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Review

Use of Mixed Methods in the Science of Hydrological Extremes: What Are Their Contributions?

Raymond Kabo *, Marc-André Bourgault, Jean François Bissonnette, Nathalie Barrette and Louis Tanguay

Department of Geography, Laval University, Québec, QC G1V 0A6, Canada; marc-andre.bourgault@ggr.ulaval.ca (M.-A.B.); jean-francois.bissonnette@ggr.ulaval.ca (J.F.B.); nathalie.barrette@ggr.ulaval.ca (N.B.); louis.tanguay.2@ulaval.ca (L.T.)

* Correspondence: raymond.kabo.1@ulaval.ca; Tel.: +1-418-929-0626

Abstract: Research in hydrological sciences is constantly evolving to provide adequate answers to address various water-related issues. Methodological approaches inspired by mathematical and physical sciences have shaped hydrological sciences from its inceptions to the present day. Nowadays, as a better understanding of the social consequences of extreme meteorological events and of the population's ability to adapt to these becomes increasingly necessary, hydrological sciences have begun to integrate knowledge from social sciences. Such knowledge allows for the study of complex social-ecological realities surrounding hydrological phenomena, such as citizens' perception of water resources, as well as individual and collective behaviors related to water management. Using a mixed methods approach to combine quantitative and qualitative approaches has thus become necessary to understand the complexity of hydrological phenomena and propose adequate solutions for their management. In this paper, we detail how mixed methods can be used to research flood hydrology and low-flow conditions, as well as in the management of these hydrological extremes, through the analysis of case studies. We frame our analysis within the three paradigms (positivism, post-positivism, and constructivism) and four research designs (triangulation, complementary, explanatory, and exploratory) that guide research in hydrology. We show that mixed methods can notably contribute to the densification of data on extreme flood events to help reduce forecasting uncertainties, to the production of knowledge on low-flow hydrological states that are insufficiently documented, and to improving participatory decision making in water management and in handling extreme hydrological events.

Keywords: epistemology; hydrological extremes; science; uncertainty; complexity; mixed methods; interdisciplinarity

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Citation: Kabo, R.; Bourgault, M.-A.; Bissonnette, J.F.; Barrette, N.; Tanguay, L. Use of Mixed Methods in the Science of Hydrological Extremes: What Are Their Contributions?. *Hydrology* **2023**, *10*, 130. https://doi.org/10.3390/hydrology10060130

Academic Editors: Monzur Imteaz, Md Jahangir Alam and Abdallah Shanbleh

Received: 23 May 2023
Accepted: 6 June 2023
Published: 9 June 2023

1. Introduction

Many studies in hydrological science aim to understand, explain, and propose solutions to low water quality and availability, as well as to flooding and water management issues [1]. However, the growth and diversification of social issues related to water scarcity [2] and floods further complexifies the study of hydrological phenomena. Traditional quantitative approaches to hydrology, although essential, remain limited to apprehended diversification of human problems linked to droughts or floods, as well as the complex human-centered dynamics related to water use and management which are better captured through social sciences. These issues now represent an avenue for enlarging research in hydrological science.

To elucidate water management problems and propose adequate solutions, hydrologists must rely on concepts and methods from several disciplines to fully understand both the multidimensional hydrological phenomenon or state they are studying and the affected social systems. Mathematical, probabilistic, statistical, and laboratory methods are used to understand the physical and chemical aspects of water-related issues (flooding, low water, water quality, and erosion) and qualitative methods from anthropology, sociology, law, economics, politics, and history are used to explain the interactions between those issues and society [3]. This involves combining several methodological approaches from different aradigms.

The use of mixed methods, which combine qualitative and quantitative approaches across four designs, can facilitate the structuring of these concepts and methods from several disciplines into a single coherent whole to better understand the system under study [4]. The possibility of structuring a plurality of methods and modes of reasoning into a coherent whole prompts the question: how can the mixed methods approach contribute to contemporary hydrological research?

The main purpose of this paper is to identify and present an overview of some of the contributions of mixed methods in hydrology studies. We first present the mixed methods approach as a concept. Second, using a literature review to support our descriptions, we highlight how, over the years, mixed methods have helped support hydrological research across three paradigms and within the four aforementioned research designs. We thus show how mixed methods are used and what benefits they provide to understanding complex hydrological phenomena according to specific paradigms, designs, and research objectives. We also highlight the limitations of each of these research contexts. Finally, the need to further include mixed methods in research focusing on hydrological extremes and water management is discussed.

2. Mixed Methods: A Pragmatic Approach

2.1. Definition and Underlying Paradigms

Mixed methods were formalized between the 1980s and the 2000s and were quickly taken up by researchers in fields such as psychology [5,6], education [7,8], health [9], environmental management [10,11], and sociology [12].

The mixed methods approach combines three paradigms. The positivist paradigm is a scientific conception according to which a phenomenon can only be known through empirical data on natural processes. This paradigm relies on quantitative measurements and methods to describe the hydrological phenomenon and predict it [13]. For instance, mathematical modeling of hydrological flow is based on the positivist paradigm through which the natural world can be explained. In contrast, actors' decisions regarding water use and management are best comprehended through post-positivism, defined as a paradigm that considers knowledge of a given phenomenon to be linked to the exploration of empirical data as much as to the consideration of human perceptions' influence in explaining and understanding the phenomenon.

Within post-positivism lies the constructivist paradigm, which considers the object of investigation to be socially constructed. It is, to a certain extent, the opposite of the positivist paradigm. The constructivist paradigm considers subjective, lived experience of individuals to contribute to the construction of reality. This paradigm seeks to produce knowledge based on the confrontation of subjective knowledge (ideas, perceptions, human representations) brought together by the social experience of two or more individuals interacting together [14]. Thus, research approaches used within this paradigm consist mainly of qualitative methods [13,15].

Drawing from these paradigms, the mixed methods approach is defined as "a type of research in which researchers combine elements of qualitative and quantitative methods (for example, data collection, analysis, inference techniques) to meet the breadth and depth of understanding and substantiation needs of the study" [16] (p. 123). The combination of quantitative and qualitative approaches can lead to a better understanding of complex phenomena [17]; raise unexplored research questions [18]; help draw more solid inferences when the two types of data lead to similar results; expose contradictions or paradoxes not otherwise observable [19]; and, foster creativity and innovation in research design [20].

2.2. Research Designs

Mixed methods can be deployed through various designs to structure the research process. Creswell et al. [21] propose four classifications of mixed methods designs: triangulation, complementarity, explanatory, and exploratory. "Triangulation is defined as a procedure that seeks to test the validity of results and insights by comparing quantitative and qualitative data. The aim of triangulation is to seek convergence or corroboration of data relating to a same phenomenon to strengthen their validity. It also allows to underline contradictory quantitative and qualitative results to highlight paradoxes and give rise to new interpretations and knowledge" [4] (p. 4). In hydrology, triangulation is used to corroborate quantitative results obtained with statistical and mathematical approaches (e.g., analysis and modeling of extreme flows) with qualitative results derived from primary sources (e.g., interviews on the perception of hydrological extremes) or secondary sources (e.g., consultation of epigraphic documents, documentary sources).

Complementarity proposes to integrate quantitative and qualitative approaches to study the same phenomenon [20]. Complementarity allows quantitative research to benefit from additional qualitative information to complement knowledge of a given phenomenon and improve understanding, and vice versa. This design is used in hydrology to provide comprehensive analyses of hydrological extremes by complementing quantitative results (mathematical or statistical modeling of the hydrological system exposed to extremes) with qualitative data (impression of risk, consideration of the plurality of values and objectives related to water resources as expressed by the local population).

"Explanatory design proposes the use of a qualitative approach to deepen and explain in more details an initial quantitative inquiry" [4] (p. 4). This design is less used in hydrology.

"The exploratory design begins with a qualitative inquiry to discover themes concerning a given issue or situation. Those themes support the development of a methodology capable of generating data from the qualitative information provided by these themes. The generated data is then processed and analysed quantitatively" [4] (p. 4). Exploratory design is used in hydrology to provide quantitative data on a qualitative water issue; for example, the multiple representations that people have of water (qualitative themes) are transformed into statistical data (percentage, numerical data).

