Use of Mixed Methods in Hydrological Science: what are their Contributions?

Raymond KABO[1], Marc André Bourgault[1], and Jean François Bissonnette[1]

[1]Université Laval

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Abstract

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Use of Mixed Methods in Hydrological Science: what are their Contributions?

Raymond Kabo[1,2], Marc-André Bourgault[1,2,3] and Jean François Bissonnette[1]

1 Department of Geography, Laval University, Québec, Canada, 2 Quebec Water Research Center, Laval University, Québec, Canada, 3 Quebec Intersectoral Flood Network.

Raymond Kabo (raymond.kabo.1@ulaval.ca)

Key Points:

Mixed methods are a pragmatic methodological approach to understand hydrological phenomena.

Mixed methods provide knowledge and reduce our ontological uncertainties.

The use of mixed methods will be a must in understanding the interactions between humans and hydrological hazards.

Abstract

Research in hydrological sciences is constantly evolving to provide adequate answers to water-related issues. Methodological approaches inspired by mathematical sciences and physical sciences have shaped hydrological sciences from its beginnings to the present day. But nowadays with the increasing complexity of hydrological phenomena, hydrological sciences have integrated approaches from the social sciences which provide missing information for the study of complex hydrological objects which is the observation and perception of water resources by users. A methodological approach: the mixed methods with their different research designs make it possible to combine the quantitative approaches of the physical and mathematical sciences and the qualitative approaches of the social sciences to understand the object of study and propose adequate solutions for its management. We detail here, the use of mixed methods in research in flood hydrology, in research on low flow conditions and on the management of these hydrological extremes. Mixed methods contributions to these studies are diverse and pragmatically relevant for hydrology. They range from the densification of data on extreme flood events to reduce forecasting uncertainties, to the production of knowledge on low-flow hydrological states that are insufficiently documented and finally to support participatory management decision-making about extreme hydrological events and water management.

1 Introduction

Research in hydrological science aims to understand, explain, and provide solutions to the lack of water in quantity and quality, as well as flooding and water management problems. The fundamental issue of research in contemporary hydrology is the ability to fully grasp the complexity of the hydrological phenomenon or state under study in its entirety, to monitor it or propose appropriate recommendations to solve problems. It is the growth and diversification of contemporary water-related social problems that make the hydrological phenomena studied more complex. Socio-economic problems contribute to the complexity of the phenomena (Gober & Wheater, 2015), but at the same time open an avenue for research and the refinement of hydrological science. To evolve, hydrological science must no longer simply satisfy scientific curiosity, but must add to this fundamental character, a dimension applied to the resolution of social problems and better identify the relation between human and water body (Xu et al., 2018). One can conceive of hydrology as the organization, in several coherent sets, of knowledge resulting from the activity of research, an activity oriented to identify, define and elucidate a question of scientific interest and to solve a social problem (Sasseville & De Marsilly, 1998). The hydrological researcher must then rely on the concepts and methods from several disciplines to fully understand the multidimensional hydrological phenomenon or state he is studying. Mathematical, probabilistic statistic and laboratory methods are used to understand the physical and chemical aspects of the hydrological problem (flooding, low water, water quality and erosion) and qualitative methods from anthropology, sociology, law, economics, and history are used to understand the interactions between the problem and the society. The use of mixed methods (a methodology combining qualitative and quantitative approaches) can facilitate the structuring of these concepts and methods from several disciplines into a single coherent whole to understand the state or phenomenon under study (Aldebert & Rouzies, 2014). The possibility offered by mixed methods of being able to structure in a coherent whole a plurality of methods, of styles of reasoning prompt us to ask ourselves: what can be the contribution of the mixed methods approach in contemporary research in hydrology?

The main purpose of this paper is to identify and present the different contributions of the use of mixed methods in hydrology studies. The presentation of mixed methods is then necessary in a first step, to better understand the use of this type of approach in research. Secondly, it will be shown how mixed methods are used and what benefits the authors seek by adopting this type of approach in their studies to understand complex hydrological phenomena. Finally, the need to include mixed methods in new research in hydrology and water management will be discussed:

2 A New Epistemology of Sciences Favoring a Plurality of Methods

The objects of environmental studies are undoubtedly complex, dynamic, and variously contextual (Deléage & Coutellec 2015). They bring into their understanding a diversity of expertise and disciplines which can only be approached through interdisciplinarity. This interdisciplinarity assumed by the life and natural sciences allows them to recognize the fact that a plurality of styles of scientific reasoning or methods is necessary to characterize their aims and phenomena. However, the choice of styles of reasoning or methods must be based on criteria of relevance as to the way of understanding the object in depth and on criteria of fertility, i.e. the ability to create new questions, new subjects for reflection (Coutellec, 2015). The interdisciplinary approach allows the researcher to go beyond the epistemological limits of his discipline and to arrive at co-constructing an answer to a question which is not treated or treatable only with the tools and knowledge of his discipline of affiliation (Mathieu & Schmid, 2014). This framework promotes the creation of a creative space, a place that Mathieu and Schmid (2014) calls a place of "inter-discipline" or a field and a concept, or local and universal, or natural sciences and human sciences, coexist and form similarities. The greatest capitalization in this exercise of co-constructing the response is of a methodological nature, because to structure the response and create this creative space, it is necessary to rely on a pragmatic approach: mixed methods.

