nautique en saison (canot, kayak, navigation de plaisance, ski nautique)	◯	◯	◯	◯	◯
Pratique de la pêche en saison	◯	◯	◯	◯	◯
Consommation d'eau potable du robinet	◯	◯	◯	◯	◯
Consommation d'eau embouteillée	◯	◯	◯	◯	◯

Autre (veuillez préciser les usages de l'eau - optionnel)

6

	Pas préoccupant	Peu préoccupant	Moyennement préoccupant	Préoccupant	Très préoccupant	Je ne sais pas	Ne s'applique pas
Contamination fécale par les animaux de ferme	○	○	○	○	○	○	○
Contamination fécale par les animaux domestiques	○	○	○	○	○	○	○
Contamination fécale par les animaux sauvages	○	○	○	○	○	○	○
Engrais agricoles	○	○	○	○	○	○	○
Pesticides pour usage agricole	○	○	○	○	○	○	○
Engrais pour usage domestique	○	○	○	○	○	○	○
Pesticides pour usage domestique	○	○	○	○	○	○	○
Terrains de golf (engrais, pesticides, ruissellement)	○	○	○	○	○	○	○
Centres de ski (engrais, érosion, ruissellement)	○	○	○	○	○	○	○
Sels de voirie	○	○	○	○	○	○	○
Abats poussières (produits pour réduire la poussière sur les routes non-asphaltées)	○	○	○	○	○	○	○
Érosion due au développement domiciliaire	○	○	○	○	○	○	○
Érosion due à la déforestation et aux chemins forestiers	○	○	○	○	○	○	○
Érosion due à la construction de nouvelles voies carrossables	○	○	○	○	○	○	○
Érosion due à un manque de bandes riveraines en milieu agricole	○	○	○	○	○	○	○
Érosion due à un manque de bandes riveraines sur terrains riverains de plan d'eau	○	○	○	○	○	○	○
Érosion et ruissellement d'eau due à des surfaces dénudées (milieux ouverts)	○	○	○	○	○	○	○
Contamination due à des sites d'enfouissement (déchets)	○	○	○	○	○	○	○
Contaminantion par des résidus (médicaments)	○	○	○	○	○	○	○
Contamination par des résidus (produits des soins corporels)	○	○	○	○	○	○	○
Contamination par des résidus (produits nettoyants)	○	○	○	○	○	○	○
Contamination par des résidus (autres - veuillez préciser)	○	○	○	○	○	○	○

Commentaire pour la question (facultatif)

8

* 9. Pensez-vous que la qualité de l'eau du cours d'eau (lac ou rivière) à proximité de votre demeure a une influence sur la valeur de votre demeure?

- Non
- Oui
- Je ne sais pas
- Autre (veuillez préciser)

* 10. Comment évaluez-vous l'influence de la qualité de l'eau du cours d'eau (lac ou rivière) à votre proximité de votre demeure sur la valeur économique de celle-ci?

- Très importante
- Modérément importante
- Peu importante
- Pas du tout importante
- Je ne sais pas
- Ne s'applique pas (je ne vis pas à proximité d'un cours d'eau)