2.3. Temporality and Weighting

Beyond the classification presented above, mixed methods can be classified into two dimensions: temporality and weighting. Temporality distinguishes sequential and simultaneous processes; researchers explain or develop data from one approach (qualitative or quantitative) using the other approach. In a sequential process, process, researchers supplement the explanation of the results obtained using one approach (qualitative or quantitative) with another method. In a simultaneous process data from both methods are processed and linked together to provide a complete analysis of the phenomenon (e.g., triangulation design). Both forms of data are collected and interpreted at the same time. Weighting corresponds to the relative weight given to each method in the analysis. The weighting is equivalent if both methods are considered in the analysis with the same importance. The weighting is dominant if the researchers favour one method more than the other in the collection or analysis phase [4].

Morse [22] proposes a system to notate mixed method designs. The use of quantitative and qualitative methods is notated QUAN and QUAL, respectively. These abbreviations are written in capitals letters 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, and the quantitative method is dominant. When the design is sequential, the arrow symbol (=>) indicates the direction of temporality, in other words, which method was used first (e.g., qual => QUAN indicates that a qualitative method precedes a dominant quantitative method) [4] (Table 1).

Table 1. Main types of mixed methods used in hydrology, according to Aldebert and Rouzies [4].

Motivation	Temporality	Weighting	Morse's Notation System [22]
Triangulation	Simultaneous	Generally equivalent	QUAN + QUAL
Complementarity	Simultaneous or sequential	Not equivalent	QUAN + qual or QUAN => qual
Explanatory	Sequential: quantitative phase then qualitative phase	Usually, quantitative dominance	QUAN => qual
Exploratory	Sequential: qualitative phase then quantitative phase	Usually, qualitative dominance	QUAL => quan

3. Mixed Methods in Hydrological Studies

Our literature review allowed us to identify hydrological studies that use mixed methods, albeit without naming them as such. We divide case studies based on whether they are anchored within a positivist, a post-positivist, or a constructivist paradigm. We show the usefulness of mixed methods in the search for solutions and in the understanding of complex hydrological phenomena, we explain why they are necessary for the advancement of several sub-disciplines, and we describe the designs most often used in hydrological research for each paradigm.

3.1. The Positivist Paradigm in Hydrology of Extremes: Towards an Openness to the Use of Mixed Methods

Researchers in positivist hydrology are beginning to explore mixed methods research designs, mainly triangulation and complementarity designs. Generally, the complementarity design is preferred for historical flood studies. As for the triangulation design, it is often used in low-flow studies. Below, we present case studies for both designs and in both of the aforementioned fields.

3.1.1. Historical Flood Studies Based on Complementarity Design

Brázdil et al. [23,24] and Barriendos et al. [25] provide a comprehensive description of how they combined or merged methods to integrate qualitative data in flood research. Extreme flood forecasting is hampered by insufficient long-term data, especially for past historical events. Systematic instrumental data are available but not for periods of time long enough to provide forecasts that are considered robust and relevant, particularly when it comes to calculating return periods for extreme events [23,26]. To solve this problem, mixed methods can be used. Brádzil et al. [23,24,27] 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 retrospective emotional loading related to property damage and loss of human life [23]. The quality and accuracy of the qualitative information recorded depends on the author's intellectual proficiency (e.g., basic education, talent for observation, motivation and aptitude to keep records), as well as their relationship to the event described, especially if the author of such information was an eyewitness [23]. Adequate selection of sources is necessary to ensure data reliability; for instance, documentary sources from administrative and ecclesiastical sources are recommended because of their quality and reliability [25], including the details they contain such as the date and time of events, their durations, their extent, and their impacts.

This qualitative information was verified by testing its concordance and coherence with epigraphic marks engraved in stone, houses, bridges, and gates. Epigraphic sources allow determination of the water level of the peak discharge rate, which can be represented in flood hydrographs.

Once the qualitative data are collected, they are usually coded or categorized; for instance, Elleder [28] reconstructed the flood histogram curve of the Vltava River based on reliable qualitative documentary sources. He interpreted the documentary information and granted them sequential codes from 0 to 23, with each code constituting a stage in the evolution of the flood: from the rise of the flood to its recession. Each sequential code corresponds to a water level, validated in the field by observations of epigraphic marks and by superposition with water level measurements made by Pötzsch [29] on the Elbe, downstream at Dresden [28]. Water levels obtained were then interpreted to reconstruct the flow pattern of the event on a flood hydrograph (Figure 1).

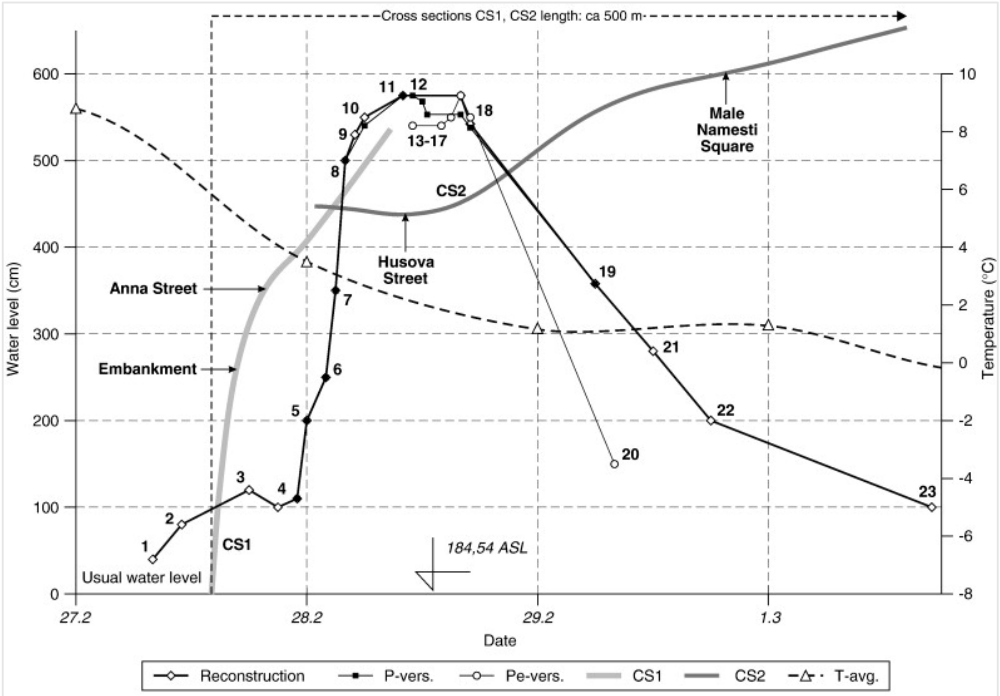

Figure 1. "The 1784 flood hydrograph as reconstructed by the author using documentary sources and flood marks in comparison with two other variants, namely, P-vers Pötzsch [29] and Pe-vers Pan [30]. Cross-sections CS1 and CS2 correspond to the terrain profiles presented in Figure 2. T-avg is the mean daily temperature recorded at Prague Klementinum Observatory" [28] (p.122). This figure was taken from Elleder [28].

Barriendos and Coeur [31] proposed another type of categorization and coding of floods described in historical sources. They based their coding on the impact and severity of the floods and on hydrological criteria. Channel overflow served as a reference for the classification of floods (ordinary floods: Level 0, extraordinary floods: Level 1, and catastrophic floods: Level 2). These classifications and codifications make it possible to extrapolate and estimate water levels of historical floods based on similar, more recent floods for which water level data are available [32,33].

Determining water levels based on historical sources is sometimes accompanied by hydraulic modeling to estimate flood flow values for these historical floods, as carried out notably by Lang et al. [34] and Barriendos et al. [35]. In such cases, non-systematic data are first subjected to a sensitivity analysis to ensure their reliability (see [36]). Once water levels are transformed into flow values, flow data from documentary and epigraphic (or non-systematic) sources can be combined with systematic data, obtained from instrumental and automatic measurements. This process is not always straightforward since the non-systematic data do not show continuity, and only the estimated extreme event discharge values are available. One solution to this issue is to model the non-systematic and systematic data as peaks over threshold (POT), or, in other words, to obtain a series presenting all events above a chosen threshold [37,38]. A generalized Pareto distribution (GPD) or generalized extreme value distribution (GEV) can then be applied to the data set, providing the return periods of these extreme events.