2.1 Mixed Methods, a Pragmatic Approach

The natural sciences have been largely invested in mathematical methods which introduce abstract entities like complex numbers, statistics with notions of populations and probabilities and physical methods which create unobservable variables like the atom, etc. (Coutellec, 2015). The positivist philosophy of Auguste Comte propelled the use of these approaches in the natural sciences. Indeed, positivism considers valid only those areas of knowledge to which the positive, that is, scientific method applies (Pickering, 2011). Positivism insists on the need to make observations, direct or indirect, of concrete facts, to use these facts to create scientific laws that explain how the phenomena operates, and not why ... To be truly scientific, these laws must be predictive; they must allow the passage from the present to the future and from the known to the unknown (Pickering, 2011). This philosophical current explains the preponderance of the use of statistics and probability in the natural sciences. These quantitative methods have helped to build the foundations of sciences such as hydrology, biology, ecology, biochemistry, physic, etc. However, with the evolution of problems, the natural sciences cannot be limited only to quantitative methods to understand contemporary complex objects, especially when it comes to managing social problems related to human uses (Timma et al., 2015). Increasingly, the post-positivist paradigm, a critical attitude towards the conception of an objective and universal reality, that draws attention to value-laden background, is being considered in hydrological research (Seidl & Barthel, 2017; Sharp et al., 2011). In fact, as asserted by a growing body of literature reviewers, most environmental questions, especially water related ones, are characterized by high levels of uncertainties regarding how to frame issues and which actions to prioritized (Allain et al., 2020; Ravetz, 2005). These uncertainties are related to the complex nature of water management and necessary trade-offs required between a plurality of values and goals (i.e. irrigation, fishing, recreation, biodiversity) (Lévesque et al., 2020). In this context, the adoption of qualitative methods from the human and social sciences in the analysis process provides new information allowing a better grasp and understanding of the aim of study or the phenomenon. As with mathematics and statistics, which have played an important role in the development of the natural sciences, we are witnessing the situation where the human and social sciences are now participating in the co-construction of knowledge in the life sciences and of nature. The methodology proposed by Elinor Ostrom (2011) and his team for the management of socioecological systems (SES) is a strong example of the need to use in addition to quantitative approaches, qualitative approaches in natural science (Jansen et al., 2011). This pragmatic approach is facilitated by mixed methods which aim to provide a set of conceptual tools and approaches to fully understand the problem and then solve it (Creswell, 2009).

Mixed methods are defined as: a type of research in which a researcher or a team of researchers combines elements of qualitative and quantitative methods (for example, the use of qualitative and quantitative perspectives, data collection, analysis, inference techniques) to meet the breadth and depth of the study's understanding and substantiation needs (Johnson et al., 2007). The basic concept of mixed methods studies is that the combination of quantitative and qualitative approaches can lead to a better understanding of research problems and complex objects rather than these two approaches taken alone (Creswell & Plano Clark, 2007). Mixed methods constitute a relevant methodological option allowing to develop a more detailed and richer understanding of the studied objects. The combination of the two methods can raise unexplored research questions (Hammond, 2005), make it possible to draw more solid inferences when the two types of data lead to similar results, and give rise to contradictions or paradoxes not otherwise observable (Teddlie & Tashakkori, 2009). The use of mixed methods would stimulate the creative development of data collection. It would help to obtain richer data and finally would offer possibilities to better estimate the errors and risks of measurements. According to Wilkins and Woodgate (2008); Larue et al. (2009), mixed methods allow a broader and more rigorous understanding:

1) fostering creativity and innovation to understand objects;

2) presenting a more complete vision of an object by integrating different perspectives;

3) interpreting the results with data from different sources.

Depending on their research question, the researcher can choose the mixed method design that best matches. As the motivations for research can be diverse (exploration, confirmation), the researcher can combine several designs of mixed methods.

2.2 Mixed Methods: their Different Designs

Mixed method designs give the flow of mixed research. Creswell et al. (2003) propose four classifications of mixed methods designs. We can mention triangulation, which makes it possible to obtain different data on the same subject to better understand the problem. One of the goals of triangulation is to find convergence or corroboration of results on the same phenomenon to strengthen the validity of the study. It can also mean intentionally confronting contradictory quantitative and qualitative results to bring out paradoxes that lead to new interpretations of the same phenomenon and to the potential creation of new knowledge.

Complementarity is a design that allows the researcher to consider different levels of analysis of the same phenomenon (Larue et al., 2009). This design aims to verify whether the data from a complementary method used (e.g. qualitative data) brings additional information to the results of the primary method (e.g. quantitative data) and vice versa. Complementarity or integration makes it possible to answer different questions requiring different kinds of data; thus, to have a richer understanding of the phenomenon. In explanatory designs, one type of research is followed by other types of research to further explain what was found in the first part. Qualitative data deepen and explain in more detail the first quantitative results and vice versa. An exploratory design is also a design that involves using qualitative methods to uncover themes about an issue, then use those themes to develop and administer an instrument that will generate data that will be analyzed quantitatively. This method is used when measurements or instruments are not available, or the variables are unknown. This method is mainly used in hydrology for historical flood and low flow studies.

