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Socio-hydrology: Spatial and Temporal Dynamics of Coupled Human-Water Systems

Inspiring a Broader Socio-Hydrological Negotiation Approach With Interdisciplinary Field-Based Experience

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Key Points:
- In socio-hydrology, modeling frameworks for coupled human-water systems are currently designed by hydrologists
- These frameworks have axiological and epistemological limitations to integrating social dynamics
- A negotiation approach enables to apprehend the mutual shaping of the relations between water and society

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Abstract Socio-hydrology advanced the field of hydrology by considering humans and their activities as part of the water cycle, rather than as external drivers. Models are used to infer reproducible trends in human interactions with water resources. However, defining and handling water problems in this way may restrict the scope of such modeling approaches. We propose an interdisciplinary socio-hydrological approach to overcome this limit and complement modeling approaches. It starts from concrete field-based situations, combines disciplinary as well as local knowledge on water-society relationships, with the aim of broadening the hydrocentric analysis and modeling of water systems. The paper argues that an analysis of social dynamics linked to water is highly complementary to traditional hydrological tools but requires a negotiated and contextualized interdisciplinary approach to the representation and analysis of socio-hydro systems. This reflection emerged from experience gained in the field where a water-budget modeling framework failed to adequately incorporate the multiplicity of (nonhydrological) factors that determine the volumes of withdrawals for irrigation. The pathway subsequently explored was to move away from the hydrologic view of the phenomena and, in collaboration with social scientists, to produce a shared conceptualization of a coupled human-water system through a negotiated approach. This approach changed the way hydrological research issues were addressed and limited the number of strong assumptions needed for simplification in modeling. The proposed socio-hydrological approach led to a deeper understanding of the mechanisms behind local water-related problems and to debates on the interactions between social and political decisions and the dynamics of these problems.

Plain Language Summary This paper provides a collective reflection on the ways to articulate an understanding of social dynamics within hydrological approaches, based on interdisciplinary experience gained in the field in North Africa. Fundamentally, the socio-hydrological approach proposed here enabled a better understanding of the mechanisms behind human-water dynamics and hence of the impacts of social and political decisions on future changes. The major shift in this interdisciplinary approach is that it provides evidence that things do not simply interact in a positive or negative way, but also combine and shape together. So we need to look for pragmatic ways to link the analysis of social dynamics with the understanding of the hydrological processes. This requires hydrology to open up further to different approaches and methods used in other scientific disciplines, especially human sciences. This could lead to a radically innovative way of conceiving and representing coupled human-water systems.

1. Introduction

The need to consider human interactions in hydrological studies has long been recognized (e.g., Falkenmark, 1977, 1979), but remained relatively discrete in the academic literature until less than a decade ago. A seminal paper on socio-hydrology written by Sivapalan et al. (2012) and endorsed by the declaration for the 2013–2022 IAHS Panta Rhei scientific decade (Montanari et al., 2013) proposed to improve the "capability to make predictions of water resources dynamics to support sustainable societal development in a changing environment." Various water-related issues were then addressed by socio-hydrological studies, from flooding to collapse of civilizations, predominantly using modeling approaches (Mostert, 2018). In 2016, Blair and Buytaert published a review of "socio-hydrology as a discipline" and discussed the "reasons for modeling."

This line of thought, which originated from hydrology, intersects other lines of thought in the fields of natural resources management and social-ecological systems (e.g., Folke et al., 2005; Nelson et al., 2010; Ostrom, 1990). Many epistemic communities have developed their own frame of reference for the analysis of natural resources management, for example, in the fields of common pool resources management (Ostrom, 1990, 2005), complex adaptive systems (Miller & Page, 2009), resilience of social and ecological systems (Folke, 2006; McGinnis & Ostrom, 2014; Walker et al., 2002), or for the hydrosocial cycle by critical geographers and political ecologists (Linton & Budds, 2014; Swyngedouw, 2009). But the percolation of ideas between these communities remains limited in the literature and dialog is difficult (Wesselink et al., 2016). The need for interdisciplinary collaboration between natural and social sciences is frequently pointed out but there is obviously a gap between discourse and implementation (for science in general see Nature, 2015; for groundwater research see Barthel & Seidl, 2017). By remaining largely anchored in their community of origin (i.e., hydrology) the approaches advocated by the socio-hydrology community therefore run the risk of unwittingly producing skewed representations of water-society interactions.