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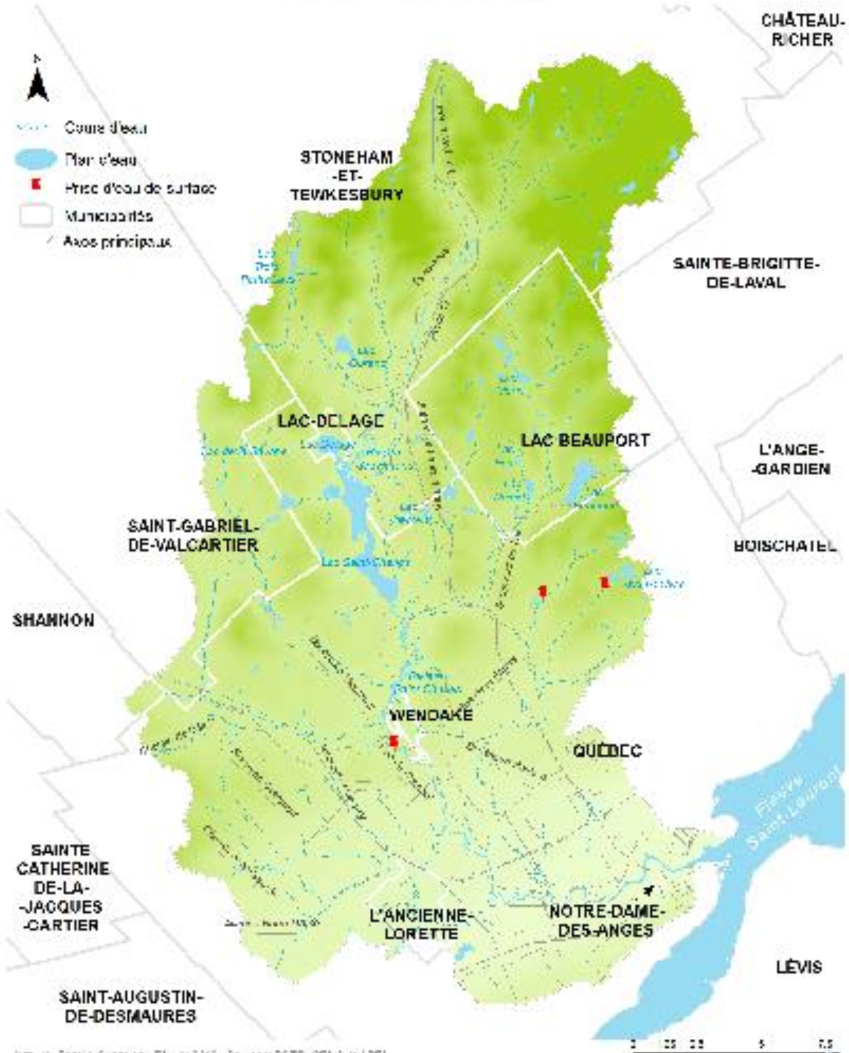
5. Renseignements généraux - type d'organisation

*** 11. Sur quelle territoire oeuvrez-vous?**

- [ ] Municipalité des Cantons unis de Stoneham-et-Tewkesbury
- [ ] Ville de Lac-Delage
- [ ] Sainte-Brigitte-de-Laval
- [ ] Saint-Gabriel de Valcartier
- [ ] Ville de Québec
- [ ] Municipalité du Lac-Beauport
- [ ] Ville de L'Ancienne-Lorette
- [ ] Wendake
- [ ] Autre (veuillez préciser)

* 12.

LE BASSIN VERSANT DE LA RIVIÈRE SAINT-CHARLES ET SES MUNICIPALITÉS



Oeuvrez-vous dans le bassin versant de la rivière Saint-Charles (Territoire en vert)?

- ◯ Oui
- ◯ Non - veuillez tout de même répondre au sondage
- ◯ Je ne sais pas - veuillez tout de même répondre au sondage
- ◯ Autre (veuillez préciser) - veuillez tout de même répondre au sondage

[ ]

11

*** 13. À quel type d'organisation appartenez-vous?**

- ◯ Industrie et commerces (incluant petites et moyennes entreprises)
- ◯ Foresterie
- ◯ Construction (promoteur, compagnie de construction)
- ◯ Consultant
- ◯ Institution financière
- ◯ Compagnie d'assurance
- ◯ Organisme sans but lucratif
- ◯ Association d'affaires
- ◯ Agriculture (incluant élevage)
- ◯ Municipalité
- ◯ Municipalité régionale de comté (MRC)
- ◯ Ministère
- ◯ Communauté métropolitaine de Québec
- ◯ Secteur académique (École, CÉGEP, Université, etc.)
- ◯ Club sportif (Quad, Skidoo, Sport nautique, etc.)
- ◯ Centre de villégiature (Golf, Ski, SPA, Camping)
- ◯ Hôtellerie (Hotel, Auberge, Restaurant)
- ◯ Communauté réligieuse
- ◯ Société d'État
- ◯ Autre

Pourriez-vous spécifier davantage le département ou la section, peu importe à quel type d'organisme vous appartenez

*** 14. Origine de l'eau utilisée par l'organisation**

- ☐ Nous consommons l'eau en provenance du bassin versant de la rivière Saint-Charles (Usine de traitement de l'eau de Québec)
- ☐ Nous consommons l'eau en provenance du fleuve Saint-Laurent (Usine de traitement de l'eau de Sainte-Foy)
- ☐ Nous consommons l'eau en provenance de la rivière Montmorency (Usine de traitement de l'eau de Beauport)
- ☐ Nous consommons l'eau en provenance de la rivière des Sept-Ponts et du lac des Roches (Usine de traitement de Charlesbourg)
- ☐ Nous consommons l'eau en provenance d'un puits municipal
- ☐ Nous consommons l'eau en provenance de notre puits personnel
- ☐ Nous consommons l'eau en provenance d'un puits commun
- ☐ Information non disponible