Beyond the classification presented above. Mixed methods can also be classified into two dimensions: temporality and weighting. A distinction is made for temporality, sequential processes, and simultaneous processes. In a sequential process, the researcher explains or develops the results from one method using another method: for example, qualitative study (exploration) followed by a quantitative study (a generalization of results) (example of exploratory design). Or a quantitative study (test of theories) followed by a qualitative study (detailed analysis of a few cases using a specific methods) (example of explanatory design). In a sequential process, the different types of data are collected and analyzed one after the other.

For a simultaneous process, the researcher brings together quantitative and qualitative data to provide a complete analysis of the research question (example of the triangulation design). In this design, both forms of data are collected at the same time and are then integrated into the interpretation of the overall results (the example of the complementarity design, bowever, this design can also be sequential). The weighing corresponds to the relative weight and status of each method. The equivalent status corresponds to the situation where the two methods have the same importance. The dominant status indicates that one of the two methods was preferred in the collection phase or in the analysis phase (Aldebert & Rouzies, 2014).

Morse (1991) highlights a system for rating mixed-method designs. The use of quantitative methods is rated QUAN and that of qualitative methods is rated QUAL. These abbreviations are written in capitals to indicate the dominance of one method over the other. When the methods are used simultaneously, they are separated by a + sign (for example, QUAN + qual corresponds to a design where the methods are used simultaneously, the quantitative method is the dominant method). When the design is sequential, the arrow symbol (=>) indicates the direction of temporality (eg qual => QUAN indicates that a qualitative method preceded a dominant quantitative method). Table 1 below summarizes the main types of designs for mixed methods or motivation, temporality and weighting according to Morse's notation (1991).

Table 1

The Main Types of Mixed Methods according to Aldebert and Rouzies (2014)

Motivation	Temporality	Weighting
Triangulation	Simultaneous	Generally equivalent
Complementarity	Simultaneous or sequential	Not equivalent
Explanatory	Sequential: quantitative phase then qualitative phase	Usually quantitative dominance

3 Mixed Methods in Hydrological Studies

Hydrological science continues to evolve over time. It has long been brought into the use of quantitative processes and approaches to analyze phenomena and objects of study. This is explained by the influence that physics and mathematics may have had on this discipline, and which dominated its practices in the 1930s. We focused more on the explanation of phenomena observable by quantitative and objective measurements (Pickering, 2011). It was mathematics that helped provide hydrology with a solid foundation. Mathematical approaches such as those offering mathematical models with many scenarios have greatly accelerated research on water-related problems. Significant investments in the development of these two disciplines in hydrology have made it possible to make measurement systems more efficient for the characterization of natural waters (Sasseville & De Marsilly, 1998; Baker, 2008). These investments also aimed to take advantage of advances in computer science to promote the development and diversified use of prediction models. This had the function of expanding explanatory and instrumental knowledge (Asabina, 2004).

Recently, it is more the growth and diversification of socioeconomic problems linked to droughts or floods that are driving the exploration of new areas of knowledge about water, with a view to finding lasting solutions to these problems (Xu et al., 2018). This implies using quantitative and qualitative methods in hydrological research. Combinations of the two approaches in hydrology are increasingly common. They are often made without in-depth knowledge of mixed methods (Aldebert & Rouzies, 2014). In this part, we will analyze the case studies where mixed methods have been used in hydrological research. To show their usefulness in the search for solutions and in the understanding of complex hydrological objects. But also, to show which designs are the most used in this research.

3.1 The Positivist Paradigm in Hydrology: Towards an Opening to the Use of Mixed Methods

In a positivist approach to hydrology, it is well to remember from the outset that the research designs used (exploratory, triangulation and complementary) are presented with a clear dominance for quantitative statistical methods. Generally, it is the exploratory design that is most used to enable researchers to transform data measured with qualitative methods into quantitative data, analyzed quantitatively.

3.1.1 Historical Floods Studies

Historical flood studies are examples of the openness of positivist hydrology to the use of mixed methods. A literature review has identified hydrological studies that use mixed methods without naming them. The analysis of these studies shows the usefulness of mixed methods. The research of Brázdil et al. (2006), (2010); Benito et al. (2015) in Europe, gives a comprehensive description of combinations, mergers of methods (mixed methods) used to integrate qualitative data in flood research. This approach aims to fill the data gap on rare or extreme flood events.

Barriendos and Rodrigo (2006); Brázdil et al. (2010); Benito et al. (2015) etc. have interpreted this contribution of qualitative data and mixed methods in their study. According to the authors, extreme flood forecasting is marked by a problem related to the availability of long-term data, especially for past historical events. Systematic instrumental data are available but are not long enough to provide forecasts that are considered robust and relevant, particularly when it comes to calculating return periods for extreme events (Brázdil et al., 2006). To increase the density and richness of the chronicles of data, the solution is found in the use of mixed methods that make it possible to translate qualitative data of great importance into quantitative data used subsequently for hydrological modeling (Garnier, 2018).