In this paper, our aim is to suggest ways to enrich this literature by building on the above mentioned fields and on our experience with local-scale interdisciplinary studies of the relations between water and society, mainly in water scarce areas. Sivapalan et al. (2012) proposed a theoretical framework and an approach to incorporate social aspects in hydrological dynamics as part of the new field of socio-hydrology. Human beings should be treated "as endogenous to the system, not as mere boundary conditions" (Sivapalan & Bloschl, 2015). However, this objective can be implemented in different ways. Mobilizing alternative approaches is a way to (1) contribute to the reflection about "the issue of rational behavior" in socio-hydrology (Sivapalan & Bloschl, 2015), (2) alter the predominance of economics and environmental sciences in defining what is "optimal," or (3) view IWRM (integrated water resources management) as a political construct rather than as the standard way to handle water issues (Molle, 2008; Trottier, 2008).

This paper draws attention to the benefits of building on several epistemic communities to explore the coevolution of water and society with the aim of understanding, conducting foresight exercises, and supporting dialog and negotiation between actors. This reflection stems from the difficulties we experienced in accounting for the dimensions described by terms such as "human," "social," "behavioral," "anthropic," "societal" using the current conceptual tools of socio-hydrology. It is the result of interdisciplinary debates and experience gained in the field in North Africa in two research projects dedicated to the study of the coevolution of water and society in rural and peri-urban areas. The paper starts with a critical analysis of current thinking in socio-hydrological approaches and then illustrates the challenges and limits of integrating social dynamics in socio-hydrological modeling frameworks, based on a Tunisian case study. Next, the need to associate the analysis of social dynamics with hydrological modeling using a "negotiated" interdisciplinary approach is justified based on two other case studies in Tunisia. The paper concludes by underlining the advantages of studying social dynamics and water dynamics simultaneously through a field-based approach founded on interdisciplinary dialog between social and hydrological scientists.

2. Social Components Versus Social Dynamics: The Limit to Socio-Hydrological Approaches?

The self-assigned objective of socio-hydrology is "understanding the dynamics and coevolution of coupled human-water systems" (Sivapalan et al., 2012). The most frequent approach proposed in the literature is based on modeling frameworks in which variables depicting "human behavior" interact with hydrological variables (see reviews in Blair and Buytaert, 2016 and Troy et al., 2015a, 2015b). Loucks (2015) suggests that two such modeling approaches are able to meet this objective. The first includes a "social component" in the hydrological model, in the expectation that emergent or future social behaviors will be identified and characterized. In that case, the "social component" is represented by a set of variables and relations among them, together with hydrological variables that can be translated into equations. This social component is assumed to be significantly representative of human behaviors and social dynamics. The second approach does not associate social and hydrological components in the same model but creates an interface between hydrological simulations and the stakeholders who test the effects of their decisions on hydrologic dynamics (e.g., water-use scenarios, infrastructure development, management strategies).

Socio-hydrology recently enhanced its capacity to model complex socio-hydrological systems (e.g., Di Baldassarre et al., 2013; Elshafei et al., 2014, 2016; Liu et al., 2015; Srinivasan, 2015; van Emmerik et al., 2014). However, the models developed are restricted to the description of a few specific drivers of behaviors and of decision making. For example, Srinivasan et al. (2012) identified four dominant water patterns among 22 cases affected by a water crisis: changes in demand, supply, systems of governance, and infrastructure/technology. Furthermore, in these models what is termed “human behavior” is, in practice, reduced to a few alternative choices. In the study of the Kissimmee River basin by Chen et al. (2016), for example, the represented “society” only distinguishes between “upstream” and “downstream” groups whose social descriptors are limited to a different “community sensitivity” to floods and wetlands. While physical sciences found a way to cope with uncertainties by using modeling approaches, the question of dealing with the great complexity of “social dynamics” in social and policy domains remains a vexing issue (Westerberg et al., 2017).