Autre (veuillez préciser toute autre source d'eau pour votre consommation)

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6. Les usages de l'eau

*** 15. Pour les usages de l'eau suivants, veuillez spécifier la fréquence d'usage de votre organisation (selon votre connaissance)**

	Quotidiennement	Fréquemment (2-3 fois semaine)	Parfois (2-3 fois par mois)	Jamais	Ne s'applique pas
Arrosage et entretien extérieur en saison avec **l'eau du robinet** (pelouse, jardin, piscine, lavage voiture, etc.)	◯	◯	◯	◯	◯
Arrosage et entretien extérieur en saison avec **l'eau pluviale récupérée**	◯	◯	◯	◯	◯
Utilisation pour des fins industrielles (incluant les chantiers de construction)	◯	◯	◯	◯	◯
Utilisation pour spas et ou piscines	◯	◯	◯	◯	◯
Baignade de vos clients dans les lacs ou cours d'eau	◯	◯	◯	◯	◯
Consommation d'eau potable du robinet	◯	◯	◯	◯	◯
Consommation d'eau embouteillée	◯	◯	◯	◯	◯
Pratique d'activités nautiques de vos clients (canot, kayak, navigation de plaisance, ski nautique, etc.)	◯	◯	◯	◯	◯
Pratique de la pêche de vos clients	◯	◯	◯	◯	◯

Veuillez préciser les usages de l'eau de votre organisation

*** 16. En faisant référence aux usages énumérés à la question précédente, quelles sont vos principales préoccupations par rapport à l'eau?**

	Pas préoccupant	Peu préoccupant	Modérément préoccupant	Préoccupant	Très préoccupant	Ne s'applique pas
Qualité de l'eau potable insuffisante pour l'approvisionnement	◯	◯	◯	◯	◯	◯
Quantité d'eau potable insuffisante pour l'approvisionnement	◯	◯	◯	◯	◯	◯
Approvisionnement en eau insuffisant pour d'autres usages que l'eau potable	◯	◯	◯	◯	◯	◯
Insalubrité de l'eau pour la baignade	◯	◯	◯	◯	◯	◯
Insalubrité de l'eau pour les activités nautiques	◯	◯	◯	◯	◯	◯
Présence d'algues bleu-vert (cyanobactéries)	◯	◯	◯	◯	◯	◯
Prolifération des plantes aquatiques et des algues (eutrophisation)	◯	◯	◯	◯	◯	◯
Présence de coliformes fécaux	◯	◯	◯	◯	◯	◯
Diminution des stocks de poissons	◯	◯	◯	◯	◯	◯
Inondations	◯	◯	◯	◯	◯	◯
Impact de la **qualité de l'eau de surface** sur la valeur des biens immobiliers de l'organisation	◯	◯	◯	◯	◯	◯
Impact de la **qualité de l'eau potable** sur la valeur des biens immobiliers de l'organisation	◯	◯	◯	◯	◯	◯
Impact de la **qualité de l'eau de surface** sur la valeur des biens immobiliers de vos clients (par exemple dans le cas où votre organisation est une institution financière ou une compagnie d'assurance)	◯	◯	◯	◯	◯	◯
Impact de la **qualité de l'eau potable** sur la valeur des biens immobiliers de vos clients (par exemple dans le cas où votre organisation est une institution financière ou une compagnie d'assurance)	◯	◯	◯	◯	◯	◯

Commentaires (facultatif)

*** 17. Est-ce que, selon vous, les différentes sources de contamination dans le bassin versant de la rivière Saint-Charles sont préoccupantes?**

	Je ne sais pas	Pas préoccupant	Peu préoccupant	Moyennement préoccupant	Préoccupant	Très préoccupant	Ne s'applique pas
Eaux usées en provenance d'installations septiques	○	○	○	○	○	○	○
Eaux usées en provenance de rejets d'usines municipales	○	○	○	○	○	○	○
Eaux usées en provenance de rejets d'usines industrielles	○	○	○	○	○	○	○
Déversements illicites (veuillez préciser)	○	○	○	○	○	○	○
Contamination fécale par les animaux de ferme	○	○	○	○	○	○	○
Contamination fécale par les animaux domestiques	○	○	○	○	○	○	○
Contamination fécale par les animaux sauvages	○	○	○	○	○	○	○
Engrais agricoles	○	○	○	○	○	○	○
Pesticides pour usage agricole	○	○	○	○	○	○	○
Engrais utilisé pour usage domestique	○	○	○	○	○	○	○
Pesticides pour usage domestique	○	○	○	○	○	○	○
Terrains de golf (engrais, pesticides, ruissellement)	○	○	○	○	○	○	○
Centres de ski (engrais, érosion, ruissellement)	○	○	○	○	○	○	○
Sels de voirie	○	○	○	○	○	○	○
Abats poussières (produits pour réduire la poussière sur les routes non-asphaltées)	○	○	○	○	○	○	○
Érosion due au développement domiciliaire	○	○	○	○	○	○	○
Érosion due à la déforestation et aux chemins forestiers	○	○	○	○	○	○	○
Érosion due à la construction de nouvelles voies carrossables	○	○	○	○	○	○	○
Érosion due à un manque de bandes riveraines en milieu agricole	○	○	○	○	○	○	○
Érosion due à un manque de bandes riveraines de terrains riverains	○	○	○	○	○	○	○