Brádzil et al. (2006), (2010), (2012) have done so by consulting narrative written sources, church registers, personal correspondence, special newspaper editions and official economic records to reconstruct a series of significant flood events since 1500 in Europe. These sources present a qualitative description of events with varying degrees of detail and a high emotional burden on property damage and loss of human life. The quality and accuracy of the qualitative information recorded depends on the author's level of education (e.g. among other things, basic training, talent for observation, motivation to keep records), as well as his relationship to the event described, especially if the writer was an eyewitness (Brádzil et al., 2006). The selection of sources is necessary to ensure data reliability. Case studies have shown that documentary sources from administrative and ecclesiastical sources provide better quality information and high reliability (Barriendos et al., 2003; Garnier, 2018). The information available in these data collections concerns the dates of the events, the durations, the times of the floods, the extent of the floods and the impacts of these hydrological extremes.

It is the complementarity design that allows the integration of qualitative hydrological data from discourse analysis and documentary sources with evidence from graphic sources such as photographs of the event, illustrative tables of the severity of the event, maps of the affected area and quantitative data from articles and scientific communications on the analysis of the event. Complementarity makes it possible to move from documentary sources and epigraphic sources to the reconstitution of the height of the historic flood. This is done by analyzing the concordance and coherence of the accounts concerning the epigraphic marks engraved in stone, houses, bridges and doors, which allows us to simulate the height of water in the flood hydrographs and to simulate the flow. Roggenkamp and Herget (2014) used this design to reconstruct the flood hydrograph of the 1910 flood of the Ahrat Ahrweiler river in Germany. However, such qualitative data (narratives), as important and relevant as they are, need to go through a validation step before being used as they may suffer from a distortion of reality, biased by a false perception of the source author.

It is for this reason that the triangulation design is used to corroborate or invalidate the validity of two types of data and findings from qualitative narrative sources and qualitative and sometimes quantitative illustrative and epigraphic sources. Barriendos et al. (2014); Sturm et al. (2001) have used the types of data described above and the triangulation design in their studies to measure the degree of validity of the information. This approach allowed the authors to densify the historical flood data and to obtain continuous and reliable data sets over time. The use of mixed methods gives researchers the possibility to access a goldmine of information neglected according to Garnier (2018), due to the difficulty for some researchers to find methodologies to infer in their research relevant and available historical information, but which are qualitative in nature. Thus, with these methods, it is possible to extend the measurement of flood flows over several hundred years, thus making research on historical floods more robust (Baker, 2008).

Exploratory design for data transformation

An exploratory design is used by the researchers at this stage. The qualitative data collected is coded or categorized, depending on the magnitude and severity of the flood event. Elleder (2010) reconstructed the flood histogram curve of the Vltava River from qualitative documentary sources transformed into quantitative data with an exploratory design. He interpreted the documentary information and granted them sequential codes from 0 to 23, each code constituting a stage in the evolution of the flood: from the rise of the flood to the recession. Each sequential code corresponds to a water level or water height in cm, validated in the field by observations of epigraphic marks and by comparison with the water level measurements of Pötzsch (1784) on the Elbe in downstream at Dresden. The water levels are then transformed into the flow, which makes it possible to reconstruct the flood hydrograph. Barriendos et al. (2003) propose a classification of historical floods recorded on French and Spanish rivers based on the impacts of floods and hydrological criteria.

The overflow of the channel serves as a reference for the classification of floods (ordinary floods, extraordinary floods and catastrophic floods). This classification then makes it possible to extrapolate and estimate the flow rates of floods for which we do not have the water levels from the floods for which the water levels are available (Cœur et al., 2002). It is possible to define from this classification the recurrence of floods. However, for the quantification of documentary data to be possible, it would be necessary to have sufficient and quality documentary and epigraphic sources. The determination of the water levels is then accompanied by hydraulic modeling to determine the values of the flood flows of these historic floods.

Lang et al. (2004) ; Naulet et al. (2005) propose a model of the historical water levels rendered inflow. Remember that this modeling has a better chance of simulating flows representative of the historical flood if the river has low sensitivity (the flow Q does not vary much even if a variation in the water level is recorded) (Barriendos et al., 2003). The modeling assumes a one-dimensional (1D) type of flow with the most frequent use of Manning's equation (Benito &Thorndycraft, 2004) of the following form (1):

$Q = \left(\frac{1}{n}\right) A\,(R)^{2/3}\,(\mathrm{S}_0)^{1/2}$ (1)

Where:

Q is a discharge (m3/s),

n the Manning coefficient,

A the cross-sectional area (m^2),

R the hydraulic radius in m ($R = A/P$ with P the wetted perimeter),

S_0 is the lower slope (m/m).