The difficulty involved in accounting for social components in socio-hydrology can also be attributed to a holistic and mechanistic bias inherited from hydrology and more generally from a positivist view of science (see e.g., Molle & Valette, 1994; Wesselink et al., 2016). A large part of social sciences, including those involved in the current study (social anthropology, qualitative sociology, and political ecology), have abandoned Durkheim’s (1964) goal “to extend scientific rationalism to human conduct,” especially under the influence of Max Weber, for whom cultural acts cannot be reduced to a mere set of laws (Galey & Lenclud, 1991). With the nearly total abandonment of holistic objectives in the course of the 20th century, social sciences have focused on understanding the links between the various “social” entities and their evolution, in other words “social dynamics.” If one looks at the four dominant patterns proposed by Srinivasan et al. (2012), understanding coupled human-water systems would be enhanced by investigating the way these four elements interact, the way they have been combined throughout history to give rise to specific situations, each of the four elements with its own “dynamics.” Explaining dynamics is more challenging than representing a static situation because of the need to account for the interdependence between the determinants of selected processes. Accordingly, modeling attempts often consist in translating causal hypotheses into equations with retroaction loops that only lead to reproducing the very same logic used in the hypotheses (e.g., Di Baldassarre et al., 2013; Pande et al., 2014). The added value of such models is to produce patterns at an integrated level that could not be computed without these models. They can then be used either to interpret the discrepancy between observations at this level and what the model suggests, or to predict the evolution of the system.

In this paper, we argue that the representation of the “human factor” or the “social component” in understanding hydrological dynamics should be inspired by research into the links between the elements of the system and its history. This means treating the understanding of social dynamics as comprehensively as the way hydrological dynamics are generally studied and represented. In the socio-hydrology literature, the concept of “dynamics” proposed by hydrologists is very different from that proposed by social scientists. For hydrologists, social dynamics are to be considered in the same way as the resource, i.e., quantifiable and suitable for mathematical representation (e.g., Di Baldassarre et al., 2015). This avoids the fundamental epistemological debate that distinguishes social sciences from physical sciences (see Wesselink et al., 2016 with respect to socio-hydrology, and e.g., Stengers, 2002 or Oreskes, 2015 for a wider view of the epistemological gap between social and physical sciences). In addition to differences in terms of content, methods and objectives, physical and social scientists look at the same phenomenon but not from the same angle. This results in misunderstandings, especially regarding key epistemologically laden concepts in social sciences, such as “dynamics” or “change” that are linked to very different schools of thought and theoretical foundations. We argue that this can only be overcome by making these differences explicit for a given case and open to debate and negotiation.

3. Challenges and Limits of Integrating Social Dynamics in Hydrocentric Models: A Practical Example

The Wadi Merguellil watershed and the downstream Kairouan Plain have been the focus of more than 25 years of hydrological scientific research (e.g., Leduc et al., 2007). The watershed is one of the three large river basins in central Tunisia whose headwaters originate from the Tunisian Dorsal mountains. Average annual rainfall ranges from 300 to 500 mm between downstream and upstream parts of the 1,200 km^2