The case studies presented above show how mixed methods can support researchers in the analysis of qualitative information from documentary sources, even though those often lie outside their usual field of practice. The use of complementarity design thus allows the production of new quantitative data on historical flooding events, notably to extend the temporal coverage of those events' time series, which is not otherwise possible. The complementarity is used in these case studies, with a sequential temporality and a predominantly quantitative weighting. The scoring system used here is qual => QUAN, which means that qualitative data complements quantitative data.

As a result, the accuracy in forecasting such events is improved, as is the understanding of their evolution (reduction in the uncertainty of the frequency of large floods) [36]. Moreover, some studies in Europe showed how the addition of historical flood events to time series highlighted certain similarities in the recurrence of events when comparing historical and more recent flood events, supporting the improvement in flood warning systems [33].

The positivist approach presented here, which uses the complementarity design, does not necessarily exploit all the relevant qualitative information available in the documentary sources under scrutiny. While those sources are used to seek more data on historical flood events, valuable information such as accounts of the severity of the event, the damage caused, or the distress and apprehension of populations in the face of such extremes constitute important feedback for contemporary flood management.

3.1.2. Low-Flow Studies Based on Triangulation Design

As with historical flood studies, research on low flows and water scarcity suffers from the paucity of data and documentation available. The discontinuity and irregularity of low-flow phenomena explain the less significant scientific investment in them [39]. However, renewed interest is emerging with the European Water Framework Directive (DCE) which, since 2000, has strongly supported the preservation of aquatic environments in semi-arid and arid zones [40]. Hydro-ecological studies are being realized 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 [41].

Gallart et al. [42,43] studied how hydrological regimes condition the aquatic states of rivers with intermittent flows in Spain and France. The objective was to measure the hydro-ecological quality of these rivers for six pre-defined aquatic states. Gallart et al. [43] used flow measurements during periods of flow transit recorded at gauging stations and simulated streamflow during periods for which data recording was not possible (pristine conditions) to define the six aquatic states (Hyperheic, Eurheic, Oligorheic, Arheic, Hyporheic, and Edaphic) [43]. The first three states (Hyperheic, Eurheic, Oligorheic) correspond to periods when flow is measurable and flow data are available. The last three states (Arheic, Hyporheic, and Edaphic) correspond to periods when there is no flow or flow data are impossible to measure, but aquatic habitats are still maintained by temporary pools [43].

To confirm the characterization of the hydrological regime of intermittent rivers with these aquatic states, two metrics (M_f, Sd_6) were calculated. The metric M_f measured "the permanence of flow (long-term mean annual relative number of months with flow, taking values between 0 and 1)" [43] (p. 3172), while the metric Sd_6 measured the seasonal predictability of non-flow periods over six months. Both metrics were calculated first based on the flow data and the rainfall–flow simulation data. These metrics were then calculated based on interview data from respondents living near the watercourse. In the interviews, questions revolved around the general characteristics of the hydrological regime of rivers and the frequency of aquatic states and mesohabitats. Data were coded according to the importance of flow from 0 (very low) to 3 (very frequent). The coded responses facilitated the identification of the different aquatic states and allowed the evaluation of the two metrics M_f and Sd_6 with information of a qualitative nature.

Quantitative and qualitative metrics were contrasted to evaluate the validity of the results and to test the consistency or dissonance between the two types of results. Results on the discretization of the different states provided by the flow permanence metric M_f, calculated from both the flow data and the interview data, provided similar interpretations. Based on the comparison between Sd_6 (quantitative) and $Sd_{6'}$ (qualitative), Gallart et al. [43] noted discrepancies, with qualitative data showing in some cases an overestimation, and in other cases an underestimation, of $Sd_{6'}$. These divergent results prompted the researchers to investigate the reason for such discrepancies and to inquire using innovative research questions to deepen their knowledge of the perception of dry months among stakeholders.

The triangulation design allowed the validity of hydrological regimes and aquatic states defined by the quantitative data to be confirmed or refuted, especially the three states defined in dry conditions (without flows), which would have been impossible to validate without the qualitative information. Indeed, during periods with unrecorded flow measurements, temporary pools could be observed by people living close to the streams, hence the relevance of qualitative data. Triangulation is used with a simultaneous temporality and a predominantly quantitative weighting. The notation used is QUAN + qual, which means that the quantitative and qualitative results are compared simultaneously to corroborate the reliability of the results (Figure 2).

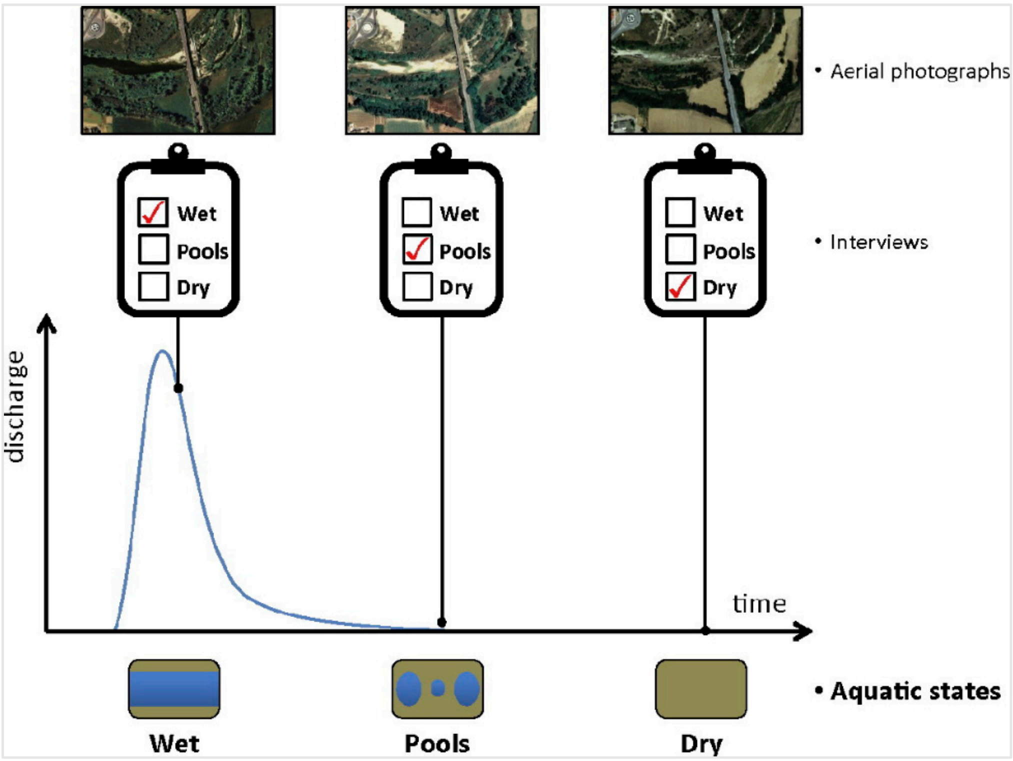

Figure 2. Graphical abstract proposed by Gallart et al. [43] to corroborate the results of the different approaches used in the study. This figure was taken from Gallart et al. [43].

In addition to validating the aquatic states, the mixed methods approach provided substantial additional information on the regimes and mesohabitats existing in these intermittent rivers compared to what a purely quantitative methodology could have contributed. Table 2 summarizes the objectives for which authors in positivist hydrology have used mixed methods.

Table 2. Summary of the results of the content analysis in positivist hydrology.

Research Areas	Period of Publication	Paradigms	Main Authors	Motivation	Designs	Temporality and Weighting	Results
Historical Floods	1999 to 2018	Positivism	Bradzil et al. [23,24,27] Barriendos et al. [25] Elleder [28]	Increase data on flooding events.	Complementarity	Sequential qual => QUAN	Complete or extend time series on extreme flood events. Reduce uncertainties in the frequency of extreme flood events.
Low Flow	2000 to 2016	Positivism	Gallart et al. [42,43]	Strengthen the validity of the results on hydrological states that are difficult to study due to gap of data.	Triangulation	Simultaneous QUAN + qual	To know the hydrological regimes of intermittent rivers. Generate knowledge on understudies' extreme hydrological states.