	Je ne sais pas	Pas préoccupant	Peu préoccupant	Moyennement préoccupant	Préoccupant	Très préoccupant	Ne s'applique pas
Érosion et ruissellement d'eau due à des surfaces dénudées (milieux ouverts)	◯	◯	◯	◯	◯	◯	◯
Contamination due à des sites d'enfouissement	◯	◯	◯	◯	◯	◯	◯
Contamination par des résidus (médicaments)	◯	◯	◯	◯	◯	◯	◯
Contamination par des résidus (produits des soins corporels)	◯	◯	◯	◯	◯	◯	◯
Contamination par des résidus (produits nettoyants)	◯	◯	◯	◯	◯	◯	◯

Commentaire pour la question (facultatif)

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7. Votre impact sur la qualité de l'eau

*** 18. Veuillez répondre aux énoncés suivants**

	Oui	Quelques-unes	En planification	Plusieurs	Non	Ne s'applique pas	Je ne sais pas
Notre organisation a mis en place des mesures de réduction de la consommation d'eau potable	◯	◯	◯	◯	◯	◯	◯
Notre organisation a mis en place des mesures de réduction des déchets envoyés dans les égouts (résidus de la production, utilisation de produits biodégradables, etc.)	◯	◯	◯	◯	◯	◯	◯
Notre organisation a mis en place des mesures de récupération de l'eau de pluie (par exemple pour les toilettes, l'arrosage de l'aménagement externe, etc.)	◯	◯	◯	◯	◯	◯	◯
Notre organisation a mis en place des mesures de réduction de l'utilisation des engrais	◯	◯	◯	◯	◯	◯	◯
Notre organisation a mis en place des mesures de réduction des pesticides	◯	◯	◯	◯	◯	◯	◯
Notre organisation a mis en place des mesures de réduction de déversements dans l'égout pluvial (ex.: vidange des piscines, spas, etc.)	◯	◯	◯	◯	◯	◯	◯
Notre organisation a mis en place des mesures pour appliquer les réglements en place concernant les rejets de ses activités	◯	◯	◯	◯	◯	◯	◯
Notre organisation a mis en place des mesures de contôle d'érosion lors de travaux extérieurs	◯	◯	◯	◯	◯	◯	◯

Autre (veuillez préciser)

*** 19. Veuillez répondre aux énoncés suivants**

	Oui	Non	En partie	Je ne sais pas
Les eaux usées de notre organisation sont traitées par une usine de traitement des eaux usées	◯	◯	◯	◯
Les eaux usées de notre organisation sont traitées par une installation septique	◯	◯	◯	◯

Autre (veuillez préciser)

*** 20. Comment évaluez vous votre impact sur la qualité de l'eau du cours d'eau (lac ou rivière) se trouvant à proximité de l'emplacement de votre organisation?**

- ◯ Très important
- ◯ Modérément important
- ◯ Peu important
- ◯ Pas du tout important
- ◯ Je ne sais pas
- ◯ Ne s'applique pas

*** 21. Veuillez préciser de quelle façon votre organisation dépend d'une eau en qualité et en quantité suffisante pour assurer son bon fonctionnement**

*** 22. Veuillez préciser de quelle façon votre organisation intervient afin de protéger la ressource eau**

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8. Votre impact sur la qualité de l'eau