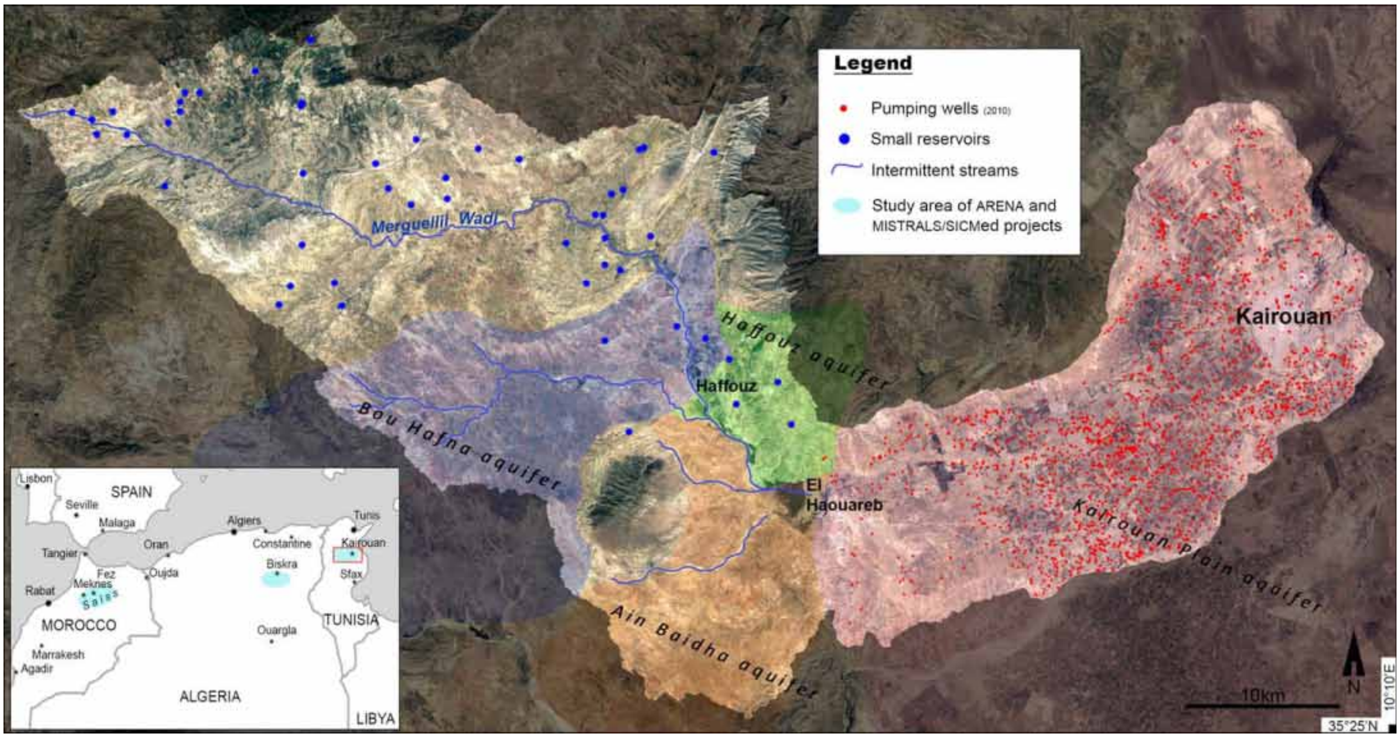

Figure 1. Overview of the study sites and detailed features related to the Tunisian case study (red border inset).

upper catchment. In this semiarid climate, wadi flows are intermittent and floods last a few hours or, in exceptional cases, a few days. The region is nevertheless endowed with the water resources in the form of four main aquifers (Figure 1). Used for drinking water in the early 20th century, the water table has been increasingly exploited for agriculture and impacted by the construction of small and large dams and irrigation systems. Groundwater resources are declining, as evidenced by the drop of about 30 m in piezometric levels over the last 30–40 years (Leduc et al., 2007). Hydrological modeling was conducted at the subbasin level, including the characteristics and dynamics of water use as changes in irrigated areas, water needs and withdrawals (Lacombe et al., 2008). Subsequent studies included agro-economists, and the “social changes” were extended to changes in farming systems, irrigation technologies, and to quantifiable variables such as the cost of inputs and crop yields (Le Goulven et al., 2009). Despite the progress in research, major elements related to the history of water were still lacking to understand changes in the water resource and its physical and sociopolitical repercussions. These approaches actually failed to represent water interactions with society, for instance, the reactions of the different social groups to the decline in the water tables. Similarly, the January 2011 “revolution” not only upset the patterns of groundwater access and uses, but also more generally the role and power of the different stakeholders, for example, the weakening of state authority. In the rapidly changing Tunisian socio-political and hydrological dynamics, the need to account for “anthropogenic factors” became increasingly clear.

Reflexive interdisciplinary research in this watershed by hydrologists and anthropologists (Riaux & Massuel, 2014) revealed the extremely varied perceptions of what the concept of “society” implied for researchers from each discipline, and that none of the approaches implemented (hydrological and agro-economical) addressed the nature and importance of sociopolitical links around water, for example, the difficulties faced by water user associations and the individualization of water access strategies, the relationship between the public administration and the water users, the changes in the land markets or forms of sharecropping, the possible drop in remittances from abroad, or the shift in customary rules governing the inheritance of land. The possible consequences of these socio-political aspects in terms of water access, decision making for drilling a borehole, management and use of wells, or changes in water use were not understood because they remained invisible.