Despite the advantages explored above, the positivist paradigm of low floods studies, as is the case with historical floods studies, does not fully integrate the benefits brought about by mixed methods. These studies use research designs that permit filling the data gaps at extremes to better understand their frequency of occurrence, but do not enable a comprehensive understanding of the phenomena. In the post-positivist paradigm, researchers respond to the latter objective by using triangulation design, complementarity design, or both combined.

3.2. The Post-Positivist Paradigm in Hydrology: Mixed Methods—An Indispensable Methodology

More recent studies on hydrological extremes aim to obtain comprehensive viewpoints of extreme hydrological phenomenon. In this context, they fit perfectly into the post-positivist paradigm where the use of triangulation and complementarity models is prevalent. This is notably the case in participatory hydrology (citizen science) and socio-hydrology studies.

3.2.1. Participatory Hydrology

Research on the management of extreme hydrological risk has been increasingly involving local populations in the production of knowledge of extremes and their effective management [40]. This emphasis on public participation aims to produce comprehensive research on these complex phenomena, where all factors that contribute to the occurrence of, and risks associated with, these phenomena are identified, understood, and analyzed. This improves the chances of proposing adequate risk management strategies, hence the relevance of integrating quantitative information (mostly statistics and mathematical models) with qualitative information that explores people's perceptions and the psychology of political decision making [40].

In their analysis of low-water periods, Canovas et al. [44] identified three dimensions related to low-water periods: water supply, water demand, and the perception of low-water periods by populations and decision makers. Low-water periods represent the range of flows below the interannual module, integrating the low-water level and the drying up of watercourses [44]. Canovas et al. [44] proposed a graphical model based on their three dimensions to monitor undesirable severe states (e.g., water crisis or water shortage) in the Cevennes region, south of France, and improve forecasting capabilities. The model was based on the analysis of water supply and water demand (i.e., physical variables such as precipitation, flow, piezometric levels, evapotranspiration, withdrawals, reserve flows, and low-water perception variables), translated into indicators and statistically modeled with the Gaussian normal law. This allowed the authors to define critical thresholds for identifying severe situations.

To evaluate the perception of risk, Canovas et al. [44] analyzed water-use restrictions formulated in prefectorial decrees as a form of policy response to critical situations. They also collected qualitative data on the hydrological regime of rivers, based on questionnaires carried out with the population as part of the HydroPop program, a popular participatory hydrology platform in the Cevennes region [45].

The collected qualitative data were often binary (absence–presence, dry–wet) and coded according to the perceived level of severity. For each level of severity, ranging from 0 (low) to 3 (high), a coefficient was assigned. The coefficients provided numerical data, which were used to define the critical thresholds of the perception dimension of severe low-water situations. With this coding procedure, the authors were able to propose a global model of critical low-water states that integrates the perception dimension.

The triangulation design used in this case study is QUAN + qual, which means that both approaches are used simultaneously, but with a clear preference for the quantitative approach in the analysis of critical states.

This mixed modeling approach allowed quick identification of the weight of each dimension in the occurrence of the hydrological phenomenon and in explaining the system evolution towards critical situations. For example, Canovas et al. [44] compared quantitative and qualitative modeling (through the frequency approach and perceived level of severity) to illustrate cognitive dissonance or consonance between the system states determined by statistical measurements and by questionnaire data. The perception of a normal state, when it is in fact critical or catastrophic, would expose the territory to obvious conflicts, and the opposite situation might encourage stakeholders to overuse water resources [44]. This shows how human perception can influence strategies for the management of hydrological extremes (for example, see [46,47]). The study of Canovas et al. [44] also shows how contemporary research of hydrological extremes evolved to become more pragmatic and to seek management solutions adapted to the observed problems in what is also known as action research, a trend that has also emerged in socio-hydrology.

3.2.2. Socio-Hydrological Modeling

Socio-hydrology is a sub-discipline of hydrology that aims to model bidirectional feedbacks between human and hydrological systems [48]. The objective of such models is to provide decision makers with a management tool that identifies the components to be addressed and that explains why and how the system is vulnerable to extremes. Socio-hydrological modeling of floods has been explored by many authors (e.g., Di Baldassare et al. [48] and Yu et al. [49]) and the same is true for socio-hydrological modeling of droughts (e.g., Van Emmerik et al. [50] and Mazzoleni et al. [51]). The fundamental processes and interactions that determine the behavior of these hydrological systems have been mathematically formalized using a set of differential equations [48]. These positivist models have identified an important factor that is not well considered in modeling, and which partly explains the vulnerability of hydrological systems to extremes, namely, the perception of risk (norms, values, representations, and human objectives). This limitation in socio-hydrological studies is due to the limited methodological skills of the above researchers to adequately analyze risk perception.

Rangecroft et al. [52] proposed a socio-hydrological study with a strong participatory dimension, to fill this gap identified by Evers [53]. To reach a holistic understanding of the system, modeling exercises benefit from being complemented by qualitative analysis of the perceptions of extremes.

Rangecroft et al. [52] used mixed methods in two stages: a first stage with a triangulation design of QUAN + QUAL (simultaneous temporality and equivalent weighting) and a second stage with the complementarity design of QUAN + qual (simultaneous temporality and quantitative dominance). They conducted a socio-hydrological analysis of future droughts and their recurrence in the Limpopo basin of South Africa. Their objective was to predict future severe droughts in the catchment through scenarios to test the capacity of policies and people to manage or adapt to those events.

For the first stage, they developed a hydrological model (SHETRAN hydrological model) of the Nwanedi River system using physical variables to estimate the years subjected to historical drought. In parallel, they analyzed the perception of risk by conducting narrative interviews with small groups of 3 to 5 people. They discussed the level of awareness of populations to past droughts. This provided Rangecroft et al. [52] with a range of information on the experiences, impacts, and coping strategies that were developed by people. The authors constructed narratives surrounding the droughts that helped to strengthen the validity of modeling results of past droughts.

Table 3 shows the quality of the results obtained with this mixed approach between modeling and drought narratives.

Table 3. "The main drought events identified for the time period 1979–2013 by the hydrological model in the baseline run (top three rows) and the main drought events mentioned by community members in the first field season group narrative interviews" [52] (p. 246).

					Major Drought Events Identified			
Modeled baseline data	Meteorological drought	1980		1992	1994			2012
	Hydrological drought	1981–1983		1991–1992	1994–1995		2002–2003	
	Soil moisture drought	1981–1983		1991–1992	1994–1995		2002	
Narrative group interview data	Elderly men	1983						
	Elderly women	1983						
	Livestock farmers		1985					
	Smallholder farmers	1983						
	Married mothers			1992				
	Ex-miners	1983	1985			1999		
	Civic group			1992				
	Orchard farmers				1994–1995			
	Civic group				1994–1995			
	Young people			1992	1994–1995	1999		

The year 1983 was identified by various sources as the most severe year, providing a clear picture of the severity of this event. Incongruent results can be observed for the year 1985, identified as a dry year by participants but not through modeling. This could be due to participants who might have perceived the persistent effects of the 1983 drought, which carried on into 1985, as a new drought event. This seemingly small difference could, however, influence management policies and strategies, thus illustrating how mixed methods analysis can help to better understand the complexity of hydrological extremes and of their long-term effects.

In the second stage of the study, Rangecroft et al. [52] used the complementarity model to measure people's preparedness and adaptation to potential future droughts. To do so, they developed scenarios of future droughts based on the modification of quantitative information, such as temperature increase due to climate change or increase in land or water use, and qualitative information in the form of narratives on past droughts to complement and generate locally relevant and adapted scenarios. In this respect, other scenario building tools are presented by Mallampalli et al. [54] and Allain et al. [55].

The drought scenarios produced by the SHETRAN model were presented to the population during the second-stage workshops. The objective of these scenarios was to stimulate and increase awareness of the risks of future severe droughts among the populations, to increase their adaptative capacity by referring to the strategies developed in the past as well as to the lived experiences, and to increase their level of preparedness to this extreme. This objective has been achieved since the populations have set up a set of strategies and policies for management and adaptation to droughts (action research). This type of pragmatic study allows not only an understanding of the phenomenon but also the identification of mitigation and management solutions. This makes the system and the exposed populations more resilient. Table 4 summarizes the objectives for which authors in post-positivist hydrology have used mixed methods.