*** 23. Veuillez répondre aux énoncés suivants**

	Jamais	Parfois	Fréquemment	Toujours	Je ne sais pas	Ne s'applique pas
J'utilise des produits biodégradables pour l'entretien ménager	◯	◯	◯	◯	◯	◯
J'utilise la toilette ou le lavabo pour rejeter des résidus (par exemple huiles et graisses, produits d'hygiène, mégots, etc.).	◯	◯	◯	◯	◯	◯
Je récupère l'eau de pluie	◯	◯	◯	◯	◯	◯
J'utilise des engrais	◯	◯	◯	◯	◯	◯
J'utilise des pesticides	◯	◯	◯	◯	◯	◯
J'utilise l'égout pluvial pour déverser des résidus (eau de piscine, huiles, etc.)	◯	◯	◯	◯	◯	◯
Je lave mon auto à la maison	◯	◯	◯	◯	◯	◯
Je lave mon entrée à l'eau	◯	◯	◯	◯	◯	◯
Lorsque je fais des travaux sur mon terrain je m'assure de réduire l'érosion	◯	◯	◯	◯	◯	◯
Je ramasse les excréments des mes chiens	◯	◯	◯	◯	◯	◯

Veuillez préciser d'autres gestes que vous posez pour protéger l'eau

*** 24. Veuillez répondre aux énoncés suivants**

	Oui	Non	Ne s'applique pas
Je fais pousser le plus possible des arbres et des arbustes sur mon terrain	◯	◯	◯
L'eau de mes gouttières se déverse sur une surface absorbante (ex.: jardin de pluie) plutôt que sur une surface imperméable (ex.: entrée d'asphalte, rue, troittoir)	◯	◯	◯

*** 25. Veuillez répondre aux énoncés suivants**

	Oui	Non	Je ne sais pas
Les eaux usées de ma demeure sont traitées par une usine de traitement des eaux usées	◯	◯	◯
Les eaux usées de ma demeure sont traitées par une installation septique	◯	◯	◯

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9. Suivi de la qualité de l'eau

*** 26. Quelle information aimeriez-vous avoir sur la qualité de l'eau des lacs et des rivières dans le bassin versant de la rivière Saint-Charles?**

	Pas important	Peu important	Moyennement important	Important	Très important	s. o.
Connaître l'état des rivières pour la baignade	○	○	○	○	○	○
Connaître l'état des lacs pour la baignade	○	○	○	○	○	○
Connaître l'état des rivières pour les sports nautiques et autres activités récréatives	○	○	○	○	○	○
Connaître l'état des lacs pour les sports nautiques et autres activités récréatives	○	○	○	○	○	○
Connaître l'état des lacs et des rivières afin d'évaluer si la qualité de l'eau destinée à la consommation est adéquate (production d'eau potable)	○	○	○	○	○	○
Connaître l'état des lacs et des rivières afin d'évaluer si la qualité de l'eau destinée à la villégiature est adéquate (spas et piscines)	○	○	○	○	○	○
Connaître l'état des lacs et des rivières afin d'évaluer si la qualité de l'eau destinée aux usages industriels est adéquate	○	○	○	○	○	○
Connaître l'état des lacs et des rivières afin d'évaluer si **la quantité** de l'eau destinée à la consommation est adéquate (production d'eau potable)	○	○	○	○	○	○

	Pas important	Peu important	Moyennement important	Important	Très important	s. o.
Connaître l'état des lacs et des rivières afin d'évaluer si la **quantité** de l'eau destinée à la villégiature est adéquate (spas et piscines)	◯	◯	◯	◯	◯	◯
Connaître l'état des lacs et des rivières afin d'évaluer si la **quantité** de l'eau destinée aux usages industriels est adéquate	◯	◯	◯	◯	◯	◯

Autre (veuillez préciser)

*** 27. De quelle façon aimeriez-vous être informé sur la qualité de l'eau des lacs et rivières du bassin versant de la rivière Saint-Charles?**

- ☐ Carte interactive (en ligne)
- ☐ Rapports
- ☐ Communiqué de presse
- ☐ Article de journal
- ☐ Bulletin spécial
- ☐ Nouvelles télévisées
- ☐ Article scientifique
- ☐ Médias sociaux
- ☐ Site Web de ma municipalité
- ☐ Panneau / affichage aux points d'accès publics
- ☐ Je ne désire pas en être informé
- ☐ Autre (veuillez préciser)

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*** 28. Connaissez-vous le rôle de ces organisations dans la gestion de l'eau?**

	Oui	Un peu	Non
Organisme des bassins versants de la Capitale	◯	◯	◯
Association pour le protéction de l'environnement du lac Saint-Charles et des Marais du Nord (APEL)	◯	◯	◯
Votre municipalité	◯	◯	◯
Municipalité régionale de comté (MRC)	◯	◯	◯
Communauté métropolitaine de Québec (CMQ)	◯	◯	◯
Ministère de l'environnement (MDDELCC)	◯	◯	◯
Université Laval	◯	◯	◯
Institut national de la recherche scientifique (INRS)	◯	◯	◯

Autre - veuillez préciser

[ ]

* 29. Selon vous, à quel point ces organisations sont impliquées dans la production de l'information sur la qualité de l'eau du bassin versant de la rivière Saint-Charles?