(1) provides the first estimate of flow, assuming that the flow conditions are uniform with Q constant, A constant and S_0 constant (Lang et al., 2004). That is, the topographic, hydro-geomorphological and geological conditions of the basin have not changed over time (as in the example of gorges or canyons). Documentary data or non-systematic data transformed into flow data must then be subjected to sensitivity analysis to ensure their reliability (see Naulet et al., 2005; Prosdocimi, 2018). The analysis of the frequency of floods can be done by combining non-systematic data with systematic data (from instrumental and automatic measurements). The stationarity and homogeneity of this data set must be verified. This is sometimes difficult since the non-systematic data do not show continuity (only the estimated extreme event discharge values are available). The solution found is to model the non-systematic and systematic data as peaks above a threshold i.e. to obtain a series presenting all events above a threshold (Macdonald & Black, 2010). A generalized extreme value distribution (GEV) is then applied to the data set. The GEV parameters are fitted using the maximum likelihood method (Naulet et al., 2005). The GEV distribution is of the following form (2) (Engeland et al., 2018) :

$$f(x) = \begin{cases} exp - \left[-1 - k\left(\frac{x-m}{\sigma}\right)\right] 1/k \\ exp - exp\left(-\frac{x- m}{\sigma}\right) \end{cases} \quad (2)$$

With

m location parameter

scale parameter

k shape parameter

The use of the exploratory mixed methods design in the studies of Barriendos and Rodrigo (2006); Elleder (2010); Prosdocimi (2018); Engeland et al. (2018) etc. on historical floods has allowed these authors to integrate qualitative data of great importance in their research. This methodological approach improves the understanding of the occurrence of extreme floods in Europe through the densification of data. According to Elleder (2010), this methodological approach can lead to better control of the calibration of flood warning systems. The other benefit of this approach is recalled by Engeland (2018) in his study, namely the reduction of the uncertainty surrounding the estimates of the magnitude of rare events obtained with statistical extreme value models. Mixed methods help to improve the reliability and stability of design flood estimates (Engeland, 2018). Mixed methods are future-oriented methods that can contribute significantly to a better understanding of flood behavior and impacts on people.

3.1.2 Low Flow Studies

In low flow research, the triangulation design is used to corroborate results from a quantitative approach with those from a qualitative approach.

Research on low flows and water scarcity also suffers from the paucity of data and documentation available on these extreme events. The discontinuity and irregularity of low flow phenomena explain the less pronounced scientific interest in analyzing them (Joly, 2006). However, the situation is changing with the European Water Framework Directive (DCE), which since 2000 has shown a strong desire to preserve aquatic environments in semi-arid and arid zones (Barreteau et al., 2008; De Giralomo et al., 2015). Hydro-ecological studies are being carried out to determine the ecological reserve flows for these aquatic environments and to gain a broader knowledge and understanding of the hydrological regimes that condition the existence of mesohabitats (Stubbington et al., 2020). The difficulty of implementing a methodology that allows a global understanding of the phenomena and hydrological states of these environments is pushing researchers to adopt creative alternative methodologies (mixed methods).

Gallart et al (2012), (2016) carried out a study on the determination of the hydrological regimes that condition the aquatic states of temporary rivers in Spain and France. This study was carried out to measure the hydro-ecological quality of these rivers upon reaching each defined aquatic state. Gallart et al. (2016); De Girolamo et al. (2017) used flow measurements recorded at gauging stations during periods of flow transit at the station and flow measurements obtained by rainfall-flow relationship modeling to define aquatic states. These data were combined with questionnaire interviews to validate the frequency of occurrence of aquatic states over the year that defines the existence or not of mesohabitats. This validation was necessary as the gauging stations do not record flow measurements for any period of the year, but the stream channel may continue to support aquatic life through temporary pools.

Triangulation to confront and measure the validity of the results.

According to Gallart et al. (2016), the hydrological regimes of temporary rivers in Spain are characterised by six aquatic states (Hyperheic, Eurheic, Oligorheic, Arheic, Hyporheic and Edaphic). The last three states (Arheic, Hyporheic and Edaphic) correspond to periods when there is no flow or flow data are impossible to measure at the station, but aquatic habitats are still available maintained by temporary pools. The validity of these states was measured from information collected from people living near rivers using questionnaire surveys, until the responses were saturated (Gallart et al., 2012). For this purpose, the triangulation design was used. Two metrics are calculated for each of the two approaches (quantitative approach based on flow measurements and qualitative approach based on questionnaires) and were compared with each other. A metric for flow presence that measures the permanence of flow Mf (average annual number of months with flow taking a value between 0 and 1) and another metric for flow non-existence that measures the seasonal predictability of non-flow periods over six months (Sd6) which is the most important for the low flow study. Sd6 was calculated for the flow method by the following formula (3) :

$$\mathrm{Sd6} = \sum_{1}^{6} \mathrm{Fdi} / \sum_{1}^{6} \mathrm{Fdj} \quad (3)$$

$\mathrm{Fd_i}$ represents the multi-annual frequencies of 0-flow months for the contiguous 6 wetter months of the year and

$\mathrm{Fd_j}$ represents the multi-annual frequencies of 0-flow months for the remaining 6 drier months.