Table 4. Summary of the results of the content analysis in post-positivist hydrology.

Research Areas	Period of Publication	Paradigms	Main Authors	Motivation	Designs	Temporality and Weighting	Results
Participatory Hydrology	2008 to present	Post-Positivism	Canovas et al. [44]	Analyze extremes comprehensively (facts and values). Understanding the complexity of extreme phenomena (all factors of extreme are known and analyzed).	Triangulation	Simultaneous QUAN + qual	Deepen the knowledge of the extreme phenomenon. Untangle the uncertainties. Improve management and forecasting of extreme events.
Socio-Hydrology	2014 to present	Post-Positivism	Rangecroft et al. [52]	Understanding the complexity (conduct comprehensive and interdisciplinary analyses)	Triangulation Complementarity	Simultaneous QUAN + QUAL QUAN + qual	Deepen the knowledge of the extreme phenomenon. Untangle the uncertainties. Improve management and forecasting of extreme events.

Mixed methods approaches have made it possible to grasp the complexity of extreme phenomena and to involve the populations concerned in the production of knowledge and the management of extremes. This result would not have been the same with a purely quantitative approach. This possibility of analyzing people's perceptions and involving them in the management of crisis situations should be explored by researchers who want to understand conflicts related to water use, where exploratory design is used.

3.3. The Constructivist Paradigm in Hydrology: Addressing Water-Use Conflicts with an Exploratory Design

Research on hydrological extremes aims to understand the extremes, to propose adequate management solutions, and to improve adaptation to these extremes. This last objective of adaptation is difficult to achieve because of the conflicting situations related to the different uses of water, which annihilate the consensus on adaptation solutions. To understand and provide solutions to this conflict situation, hydrology researchers will have to adopt a constructivist paradigm and favor the use of mixed methods with an exploratory design.

In exploratory design, qualitative information on a conflicting situation is used to discover themes associated with the issue at hand. Then, these themes help produce quantitative data to rationalize the issue and propose appropriate solutions.

Studies of the management of conflicts related to water use and resource conservation studies are entirely social enterprises [56]. They are interested in exploring the different social perspectives (themes) that encompass the behaviours, attitudes, and practices of users that explain the emergence of conflicts. Such data can help to develop knowledge about the issue, to understand and better communicate it, and to find adequate solutions to it. For example, Levesque et al. [57], in an analysis of conflict management surrounding the conservation of the Lac Saint-Pierre floodplain in Canada, proposed a mixed approach (Q-method). This study constitutes a reference for future studies on the management of water-use conflicts. To do so, the authors conducted interviews with a vast array of stakeholders: elected officials, farmers, researchers, government employees, members of the Waban-Aki First Nation, members of conservation organizations, hunters, and fishermen [57]. The 58 respondents selected were asked to respond to 39 statements encompassed in 3 themes to capture and categorize the respondents' perceptions on the uses that should be favored in Lac Saint-Pierre's floodplain.

They used the exploratory design with the notation QUAL => quan, which is sequential with a dominance of qualitative approaches.

Levesque et al. [57] invited respondents to rank statements in order of importance according to their approval levels on a grid with scores that fit a normal distribution. The forced normal distribution facilitated the ranking process and encouraged respondents to think about where to place each of the statements in the response grid.

Levesque et al. [57] then asked the respondents to justify their choice, thus enriching the understanding of the different perceptions of the floodplain stakeholders. These coded and categorized data were integrated into statistical analysis software and interpreted through a principal component analysis and a centroid factor analysis. Another example of using this mixed approach with the Q-method is given by Lundberg et al. [58], who analyzed stream restoration in the Driftless area, USA.

This enabled identification of the drivers of conflict among respondents' perspectives, as well as the points of convergence and divergence between the different perspectives, leading to the differentiation of two overarching perspectives. The first one is the conservation perspective from respondents who favor nature preservation, and the other one is the agricultural perspective from respondents who favor agricultural production. The quantitative data obtained also allowed the authors to determine which social perspective on Lac Saint-Pierre is favored by respondents, namely, the conservation perspective adopted by 27% of respondents. Thus, the exploratory design, as used by the authors, was able to support discussions and negotiations, to help find compromises and improve stakeholders' adherence to a proposed solution. As such, it helped to consider differences in viewpoints to build consensus.

4. Discussion

4.1. The Benefits of Mixed Methods for Hydrology Research

As we have seen, the relevance of mixed methods for hydrological research has been increasingly recognized over the last decades. These methods have proven useful in a vast array of contexts for studies framed within diverse paradigms and research designs. Each research context described in this article is indeed uniquely framed to tackle a specific objective, yet all were able to benefit from a mixed methods approach (Figure 3). While we do not prescribe any "optimal" frame through which to tackle any specific objective in hydrological research, we argue, based on our observations and literature review, that most studies can frame their objective with an appropriate design that allows for the use of mixed methods and for their benefits to manifest.

The importance of mixed methods can be further understood when analyzing case studies. In positivist hydrology, notably in historical flood and low-flow studies, one of the major problems is the unavailability of a sufficient number of measurements or data to monitor the recurrence of extreme events. However, qualitative information is available through documentary sources and interviews carried out with stakeholders. Mixed methods can help transform these qualitative data into quantitative data to extend and densify time series data of extreme events, or to propose increasingly robust forecasts.

Nevertheless, extending time series to support more robust forecasts cannot provide a comprehensive understanding of the complexity of hydrological extremes. It is also unsuitable to inform adequate management or mitigation solutions. Such an endeavor is, however, achievable through the post-positivist paradigm in hydrology. As described above, this latter takes a pragmatic approach to explaining hydrological extremes, as well as their complexity and impact to guide management strategies. In socio-hydrology and participatory hydrology, finding management solutions for hydrological extremes requires considering all components that influence the extreme or are part of its complex dynamics, which are responsible for uncertain forecasts [59]. Hence, mixed methods are here again capable of providing analysis of all system components by integrating the physical and social aspects of extremes as well as their interactions (co-evolution between humans and water). The necessity to take the experience of populations exposed to extremes into account when attempting to understand complexity and improve the system management strategies is highlighted by these studies [60]. This action-research approach can hardly be realized without mixed methods.