	Pas du tout	Un peu	Moyennement	Beaucoup	Acteur principal	Je ne sais pas
Organisme des bassins versants de la Capitale	◯	◯	◯	◯	◯	◯
Association pour la protection de l'environnement du lac Saint-Charles et des Marais du Nord (APEL)	◯	◯	◯	◯	◯	◯
Votre municipalité	◯	◯	◯	◯	◯	◯
Municipalité régionale de comté (MRC)	◯	◯	◯	◯	◯	◯
Communauté métropolitaine de Québec (CMQ)	◯	◯	◯	◯	◯	◯
Ministère de l'environnement du Québec (MDDELCC)	◯	◯	◯	◯	◯	◯
Université Laval	◯	◯	◯	◯	◯	◯
Institut national de la recherche scientifique (INRS)	◯	◯	◯	◯	◯	◯

Autres organisations impliquées dans la production de l'information sur la qualité de l'eau du bassin versant de la rivière Saint-Charles (veuillez préciser)

* 30. Selon vous, qui devrait coordonner le suivi de la qualité de l'eau dans le bassin versant de la rivière Saint-Charles?

- ☐ Organisme des bassins versants de la Capitale
- ☐ Association pour le protection de l'environnement du lac Saint-Charles et des Marais du Nord (APEL)
- ☐ Votre municipalité
- ☐ Municipalité régionale de comté (MRC)
- ☐ Communauté métropolitaine de Québec (CMQ)
- ☐ Ministère de l'environnement du Québec (MDDELCC)
- ☐ Université Laval
- ☐ Institut national de la recherche scientifique (INRS)

Autre (veuillez préciser)

*** 31. Selon vous, qui devrait contribuer financièrement au suivi de la qualité de l'eau?**

- [ ] Votre municipalité
- [ ] Municipalité régionale de comté (MRC)
- [ ] Ministère de l'environnement du Québec (MDDELCC)
- [ ] Communauté métropolitaine de Québec (CMQ)
- [ ] Association pour la protection de l'environnement du lac Saint-Charles et des Marais du Nord (APEL)
- [ ] Organisme des bassins versants de la Capitale
- [ ] Université Laval
- [ ] Institut national pour la recherche scientifique (INRS)
- [ ] Je ne sais pas
- [ ] Autre (veuillez préciser)

*** 32.**

Veuillez répondre aux énoncés suivants

	Pas du tout d'accord	Peu d'accord	Modérément d'accord	Tout à fait d'accord	Je ne sais pas
Ma municpalité rend facilement accessible des informations sur la qualité de l'eau	○	○	○	○	○
Je suis au courant de l'état des lacs et des rivières dans mon secteur	○	○	○	○	○
Je suis au courant de la qualité de l'eau potable que j'utilise à la maison	○	○	○	○	○

Veuillez préciser l'origine de votre information (Par exemple: Réseau de suivi volontaire des lacs, site Web de votre municipalité, etc.)

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10. Suivi de la qualité de l'eau en place

*** 33. Êtes-vous au courant des initiatives de suivi de la qualité de l'eau?** (Par exemple: Réseau de surveillance volontaire des lacs, Programme de suivi de la qualité de l'eau du bassin versant de la rivière Saint-Charles, Association pour la protection de l'Environnement du lac Saint-Charles et des Marais du Nord, etc.)

- ◯ Oui
- ◯ Non
- ◯ Si vous avez indiquez oui, veuillez préciser

*** 34. Je suis ou j'ai déjà été impliqué dans un suivi de la qualité de l'eau**

- ◯ Oui
- ◯ Non

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11. Suivi de la qualité de l'eau en place

Si vous étés impliqué dans un suivi de la qualité de l'eau, veuillez indiquer vos coordonnées afin que nous puissions vous contacter pour des entrevues semi-dirigées (facultatif)

35. Adresse

Nom	
Société	
Adresse	
Ville	
État/Province	
Code postal	
Pays	
Adresse e-mail	
Téléphone	

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12. Quelle est la qualité de l'eau que vous aimeriez avoir?