(3) is dimensionless and takes a value of 0 when flows are zero over the year and over a long period of time and 1 when zero flows occur only over the same six-month period in each year. Sd6 is also calculated on the data collected from the questionnaire surveys, coded and transformed into quantitative data from an exploratory design. Sd6 calculated from the interviews is of the form (4) :

$$Sd6 = \ 1 - \ (\frac{\mathrm{Swet}}{\mathrm{Sdry}}) \quad (4)$$

Where

S_{wet} semester with fewer dry months and

S_{dry} semester with more dry months.

Using the triangulation design, it was found that the results provided by the flow permanence metric (Mf) calculated on the flow data and the Mf calculated from the questionnaires provided similar interpretations. The triangulation of results is more interesting for the Sd6 metric, which measures the seasonal predictability over six months of periods without flow. This metric validates the manifestation of hydrological regimes of temporary rivers when they no longer have flow. Gallart et al. (2016) note discrepancies in the results obtained by the two approaches. For some of the wetter rivers in the sample, an overestimation of the predictability of no-flow periods is noted for the questionnaire surveys and an underestimation is noted for the drier rivers. These results may raise further research questions for researchers about users' perception of the impossibility of satisfying their needs during dry months, which they may or may not consider to be early. The authors of this study made inventive transformations of data from one type to another (quantitative, qualitative; qualitative, quantitative), allowing highly integrative analyses. This research clearly illustrates a dialectical framework, in that not only were different methods combined, but also different assumptions and paradigmatic features were adopted (Greene et al., 2001). The approach allowed for a better understanding of the object of study: the hydrological regime of temporary rivers. The triangulation design allowed the results to be compared and paradoxes to be highlighted. The use of mixed methods finally allowed this study to provide knowledge and information on unknown water bodies, to characterise them and to bring out paradoxes in the measurements of aquatic states made with two different approaches. The contradictions posed in this study allow researchers to reflect in depth and to evolve their research questions for a better knowledge of temporary watercourses.

3.2 The Post-Positivist Paradigm in Hydrology: Mixed Methods as an Indispensable Methodology

Recent studies give a special weight to the social sciences in hydrological research, especially for studies on the management of hydrological extremes. This stems from the need for researchers to have a holistic understanding of the hydrological phenomena under study. In this paradigm shift where more emphasis is placed on qualitative approaches to understanding phenomena, triangulation design is used to enhance the validity of the results.

3.2.1 Water Management and Hydrological Extremes Management Studies Through Modeling

The use of mixed methods in hydrological extremes and water management studies makes sense when it comes to managing complex phenomena including human and natural systems, such as floods, droughts, water quality, etc. According to Walker et al. (2003), there are at least two types of uncertainty: epistemic type uncertainties due to the imperfection of our knowledge and therefore which could be reduced by more research and empirical efforts; and ontological uncertainties due to the inherent variability observed in complex systems, especially human and natural. Here, we believe that ontological uncertainties can be better dealt with through the multiple perspectives of various related methods (mixed methods) than through the perspective of just one (Yates et al., 2017). This vision of a paradigm shift recalled by Kuhn according to Ravetz

(2005) is also shared in hydrology by authors such as Evers et al. (2017); Seidl and Barthel (2017); Wagener (2010); Xu et al. (2018); Yu et al. (2017).

Socio-hydrology: within the framework of socio-hydrology, which aims to model the bidirectional feedbacks between human and hydrological systems, Pande and Sivapalan (2016) believe that the consideration of human norms and values in socio-hydrological modelling seems increasingly inevitable. This had been partially mentioned by Di Baldassare et al. (2015); Yu et al. (2017) who proposed types of socio-hydrological modelling to understand the effect of floods and propose a management model. Di Baldassare et al. (2015) based on the study of interaction dynamics between physical and social processes of hydrological systems subjected to floods to search for the factor that explains the vulnerability of populations to floods. The fundamental processes and interactions that determine the behaviour of these hydrological systems were formalised (mathematically) using a set of differential equations. The proposed socio-hydrological modelling took into consideration four variables of four major sub-components of the system (flood memory (M) of the society sub-component, the population density (D) of the demography sub-component, the construction of dikes and flood dams (H) of the technology sub-component and the water level (F) of the hydrology sub-component).

The most important sub-component of the system that explains the differences in losses and risk exposure for the two societies modelled (an ecological society that lives with floods by settling far from the banks and that develops a flood memory and a technological society that uses technological means to protect itself against floods) is the flood memory (risk perception) developed or not by the societies. The results show that ecological societies that live with floods are less exposed to extreme events and suffer fewer losses than technological societies protected by dykes and dams and which gradually lose the notion of flood memory.

These models allow for the reduction of epistemic uncertainties with innovative empirical approaches that include societal risk factors in the equations. However, these modelling approaches are not without criticism, as they are purely positivist and consider the social memory of risk as a mathematical parameter that can be modelled.

Risk perception (social memory) is much more complex than the simple parameter (M) being modelled (Gober & Wheater, 2015). As a result, these models do not currently allow for the reduction of ontological uncertainties often reinforced by human activities and behaviours (Binder et al., 2016). This limitation in socio-hydrological studies can be explained by the training of hydrologists, which is often based on the use of a single approach: quantification, rather than the combination of quantitative and qualitative approaches in a holistic modelling approach. What can be changed, we believe, is by using mixed methods.