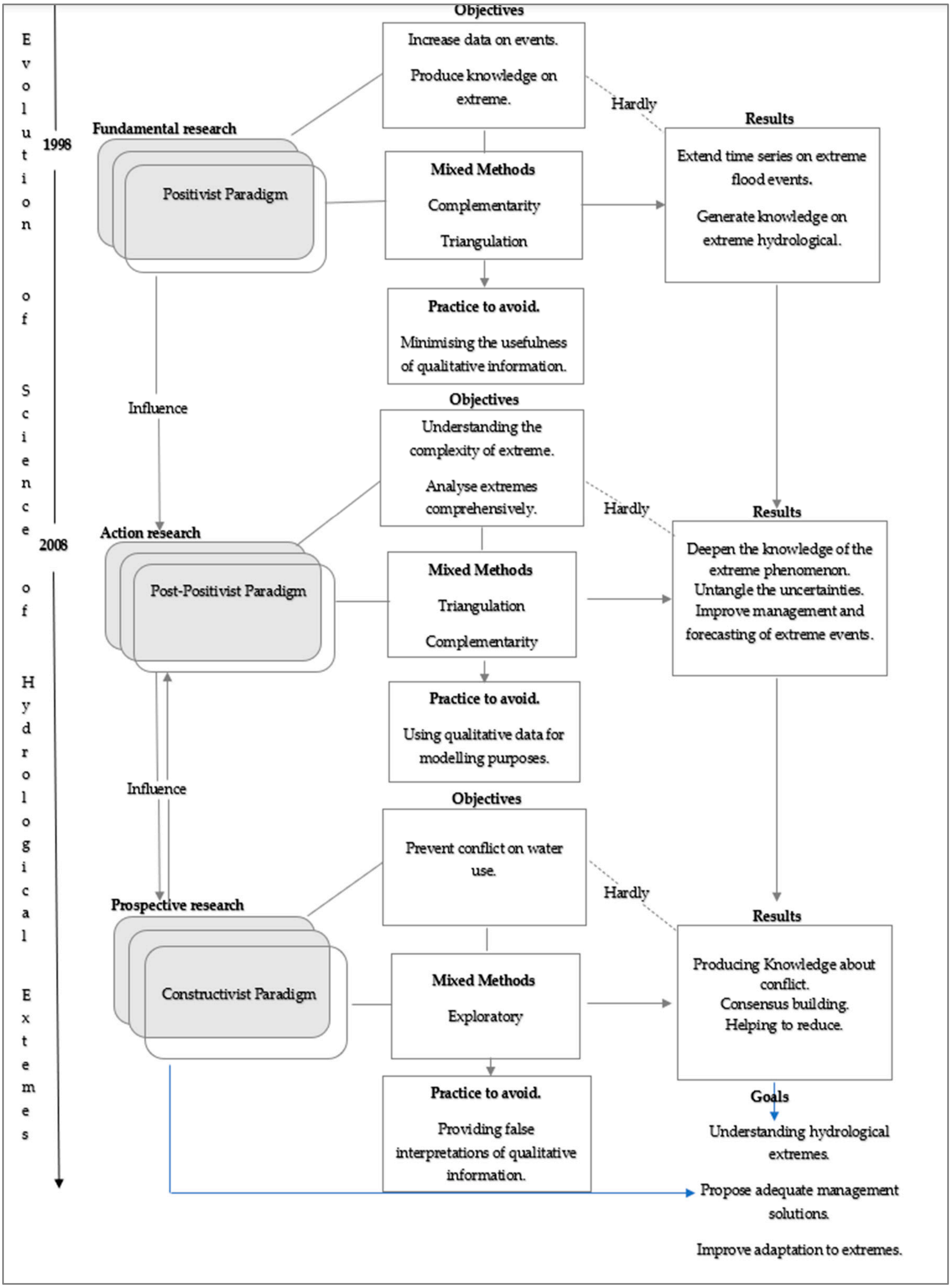

Figure 3. Summary of the benefits of using mixed methods in different research paradigms in hydrological extremes sciences.

Therefore, new studies in participatory hydrology and socio-hydrology will need to use mixed methods by offering two approaches (modeling and participatory) to reduce epistemic and ontological uncertainties about hydrological systems. Epistemic uncertainties are uncertainties due to the imperfection of our knowledge, and ontological uncertainties are uncertainties due to the inherent variability observed in complex systems, especially human and natural ones [60]. This can be done in the context of large-scale research projects involving hydrological and social scientists, such as the HydroPop Program studied by Canovas et al. [44], or the CreativeDrought project studied by Rangecroft et al. [52].

The use of mixed methods will be even more desirable in studies founded on constructivist hydrology and focusing on the management of conflicts related to water use. This is because these studies primarily analyze perceptions by providing measurable information to guide decision making, which is a pragmatic approach to solving hydrological problems. The future of studies on hydrological extremes is therefore linked to the use of mixed methods and their development when human societies and management strategies are involved.

This summary figure presents all the advantages that mixed methods bring to research on hydrological extremes, from their use for data densification purposes (positivist paradigm) to the prediction of future conflicts due to these extremes.

The advantages of using mixed methods are accompanied by practices to be avoided, as shown in Figure 3 above. In the positivist paradigm, researchers should avoid exploring qualitative information with the aim of extracting only quantitative data to fill in the event series. With this practice, researchers lose a body of quality information that is rich in evidence and insights into the impacts of extremes in human psychology.

In the post-positivist paradigm, the pressure felt by researchers to propose a model of extremes leads them to distort qualitative information to meet this requirement. This can have the opposite effect, i.e., to make the understanding of the extreme more complex. Qualitative information must therefore be analyzed with an adapted approach. For the constructivist paradigm, on the other hand, the uncontrolled transformation of perceptions into quantitative data can also distort the qualitative information and lead to misinterpretations of the collected qualitative information.

In addition to these practices that should be avoided, the use of mixed methods may have limitations.

4.2. Limitations

Despite the numerous contributions of mixed methods to the study of hydrological extremes, this approach has limitations. The main one is that these methods are time-consuming and resource-intensive [59]. The use of mixed methods requires researchers to devote considerable time to the implementation of the chosen methods to produce a complete, reliable, and rigorous study [61,62]. A second limitation is that mixed methods require researchers to have a wide range of skills for applying both qualitative and quantitative methods, as well as analyzing and interpreting both types of data [63]. The analysis may be biased if one of the approaches is poorly mastered. A solution to these two limitations is to integrate mixed methods studies into larger projects that bring together quantitative and qualitative researchers (e.g., HydroPop and CreativeDrought programs).

Finally, mixed methods studies can suffer from publication constraints in some journals where the rules for article presentation are restrictive and are generally related to the limited number of pages to describe the entire mixed methods research [17].

5. Conclusions and Perspectives

Interdisciplinary methods and tools are required to address the many and varied water-related challenges in the Anthropocene [64]. Mixed methods are a relevant representation of these interdisciplinary methods, as we have seen in the case studies presented above. Thanks to the different designs proposed, mixed methods can access relevant data that are harder to grasp through classical quantitative approaches in hydrology. The acquisition and analysis of these data allows the improvement in the forecasting capabilities of models regarding hydrological extremes such as floods and low-flow river regimes.

In addition to offering a practical solution to help study extremes in a more comprehensive manner, mixed methods address the epistemological concerns of the discipline of the hydrology of extremes. Indeed, the idea that humans participate in, explain, and manage hydrological extremes is fully accepted today. However, finding a methodology to integrate quantitative and qualitative aspects in a single study has always been difficult. This difficulty can be overcome, as we have pointed out in the case studies framed by post-positivist hydrology, by using mixed methods.

In perspective, it is also interesting to see that in recent studies using Big Data, mixed methods are also a preferred methodological option.

Pioneering studies on hydrological extremes have already used Big Data approaches to propose management plans [61,65,66]. They relied on the social network Twitter, which transmits flood information based on posts. These blocks of information are then indexed and coded with the exploratory design to produce statistics that are used in the analysis of reducing people's vulnerability to natural hazards (floods, typhoons, drought, etc.) and in the development of point solutions [65,66].

With the development of computational tools such as machine learning, combined with mixed methods, researchers will be able to explore complex hydrological issues in a holistic way by capturing all relevant information to understand these phenomena and provide management proposals. In addition, sentiment analysis, which is a technique used in natural language processing [67,68], combined with mixed methods, will be one of the research avenues to be pursued by future researchers in the hydrology of extremes.

Author Contributions: Conceptualization, R.K.; methodology, R.K. and J.F.B.; investigation, R.K., M.-A.B. and J.F.B.; resources, N.B.; writing—original draft preparation, R.K.; writing—review and editing, R.K., L.T., M.-A.B. and J.F.B.; supervision, M.-A.B. and N.B.; funding acquisition, M.-A.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Ministère des relations internationales et de la Francophonie grant number GQ132888.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: The corresponding author would like to thank Emmanuel Garnier for his pioneering ideas that led to the writing of this article. We also acknowledge support of CentrEau (Quebec Water Research Centre) and the CSBQ (Centre des Sciences de la Biodiversité du Québec). Special thanks to Marie-Hélène Vandersmissen.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. World Bank Group, T. *Technical Note on Hydrological Risk*; The World Bank Group: Washington, DC, USA, 2021. Available online: www.worldbank.org (accessed on 20 February 2023).
2. Sasseville, J.; De Marsily, G. The Water Sciences: Present and Future. *J. Water Sci.* **1998**, *11*, 223–241. [CrossRef]
3. Eakin, H.C.; Parajuli, J.; Hernandez Aguilar, B.; Yoga, Y. Attending to the social-political dimensions of urban flooding in decision-support research: A synthesis of contemporary empirical cases. *WIREs Climate Chang.* **2022**, *13*, e743. [CrossRef]
4. Aldebert, B.; Rouzies, A. What role for mixed methods in the French management research? *Manag. Int.* **2014**, *19*, 43–60. [CrossRef]
5. Creswell, J.W. Mixed method research: Introduction and application. In *Handbook of Educational Policy*; Cijek, T., Ed.; Academic Press: San Diego, CA, USA, 1999; pp. 455–472.
6. Greene, J. *Mixed Methods in Social Inquiry*; Jossey-Bass: San Francisco, CA, USA, 2007.
7. Tashakkori, A.; Teddlie, C. *Handbook of Mixed Methods in Social and Behavioral Research*; Sage: Thousand Oaks, CA, USA, 2003.
8. Hart, L.C.; Smith, S.Z.; Swars, S.L.; Smith, M.E. An examination of research methods in mathematics education (1995–2005). *J. Mix. Methods Res.* **2009**, *3*, 26–41. [CrossRef]
9. Merkouris, A.; Papathanassoglou, E.D.; Lemonidou, C. Evaluation of patient satisfaction with nursing care: Quantitative or qualitative approach? *Int. J. Nurs. Stud.* **2004**, *41*, 355–367. [CrossRef] [PubMed]