*** 36. À votre connaissance, des mesures ont-elles été prises pour protéger la qualité de l'eau du lac Saint-Charles dans le bassin versant de la rivière Saint-Charles?**

- ◯ Oui
- ◯ Non
- ◯ Je ne sais pas

Si vous avez répondu oui, veuillez préciser la nature des actions qui ont été prises et comment vous avez pris connaissance de ces mesures

*** 37. Veuillez classer en ordre de priorité (de 1 à 9) les cibles suivantes pour la qualité de l'eau**

- Les lacs et rivières du bassin versant devraient être propres à la baignade
- Les lacs et rivières du bassin versant devraient avoir une qualité permettant les sports de contact secondaire (canot, kayak)
- La qualité de l'eau des lacs et des rivières du bassin versant devraient assurer un milieu de vie pour les poissons
- Les plantes aquatiques ne devraient pas proliférer davantage dans les lacs
- Les algues bleu-vert (cyanobactéries) ne devraient pas nuire à la baignade
- Les algues bleu-vert (cyanobactéries ne devraient pas nuire à la production d'eau potable
- La qualité de l'eau des lacs et des rivières ne devrait pas se déteriorer de son état actuel
- Les concentrations des sels de voirie ne devraient pas augmenter dans les lacs et rivières
- Le nombre d'inondations ne devrait pas augmenter

38. Nous avons besoin de vos connaissances du bassin versant de la rivière Saint-Charles! Indiquez, sur cette carte, le (s) endroit (s) où vous aimeriez avoir un suivi de la qualité de l'eau et pourquoi - (veuillez suivre le lien (facultatif et confidentiel). Vous pouvez entrer plus d'un point et ajouter des photos. Veuillez noter que vous ne pouvez pas revenir à ce sondage après avoir cliqué sur le lien vers la carte interactive.

◯ https://apel.yourenki.com/surveys/1/submissions/new?token=oYNBYg

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Appendix C

Specifications on the application of Beveridge et al.'s method

The method includes a non-metric multi-dimensional scaling (NMDS), principal component analysis (PCA), Kriging, Moran's Index and leave – one – out cross validation to visualize the increase in the variance of the residues of the model when a station is removed.

First, the two multivariate analyses were applied: NMDS to add to the coordinate of each sampling station the distance to the outflow of the watershed and PCA to associate to each station one or two factorials created from the concentrations of respectively PT, CF and TSS for the complete data series (2009 – 2016). The amount of data (n) and the relation between the variables confirm the prerequisite of PCA, that of multi-normality and the linearity of the relations. Outliers are a source for distortion of these tests and were removed (any point of data that lies over 1.5 IQR (inter quartile range) below the first quartile (Q_1) or above the third quartile (Q_3) in a data set). We chose to reconstruct the missing values for PT, CF and TSS with the package MissMDA with R – for further information consult (Josse et al., 2012; Josse and Husson, 2016).

Second, we proposed several Kriging models (Krige, 1953) with the objective to identify the sampling stations which are contributing the most to predict the spatial model of the watershed and the distribution of these stations. The quality of the models was judged on the comparisons of the standard error of the residues, the values of the adjusted R^2, the significance of the model and the criteria of Akaike (Akaike information criterion – an estimator of relative quality of statistical models). The following model was retained:

Model M6 : $Log[FC] \sim Log[TSS] * Log[TP] * Dist$

Were FC = Average Fecal coliform concentration; TSS = Average Total suspended solids concentrations, TP = Average Total phosporus concentrations and Dist = distance in linear kilometers between each sampling station and the outflow of the watershed (W2).

For each model, we used the spatial distribution of the residues of the leave – one – out cross validation to visualize the increase in the variance of the residues of the model when they are removed. The stations are considered as important when their removal harms the model. Stations for which the removal does not harm the model (or cause little or no variance) are considered as those for which the information is redundant and which are suggested for removal (Beveridge et al., 2012). Finally, we also calculated for each pair of stations the Moran Index and the associated Z score. The Minimum Spanning Tree was retained; it proposes a structure were the sum of the distances between stations is minimal. Some relations were modified in order to obtain a representative relationship of the stations and the hydrographic network. The Z scores based on the Moran Index calculated on this structure provides an indicator of the redundancy of information between two or more neighbouring stations. For each station, a score $Z \leq -1{,}96$ translates to a strong dissimilarity between a station and its neighbouring stations. A score of $Z \geq 1{,}96$ indicates a strong redundancy of the values of one station and its neighbouring stations (Beveridge et al., 2012).

Appendix D

This appendix contains additional tables and figures from chapter 4.