Risk perception cannot be quantified but can be measured through mixed methods. In a holistic modelling approach where all components of the system have to be taken into account, mixed methods offer the possibility to retrieve and transform this qualitative information into measurable data that are then integrated into the modelling approach. Moreover, Xu et al. (2018) believe that considering human perceptions (societal memory, etc.) through qualitative methodologies developed by the social sciences through historical and ethnographic interpretation would succeed in strengthening the validity of modelling results. Gober and Wheater (2015);Seidl and Barthel (2017) confirm that the future of socio-hydrology cannot do without the combination and inclusion of different methodological approaches (qualitative and quantitative) from the physical and natural sciences and the social sciences to provide comprehensive modelling capable of assisting decision-makers in their decision-making. Hence the interest in using mixed methods in order to reduce our ontological uncertainties.

Citizen science, participatory or utilitarian hydrology: Research on the management of extreme hydrological risks has also benefited in recent years from a strong recommendation to consider the social demand for involvement. This imperative of participation is found at the operational level, i.e. in the implementation of tools for the management hydrological extremes. An imperative that strongly requires the processing of qualitative information on perceptions and the psychology of political decision-making (Barreteau et al., 2008). Barreteau et al. (2008) identify qualitative methods used to enrich decision-making on the management of hydrological extremes. These include focus groups, role plays and interactive simulations. In some cases, questionnaires are preferred, because they make it possible to produce knowledge and are decision-making support tools for decision-makers (Goeldner-Gianella & Humain-Lamoure, 2010). The datasets produced by these qualitative approaches are combined with quantitative results obtained after analysis of experimental data.

Canovas et al. (2016) in their analysis of low water proposed a graphical modelling of low water criticality. This modelling was intended to assist in decision making and forecasting of critical low water states. The modelling is based on the analysis of water supply and demand variables, translated into statistical indicators using a quantitative frequency approach, and on indicators of risk perception by the authorities and the population. Critical thresholds have been defined to locate the different states of the system based on standard deviation for the quantitative indicators of supply and demand. For the indicators relating to the perception of risk, they are derived from a qualitative approach based on observation data on the resource, collected from the population, often binary (absence-presence, dry-wet) and from the analysis of the levels of restrictions on use found in the prefectoral decrees.

These data were coded and transformed into quantitative data to meet the need for an explanatory design (see Canovas et al., 2016). The thresholds were defined for the qualitative approach based on an arithmetic scale graduated in deciles. The objective of the graphic modelling was to be able to compare the different states modelled by the two approaches using a triangulation design. The aim was to see if there was any cognitive dissonance or consonance between the states established by the statistical measures and the policies' judgement of this same state. The perception of a normal state, when it is critical or catastrophic, would expose the territory to clear danger and the opposite situation to waste (Canovas et al., 2016). This more theoretical approach was complemented by the HydroPop project with a more practical approach (action research) where the populations were able to participate in defining the problem and improving knowledge on low water and its different hydrological states.

The populations participate in the production of data by being simple respondents to survey questionnaires on the evolution of the resource over time, as well as voluntary readers (reading water levels sent by SMS on a cartographic platform) (Martin, 2019). The HydroPop project is based on the methodology proposed by the CrowdHydrology project developed by Lowry and Fienen (2013), which also uses mixed method designs.

The explanatory design used first allowed Canovas et al. (2016) to have a broader view and understanding of the low water phenomenon, by including in the characterisation of these different states, the human perception of the states. The qualitative perception data allowed to further test the reliability of the criticality thresholds proposed with the quantitative approach. The triangulation design allowed to confront different but complementary data to reinforce the robustness of the study. This study took advantage of the benefits of quantitative methods (analysis of flow dynamics during a season of the year) and qualitative methods (aesthetics of the phenomenon, state of satisfaction or not, etc.) to strengthen the validity of the study and propose a modelling of low water states allowing their effective management. The idea of considering people's perceptions of risk to support the understanding and management of hydrological extremes through modelling has already been proposed by Baker (2008). Baker (2008) believes that feedback on historical floods experienced by people can help develop a perception and culture of risk. These qualitative data (details, depth) combined with probabilistic analyses (trends, generalisation) by mixed methods make it possible to reduce the uncertainty on the knowledge of floods and the vulnerability of the populations to the risks.

Taking participatory hydrology studies as an example, socio-hydrology could overcome one of its major limitations in terms of methodology by adopting mixed methods which allow perceptions to be integrated into modelling. The perception of risk among populations can be measured with the tools described above by Barreteau et al. (2008) (questionnaire, focus group, role-playing, proactive framework, etc.) and transformed into quantitative data according to an exploratory design for the needs of the modelling developed by the researcher. This type of approach makes it possible to co-construct knowledge on risks with the populations and to develop their collective memory of floods or lack of water in a practical way. It will be necessary to find a model, a model that integrates different types of data by inference and produce a coherent and scientifically robust analysis that reduces uncertainties at the epistemic and ontological levels. This is what Martin et al. (2020) believe is possible with Bayesian modelling approaches. For according to Drouet (2017) Bayesianism presents itself as the best way to represent uncertainty in a decision-making context (Martin et al., 2020).