The desire for a mechanistic representation of the coupled human-water systems into which the "human factor" can be directly incorporated in mathematical representations of hydrological dynamics is subject to debate. Socio-hydrological, nonstochastic models generally seek to represent the development of systems causally and deterministically: the future of a system is only determined by past or present phenomena, and "initial conditions" defined in the "present" correspond to a single possible "future" state at each subsequent time step. In the Kairouan Plain—and the same observation was made in the Saïss Region in Morocco (Figure 1)—qualitative investigations showed that some irrigators apply the "use up the aquifer before your neighbor does" strategy, while others have a more patrimonial attitude to natural resources, for example, limiting their dependence on groundwater for farming (see Ameur et al., 2017). Projecting their behavior into a future where the aquifer will have been depleted changes their actions in different ways, illustrating how human dynamics can be influenced by hypothetical hydrologic changes. Here a retroaction loop cannot fully represent the situation because the action can occur with or without the condition of a drop in groundwater. The depletion of groundwater reserves observed and predicted by the experts is therefore both a cause and a consequence of the behavior of certain irrigators (Massuel & Riaux, 2017).

According to Oreskes (2015) "One [epistemic] implication involves the predictability of human behavior. It is not news that humans are unpredictable, yet many models in the natural sciences implicitly assume consistency in human behavior." Loucks (2015) also recognized that "There are no laws of social behavior as there are for the physics, chemistry, and biology of water and ecology. Data on past human social behavior are no indicators of future behavior." However, this does not mean that the logic of practices—or even of certain trends—is erratic, it simply means that not all the determinants are known and that they combine in ways that are largely unpredictable. With respect to the Tunisian revolution, there was a longstanding awareness of the growing pauperization in the country (Sethom, 1992), and it was also long known that the state was dysfunctional and oppressive (e.g., Hibou, 2006), but why did all this come to a head at a specific location in January 2011 (Fautras, 2015)? If this event was unpredictable, its later effects on water and water uses were to an even greater extent, including the loss of state legitimacy to regulate groundwater use.

The axiological issue (i.e., the value-dependent questions of "why gather knowledge/what should we do with it") concerning the implications of an approximate representation of the social dimension of a hydrosystem also applies to the Kairouan plain, because a representation was created without associating other disciplines. Let us consider, for example, the integration of hydroagricultural practices in a modeling framework based on the volumes of water applied to a given area. Determining such volumes is a challenge in itself and requires accounting for local farming systems and irrigation practices (Massuel et al., 2017). Faced with difficult quantification based on field measurements and field observations (the practices of irrigators are extremely variable), hydrologists often use theoretical values (e.g., FAO-56) to calculate irrigation volumes on the basis of optimal practices from a technical point of view. The underlying assumption is that the irrigators adopt practices whose rationality is based on agronomic or economic criteria. Yet irrigators' practices are also driven by social or socio-technical logics based on value systems, knowledge, and beliefs (Leeuwis, 2004; see Benouniche et al., 2014 for an application to irrigation practices in North Africa). A practice considered to be optimal in a given socio-environmental context would not be optimal for another farmer in another location or at another time. For example, in the Doukkala region (Morocco), even after they had switched to drip irrigation, farmers who were used to gravity-fed irrigation continued to apply water on a daily basis until ponding water became visible around the tree, replicating their age-old experience with surface irrigation (Food and Agriculture Organization, 2012). In the Saïss Plain (Morocco), farmers using drip irrigation achieved plot-level irrigation efficiencies ranging from 25% to 90%, as they wanted to irrigate their high-value crops abundantly (Benouniche et al., 2014). These measured values differ drastically from the theoretical ones used in models. Likewise, the values of "honor" and "prestige hierarchies," pervasive in North African cultures, clearly shape the practices of local farmers (van der Kooij et al., 2017). In the Kairouan Plain, field investigations revealed that numerous wells equipped with pumps that were not used were in reality nothing but markers of social prestige. A model taking the sum of a pump's capacity as a parameter to characterize flow abstracted from the aquifer would thus be skewed. Young men who "had succeeded in life" gifted wells to their fathers, allowing them to both gain power within the family and helping the family to feature in the local prestige hierarchies. For farmers, access to groundwater through one's own well may represent an element of emancipation from an agriculture considered to be backward and "oppress[ing] dignity and self-esteem" (Quarouch et al., 2014). The technical and financial logics involved here are thus embedded in cultural and social values. They cannot be applied in a system in which honor is not measured by material possessions (the role of technical or financial logic would be different), nor even applied more generally in the study area. The fact that such cultural and social values are site specific and hard to quantify is at loggerheads with the idea of producing universal and generalizable knowledge. Unraveling these specific forms of relations through an inductive approach and taking them into account is key to understanding the evolution of the system. The only generalization that can be made is the need to understand such local cultural traits. An ex ante choice to focus on technical or economic rationalities that are both calculable and transposable would amount to a complete distortion of reality.