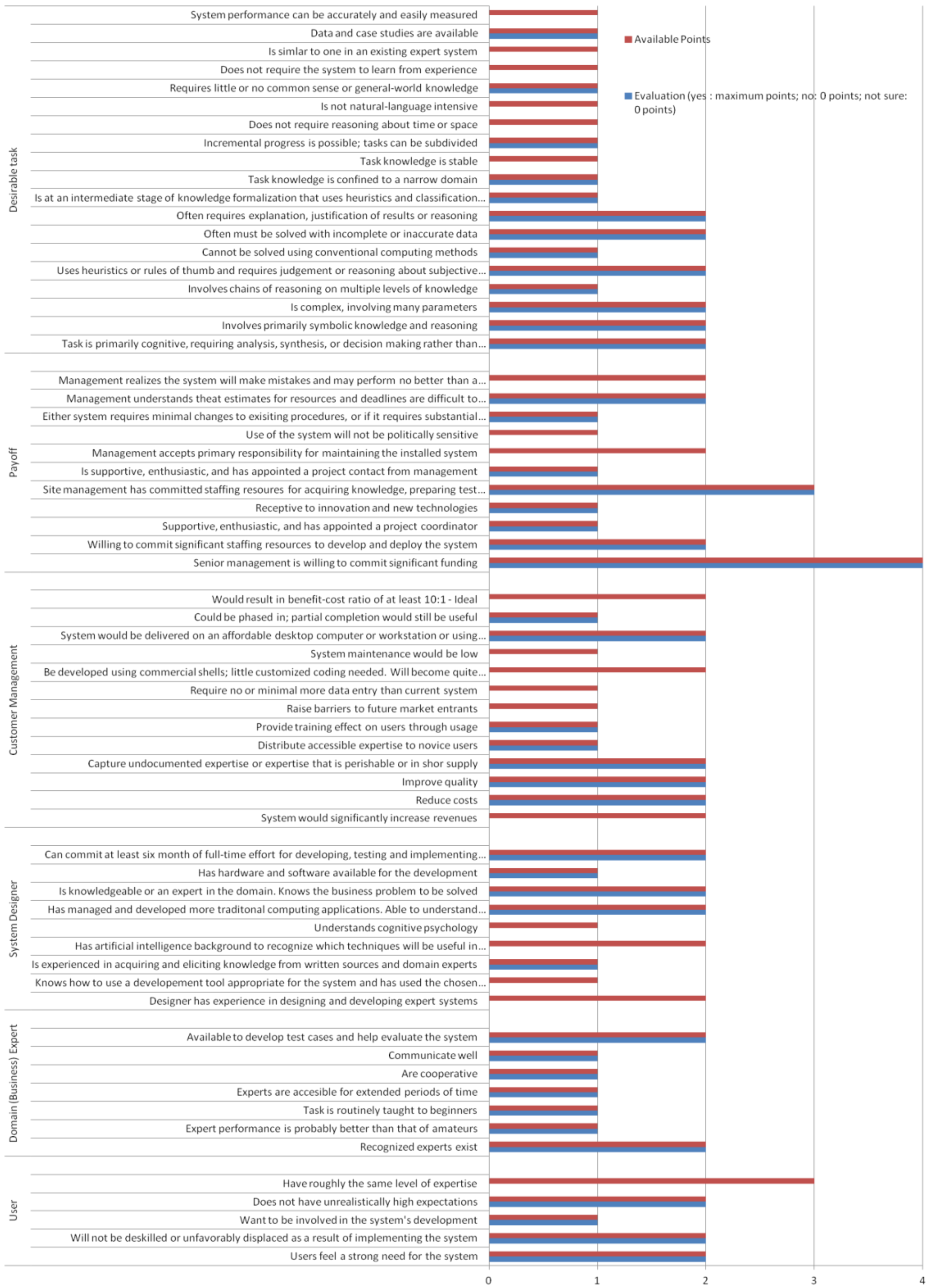

Figure 1: Results of the evaluation of the appropriateness of the subject domain and project context for the IDSS. On the outer left (vertical text) the categories are listed and the statements per category are detailed for each bar on the y axis. The x axis illustrates in red the number of points that could be achieved for each statement. The achieved points are

illustrated in blue on the x axis. The percentages of points obtained for each category in the text are based on these results (total possible score vs. achieved score) (evaluation framework drawn from Rhem 2006).

Figure 2: Subject matter expert Dr. François Proulx (Québec City) on the use case: Select and classify water quality parameters (October 2016).

Figure 3: End-user workshops – Left: APEL – Right Abrinord.