10. Ashley, P.; Boyd, B.W.E. Quantitative and qualitative approaches to research in environmental management. *Australas. J. Environ. Manag.* **2006**, *13*, 70–78. [CrossRef]
11. Molina-Azorín, J.F.; Lopez-Gamero, M.D. Mixed methods studies in environmental management research: Prevalence, purposes, and designs. *Bus. Strategy Environ.* **2016**, *25*, 134–148. [CrossRef]
12. Bryman, A. The research question in social research: What is its role? *Int. J. Soc. Res. Methodol.* **2007**, *10*, 5–20. [CrossRef]
13. Prévost, P.; Roy, M. *Qualitative Approaches in Management*; Presse de l'Université de Montréal: Montreal, QC, Canada, 2015.
14. Taylor, S.P. Critical realism vs social constructionism & social constructivism: Application to a social housing research study. *Int. J. Sci. Basic Appl. Res.* **2018**, *38*, 216–222. Available online: http://insight.cumbria.ac.uk/id/eprint/3596/ (accessed on 15 January 2023).
15. Yates, J.; Harris, L.M.; Wilson, N.J. Multiple ontologies of water: Politics, conflict, and implications for governance. *Environ. Plan. D Soc. Space* **2017**, *35*, 797–815. [CrossRef]
16. Johnson, R.B.; Onwuegbuze, A.J.; Turner, L.A. Toward a definition of mixed methods research. *J. Mix. Methods Res.* **2007**, *1*, 112–133. [CrossRef]
17. Creswell, J.; Plano-Clark, V. *Designing and Conducting Mixed Methods Research*; Sage: Thousand Oaks, CA, USA, 2007.
18. Hammond, C. The wider benefits of adult learning: An illustration of the advantages of multi-method research. *Int. J. Soc. Res. Methodol.* **2005**, *8*, 239–255. [CrossRef]
19. Teddlie, C.; Tashakkori, A. *Foundations of Mixed Methods Research. Integrating Quantitative and Qualitative Approachesin the Social and Behavioral Sciences*; Sage: Thousand Oaks, CA, USA, 2009.
20. Larue, C.; Loiselle, C.G.; Bonin, J.P.; Cohen, R.; Gélinas, C.; Dubois, S.; Lambert, S. Mixed methods promising strategies for the evaluation of nursing interventions. *Nurs. Res.* **2009**, *97*, 50–62. [CrossRef]
21. Creswell, J.W.; Plano-Clark, V.L.; Gutmann, M.; Hanson, W. Advanced mixed methods research designs. In *Handbook of Mixed Methods in Social and Behavioral Research*; Tashakkori, A., Teddlie, C., Eds.; Sage: Thousand Oaks, CA, USA, 2003; pp. 209–240.
22. Morse, J.M. Approaches to qualitative-quantitative methodological triangulation. *Nurs. Res.* **1991**, *40*, 120–123. [CrossRef] [PubMed]
23. Brázdil, R.; Kundzewicz, W.Z.; Benito, G. Historical hydrology for studying flood risk in Europe. *Hydrol. Sci. J.* **2006**, *51*, 739–746. [CrossRef]
24. Brázdil, R.; Demarée, R.G.; Deutsch, M.; Garnier, E.; Kiss, A.; Luterbacher, J.; Macdonald, N.; Rohr, C.; Dubrovolny, P.; Kolar, P.; et al. European floods during the winter 1783/1784; scenarios of an extreme event during the "little Ice Age". *Theor. Appl. Climatol.* **2010**, *100*, 163–189. [CrossRef]
25. Barriendos, M.; Llasat, M.C.; Barrera, A.; Rigo, T. The study of flood events from documentary sources: Methodological guidelines for historical source identification and flood characterization in the Iberian Peninsula. In *Palaeofloods, Historical Floods and Climatic Variability: Applications in Flood Risk Assessment, Proceedings of the PHEFRA Workshop*; Thorndycraft, V.R., Benito, G., Barriendos, M., Llasat, M.C., Eds.; CSIC: Barcelona, Spain, 2003; Volume 16, pp. 87–92.
26. Bousquet, N.; Bernardara, P. *Extreme Natural Events: Statistical Theory and Risk Mitigation*; Lavosier: Paris, France, 2018.
27. Brázdil, R.; Kundzewicz, Z.W.; Benito, G.; Demarée, G.; Macdonald, N.; Roald, L.A. Historical floods in Europe in the past millennium. In *Changes in Flood Risk in Europe, IAHS Special Publication*; Kundzewicz, Z.W., Ed.; IAHS Press: Wallingford, UK, 2012; Volume 10, pp. 121–166.
28. Elleder, L. Reconstruction of the 1784 flood hydrograph for the Vltava River Prague, Czech Republic. *Glob. Planet. Chang.* **2010**, *70*, 117–124. [CrossRef]
29. Pötzsch, C.G. *Chronologische Geschichte der grossenWasserfluthen des Elbstroms*; Walther: Dresden, Germany, 1784; p. 232.
30. Pan, J. *Frantisek Martin Pelcl. Pameti. Nakladatelstvi F.*; Borovy: Prague, Czech Republic, 1931; p. 103.
31. Barriendos, M.; Coeur, D. Flood data reconstruction in historical times from non-instrumental sources in Spain and France. In *Systematic, Paleoflood and Historical Data for the Improvement of Flood Risk Estimation. Methodological Guidelines*; Benito, G., Thorndycraft, V.R., Eds.; Centro de Ciencias Medioambientales: Madrid, Spain, 2004.
32. Cœur, D.; Lang, M.; Paquier, A. Flood knowledge: History, hydraulics, and hydrology. *Houille Blanche* **2002**, *88*, 96–102. [CrossRef]
33. Elleder, L. Historical changes in frequency of extreme floods in Prague. *Hydrol. Earth Syst. Sci.* **2015**, *19*, 4307–4315. [CrossRef]
34. Lang, M.; Fernandez Bono, J.F.; Recking, A.; Naulet, R.; Grau Gimeno, P. Methodological guide for paleoflood and historical peak discharge estimation. In *Systematic, Palaeoflood and Historical Data for the Improvement of Flood Risk Estimation*; Benito, G., Thorndycraf, V.R., Eds.; CSIC: Madrid, Spain, 2004; pp. 43–53.
35. Barriendos, M.; Ruiz-Bellet, J.L.; Tuset, J.; Mazón, J.; Balasch, J.C.; Pino, D.; Ayala, J.L. The "Prediflood" database of historical floods in Catalonia (NE Iberian Peninsula) AD 1035–2013, and its potential applications in flood analysis. *Hydrol. Earth Syst. Sci.* **2014**, *18*, 4807–4823. [CrossRef]
36. Naulet, R.; Lang, M.; Ouarda, T.B.M.J.; Coeur, D.; Bobée, B.; Recking, A.; Moussay, D. Flood frequency analysis on the Ardèche river using French documentary sources from the last two centuries. *J. Hydrol.* **2005**, *313*, 58–78. [CrossRef]
37. Macdonald, N.; Black, A.R. Reassessment of flood frequency using historical information for the River Ouse at York, UK (1200–2000). *Hydrol. Sci. J.* **2010**, *55*, 1152–1162. [CrossRef]
38. Engeland, K.; Wilson, D.; Borsanyi, P.; Roald, L.; Holmqvist, E. Use of historical data in flood frequency analysis: A case study for four catchments in Norway. *Hydrol. Res.* **2018**, *49*, 466–486. [CrossRef]
39. Joly, F. The wild waters of arid lands: Basic knowledge on the hydrology of deserts. *Géomorphology* **2006**, *12*, 285–298. [CrossRef]