It is a major scientific challenge to account for human interactions with water systems, but we argue that the way this is done also matters. Alternatives to modeling social dynamics—doomed to be a long and painstaking task—exist for specific case studies (see also Mostert, 2018). But this implies accepting that it will be necessary to leave part of the analysis outside the modeling platform.

4. Interlinking the Analysis of Social Dynamics and Hydrological Modeling Through Interdisciplinary Field Surveys

Between infinite complexity on the one hand and extreme simplification on the other, there is an intermediate area in which it is possible to produce models that are both sufficiently simple and robust to represent reality with a degree of reliability and scientifically and/or operationally "useful." We argue that in the case of coupled human-water systems, this assumption is a matter of defining a representational strategy that confronts head-on knowledge related to social and physical components, and of simultaneously designing an interdisciplinary research approach that makes it possible to identify and include important "social" factors in relation to the chosen objectives. A so-called "socio-hydrological approach" was proposed by Riaux (2013) and subsequently elaborated by Riaux and Massuel (2014) and Riaux et al. (2016).

Experience representing a socio-hydrological system in the Kairouan Plain aquifer illustrates the difficulties of such an exercise. Producing models for the regional administration to support management plans involves accounting for the volume and rate of water withdrawn from the aquifer and the way groundwater use changes over time and in space. But today, and after several decades of research, groundwater abstraction by private and/or individual wells and boreholes remains uncertain because estimates are necessarily based on the inventory of the number of pumping wells at one point. For example, the inventory made in 2010 had to span an 8 month period and was already obsolete by the time it was completed due to the rapid change in the number of wells in the field, in particular after the 2011 "revolution" (see Kuper et al., 2016, on the precautions to be taken when handling official data on groundwater use).

Answers were sought through interdisciplinary cooperation between hydrologists, anthropologists, and agronomists. This resulted in the use of an interdisciplinary questionnaire concerning groundwater use, as well as a qualitative survey of the wells and their history. An initial finding was that understanding the diversity of methods used to access groundwater could reduce the uncertainty about the extrapolation of the number of pumping wells to be correlated with the volumes of pumped water (Massuel et al., 2017). The approach showed that the relationship between the number of wells and total groundwater use (flow) was governed by a set of nonhydrological determinants, i.e., other than the classic depth to the water table, type of well/borehole, type of pump, type of irrigation system, energy source, hydrodynamic properties of the aquifer, density of the wells in the vicinity, etc. Other dimensions of the wells come into play to explain groundwater use. It is very common to find wells that have been dug but are not in use. Whether or not the well is functioning may depend on different factors. For example, the time needed to settle an inheritance dispute may last several years during which the well is not used. The choice of farming systems (choice of crops, degree of intensification) also matters here. The plots of land to be irrigated may be located too far from the pump. The water may have become brackish and needs to be mixed with freshwater from another well. The electrical connection can be delayed in the case of a dispute over the route to be taken by the cables, etc. Furthermore, the volume abstracted may differ considerably from the capacity of the pump/well if, for example, the farmer is merely seeking independence in his access to water and does not necessarily want to intensify agricultural production, or the well is owned by several heirs, or was built to achieve social prestige with little agricultural use. It could also be influenced by religious considerations, for example, when water is considered as a "gift" from God and the legitimacy of the administration to regulate groundwater use is contested (Bekkar et al., 2009). The desire to share water with one's neighbors or, on the contrary, to withhold it, also matters. All these factors change continuously over time, sometimes very suddenly, as was the case during the Tunisian revolution, which had a profound effect on the organization of access to water. For example, many farmers converted their wells into tubewells, a process which had previously been more strictly regulated by the administration.