3.2 Mixed Methods in a Constructivist Paradigm for Conflict Management in Water Governance

If we extend hydrological research to the problem of water governance and the management of conflicts related to water uses, it is possible to see that for these recent studies, mixed methods are a preferred methodological option. These new studies are interested in considering multiple norms and values to guide political and public governance of water to reduce conflicts. In this constructivist approach, qualitative methods set the tone for the research. Both exploratory and complementary designs are used here with a clear dominance of qualitative methods.

This involves the researcher establishing statements that capture and categorise people's subjective understandings of current governance (Zepharovitch, 2020). The statements are then sorted and presented in a grid. Data is collected from stakeholders: government representatives, farmers, indigenous actors, hunters/fishermen and members of civil society, based on semi-structured interviews in which participants are asked to sort the statements in order of importance based on the norms, values and representations they have of governance and to justify their choice. This approach makes it possible to identify the points of convergence, opposition, or discord at the root of the conflicts. The data obtained from the interviews is coded, categorised, and integrated into statistical analysis software based on an exploratory design. The statistical analyses then proposed to support the discussion are factorial analyses (see Lévesque et al., (2020); Zépharovitch et al., (2020)).

This type of mixed-methods approach using exploratory design and complementarity design at the end of the study makes it possible to consider different levels of analysis of the problem and to provide a complete analysis of the problem. Thanks to the complementarity design, the quantitative results obtained provide additional information and support the conclusions drawn from the qualitative results in the field of subjectivity and the analysis of the participants' representations. The mixed methods enabled the researchers to better understand the views and values of the different stakeholders in governance and to identify points of friction that lead to conflict. The identification of these points of conflict from the representations makes it possible to propose a negotiation framework that can lead to more effective governance (Lévesque et al., 2020).

4 Discussions and Perspectives

The examples of studies presented in this article show the contribution of social sciences in contemporary studies in hydrology using mixed methods. In historical flood hydrology, the discipline of climate history through its different data collection strategies has helped to increase the density of data on historical flood events. This is an important contribution to improving forecasts of extreme events. Low flow, socio-hydrology and citizen science studies incorporate a range of approaches and tools from political science, psychological and behavioural science, and economics. This is also the case for conflict management studies in water governance, but with a more ethnographic perspective. These social science approaches play an important role in improving the understanding of hydrological phenomena. The acceptance of social science approaches with different types of data and different disciplinary styles inevitably requires the use of mixed methods to be able to process large data sets and produce coherent and rigorous knowledge(Koudelova et al., 2017).

The need to use mixed methods will become evident in studies that use Big Data to propose management of hydrological extremes. Fohringer et al. (2015) study uses mixed methods to analyse data from social networks. Big data approach coupled with the use of mixed methods allowed the authors to produce a map of the extent and height of the June 2013 floods in Dresden, Germany. Forhinder et al. (2015) relied on the social network Twitter, which transmits information about floods from posts. The Tweets concern reports on flood risks, damage caused, discussions on the hazard (understanding), public debate, appeal and remarks to the government and local authorities, as well as emotional messages and expression of feelings (Le Coz et al., 2016). The analysis of Tweets on natural hazard preparedness extracted from machine learning models with keywords and event dates as input variables allows the authors to construct blocks of information on people's feelings and attitudes (positive and negative feelings). These blocks of information are then indexed and coded according to the exploratory design to be used in the analysis of the reduction of people's vulnerability to natural hazards (floods) and the development of point solutions. Antwi et al. (2021) use the same process to communicate water availability and raise awareness of water conservation during drought in the Republic of Ireland (see Antwi et al., 2021).

5 Conclusions

This paper describes the basic concept of mixed methods. It presents some examples of the application of mixed methods to hydrological studies of floods and low flows, as well as how they can be used to analyse other hydrological or water management issues. Mixed methods respond not only to the need for interdisciplinarity in the sciences, but also to a need for pragmatism that is favourable to the reduction of uncertainties in the knowledge of hydrological phenomena. They also make it possible to seek adequate solutions to social problems related to water. Mixed methods have led flood studies to produce knowledge on previously existing qualitative data, but whose analysis was impossible due to a lack of tools or an innovative and appropriate methodological framework. They are also at the origin of the studies of low flows, of the reinforcement of knowledge on these states which are difficult to apprehend because of the intermittence of their manifestations and the weakness of the existing data. The management of these hydrological risks can be done by having a holistic vision of all the components that come into play in the formation of these phenomena. This can necessarily be done by using mixed methods as mentioned above. However, for the moment, mixed methods raise a question of acceptability and legitimacy, especially when it comes to inferring qualitative information in predominantly statistical studies. Mixed methods also raise the question of feasibility for research since they are resource intensive. Consequently, for their acceptance, it is essential that current researchers trained in either research tradition combine their expertise to ensure rigour (Foss & Ellefsen, 2002). Studies using mixed methods will need to describe the strategic moments of integrations made throughout the research process and discuss the relevance of these decisions.

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