40. Barreteau, O.; Ferroudji, A.R.; Garin, P. Tools and methods to support river basin management. *Houille Blanche* **2008**, *6*, 48–55. [CrossRef]
41. Stubbington, R.; Acreman, M.; Acuña, V.; Boon, P.J.; Boulton, A.J.; England, J.; Gilvear, D.; Sykes, T.; Wood, P.J. Ecosystem services of temporary streams differ between wet and dry phases in regions with contrasting climates and economies. *Br. Ecol. Soc.* **2020**, *2*, 660–677. [CrossRef]
42. Gallart, F.; Prat, N.; Garcia-Roger, E.M.; Latron, J.; Rieradevall, M.; Llorens, P.; Barbera, G.G.; Brito, D.; De Giralmo, A.M.; Lo Porto, A.; et al. A novel approach to analysing the regimes of temporary streams in relation to their controls on the composition and structure of aquatic biota. *Hydrol. Earth Syst. Sci.* **2012**, *16*, 3165–3182. [CrossRef]
43. Gallart, F.; Llorens, P.; Latron, J.; Cid, N.; Rieradevall, M.; Prat, N. Validating alternative methodologies to estimate the regime of temporary rivers when flow data are unavailable. *Sci. Total Environ.* **2016**, *565*, 1001–1010. [CrossRef]
44. Canovas, I.; Martin, P.; Sauvagnargues, S. Heuristic modelling of low water periods criticality in the Mediterranean region. *Physio-Géo* **2016**, *10*, 191–210. [CrossRef]
45. Martin, P.; Douguedroit, A.; Cicille, P.; Sauvagnargues, S. *Popular and Participatory Hydrology?* UAPV: Avignon, France, 2019.
46. Magombeyi, M.S.; Rollin, D.; Lankford, B. The river basin game as a tool for collective water management at community level in South Africa. *Phys. Chem. Earth* **2008**, *33*, 873–880. [CrossRef]
47. Hill, H.; Hadarits, M.; Rieger, R.; Strickert, G.; Davies, E.G.R.; Strobbe, K.M. The Invitational Drought Tournament: What is it and why is it a useful tool for drought preparedness and adaptation? *Weather Clim. Extrem.* **2014**, *3*, 107–116. [CrossRef]
48. Di Baldassarre, G.; Viglione, A.; Carr, G.; Kuil, L.; Yan, K.; Brandimarte, L.; Bloschl, G. Debates perspectives on socio-hydrology: Capturing feedbacks between physical and social processes. *Water Resour. Res.* **2015**, *51*, 4770–4781. [CrossRef]
49. Yu, D.J.; Sangwan, N.; Sung, K.; Chen, X.; Merwade, V. Incorporating institutions and collective action into a socio-hydrological model of flood resilience. *Water Resour. Res.* **2017**, *53*, 1336–1353. [CrossRef]
50. Van Emmerik, T.H.M.; Li, Z.; Sivapalan, M.; Pande, S.; Kandasamy, J.; Savenije, H.H.G.; Chanan, A.; Vigneswaran, S. Socio-hydrologic modeling to understand and mediate the competition for water between agriculture development and environmental health: Murrumbidgee River basin, Australia. *Hydrol. Earth Syst. Sci.* **2014**, *18*, 4239–4259. [CrossRef]
51. Mazzoleni, M.; Odongo, V.O.; Mondino, E.; Di Baldassarre, G. Water management, hydrological extremes, and society: Modeling interactions and phenomena. *Ecol. Soc.* **2021**, *26*, 4. [CrossRef]
52. Rangecroft, S.; Birkinshaw, S.; Rohse, M.; Day, R.; McEwen, L.; Makaya, E.; Van Loon, A. Hydrological modelling as a tool for interdisciplinary workshops on future drought. *Prog. Phys. Geogr. Earth Environ.* **2018**, *42*, 237–256. [CrossRef]
53. Evers, M.; Höllermann, B.; Almoradie, A.D.S.; Garcia Santos, G.; Taft, L. The pluralistic water research concept: A new human-water system research approach. *Water* **2017**, *9*, 933. [CrossRef]
54. Mallampalli, V.R.; Mavrommati, G.; Thompson, J.; Duveneck, M.; Meyer, S.; Ligmann-Zielinska, A.; Druschke, C.G.; Hychka, K.; Kenney, M.A.; Kok, K.; et al. Methods for translating narrative scenarios into quantitative assessments of land use change. *Environ. Model. Softw.* **2016**, *82*, 7–20. [CrossRef]
55. Allain, S.; Plumecocq, G.; Leenhardt, D. Linking deliberative evaluation with integrated assessment and modelling: A methodological framework and its application to agricultural water management. *Futures* **2020**, *120*, 102566. [CrossRef]
56. Zabala, A.; Sandbrook, C.; Mukherjee, N. When and how to use Q methodology to understand perspectives in conservation research. *Conserv. Biol.* **2018**, *32*, 1185–1194. [CrossRef] [PubMed]
57. Lévesque, A.; Dupras, J.; Bissonnette, J.F. The pitchfork or the fishhook: A multi-stakeholder perspective towards intensive farming in floodplains. *J. Environ. Plan. Manag.* **2020**, *63*, 1987–2003. [CrossRef]
58. Lundberg, E.; Gottschalk-Druschke, C.; Booth, E.G. A Q-method survey of stream restoration practitioners in the Driftless Area, USA. *River Res. Appl.* **2022**, *38*, 1090–1100. [CrossRef]
59. Höllermann, B.; Rangecroft, S.; Rohse, M.; Banks, E.W.; Day, R.; Di Baldassarre, G.; Frommen, T.; Hayashi, Y.; Lebek, K.; Mondino, E.; et al. Go together, to go further! Reply to "Human–water research: Discussion of 'Guiding principles for hydrologists conducting interdisciplinary research and fieldwork with participants". *Hydrol. Sci. J.* **2022**, *67*, 2211–2213. [CrossRef]
60. Coutellec, L. *Science in the Plural: Essay in Epistemology for Involved Sciences*; Editions Quæ: Versailles, France, 2015.
61. Koudelova, P.; Kawasaki, A.; Koike, T.; Shibuo, Y.; Kamoto, M.; Tokunaga, Y. Design, and Implementation of a Training Course on Big Data Use in Water Management. *Data Sci. J.* **2017**, *46*, 46. [CrossRef]
62. Beal, C.D.; Stewart, R.A.; Fielding, K. A novel mixed method smart metering approach to reconciling differences between perceived and actual residential end use water consumption. *J. Clean. Prod.* **2013**, *60*, 116–128. [CrossRef]
63. Martin, V.Y. Four Common Problems in Environmental Social Research Undertaken by Natural Scientists. *BioScience* **2019**, *70*, 13–16. [CrossRef]
64. Sivapalan, M.; Konar, M.; Srinivasan, V.; Chhatre, A.; Wutich, A.; Scott, C.A.; Wescoat, J.L.; Rodríguez-Iturbe, I. Socio-hydrology: Use-inspired water sustainability science for the Anthropocene. *Earth's Future* **2014**, *2*, 225–230. [CrossRef]
65. Fohringer, J.; Dransch, D.; Kreibich, H.; Schröter, K. Social media as an information source for rapid flood inundation mapping. *Nat. Hazards Earht Syst. Sci.* **2015**, *15*, 2725–2738. [CrossRef]
66. Antwi, S.H.; Rolston, A.; Linnane, S.; Getty, D. Communicating water availability to improve awareness and implementation of water conservation: A study of the 2018 and 2020 drought events in the Republic of Ireland. *Sci. Total Environ.* **2022**, *807*, 150865. [CrossRef] [PubMed]

67. Harfoushi, O.; Hasan, D.; Obiedat, R. Sentiment analysis algorithms through Azure Machine Learning analysis and comparison. *Mod. Appl. Sci.* **2018**, *12*, 49–58. [CrossRef]
68. Haselmayer, M.; Jenny, M. Sentiment analysis of political communication: Combining a dictionary approach with crowdcoding. *Qual. Quant.* **2017**, *51*, 2623–2646. [CrossRef] [PubMed]