The representation of the processes that have led to the groundwater situation currently observed in the Kairouan Plain is thus based on a set of hydrological as well as social, political and cultural factors that determine the links between groundwater withdrawals and the individual and collective practices of the irrigators. Incorporating these determinants in a hydrological model is complex because they include (i) those that hydrology cannot or can only approximately incorporate because they are qualitative and diffuse by nature, (ii) those that have not been identified, and (iii) those that can be identified but are either considered to be minor or to "over-determine" groundwater use (e.g., the 2011 revolution). In the latter case, although the socio-hydrological field-based approach did not result in the construction of a socio-hydrological model, it nevertheless made it possible to deconstruct a certain number of hypotheses, especially the direct link between the number of pumping wells and groundwater abstraction, as well as the exponential expansion of the number of wells. This led to the reorientation of hydrological research toward the definition of new protocols for measuring the amount of groundwater use by including farmers' strategies and logic (Massuel et al., 2017) and specifying the differentiated contribution of various social categories (Ameur et al., 2017).

Socio-hydrological research was also conducted in the basin upstream of the Kairouan Plain focusing on the small dams of the upper Merguellil catchment (Figure 1). The aim was to accurately assess the water budget of the reservoirs to improve the accuracy of basin-wide water accounting (Ogilvie et al., 2016). Field investigations revealed that the use of these small reservoirs was influenced by a set of "classical" determinants such as the availability of the resource, the irrigation practices (type of crops, irrigation frequency, number of pumps) or the maintenance of the hydraulic facilities. But it was also influenced by diverse other aspects, including market and price structures, the impact of ongoing rural development programs on farming systems, the prospect of seasonal work in the cities, and problems with access to land and/or to credit. The relationships with the authorities as well as conflicts between water users affected farmers' ability to install a pump. The farmers' know-how and their learning experience had a significant influence on the volume of water used. Strong causal relationships are difficult to establish but these elements help understand the socio-hydrological interactions that occur around small dams and identify the drivers that affect the results of hydrological analyses.

This interdisciplinary approach associating hydrological and social sciences draws attention to the limits to estimating the variables of the hydrological budget when these are affected by human activity. The resulting difficulties for hydrology are a powerful incentive to design new approaches to represent water systems as a complement to the usual approaches used in hydrological investigations. This represents a second step in the construction of an interdisciplinary socio-hydrological approach that implies going beyond an exclusively hydrological perception of all the components of water systems.

5. Associating the Social and Hydrological Dimensions of a Water System Through a Process of "Negotiation"

In our approach, hydrology is positioned as one element in a wider research framework designed to understand the interactions between water and society. This arrangement cannot be determined in advance but needs to be constructed, and the role and contributions of the researchers negotiated in each of the different situations encountered. Two examples drawn from current research illustrate this arrangement.

The first example again concerns small reservoirs in Tunisia and questions the objectives and scale of the hydrological research. Field surveys and interviews with the local population and regional and central administrations confirmed that the sites for these reservoirs were not chosen on the basis of technical criteria but rather for political reasons (the network of local influences) or as a result of land ownership (e.g., state owned land). As a result, research that aimed to improve knowledge of runoff processes and formulas to design the dam spillways seemed only marginally relevant to improve water management in the basin. Indeed, for more than 20 years, the literature has been pointing to the limited benefits of these reservoirs for local populations (e.g., Hill & Woodland, 2003). The socio-hydrological surveys showed that if the local people had a better knowledge of hydrological dynamics (e.g., changes in the filling and emptying of the reservoir, groundwater-surface interactions in the vicinity of the lakes) at both the annual and reservoir scales, they would be able to adapt their agricultural practices to the availability of water. This research topic would then be of great help to improve water management, yet it had been previously ignored because efforts were only devoted to quantifying fluxes at the subbasin level (e.g., impacts of the reservoirs on downstream runoff, their contribution to groundwater recharge, transport and trapping of sediment, etc.). The institutional analysis commissioned by the administration confirmed that the reservoirs' usefulness had only been questioned in relation with issues of interest to hydrologists. The reasons that facilitated or hindered the use of the reservoirs had not been analyzed in detail and were not taken into account in the choice of construction sites or for designing supporting policies. Yet from a socio-political point of view, reservoirs offer considerable benefits, including the materialization and strengthening of social links between local users, the presence of the state in remote areas, the limitation of rural migration to cities, etc. The reservoirs can also be linked to private political interests (clientelism) or financial mismanagement (corruption associated with contracts) that shift the analytical lens. Hence defining the role of a given reservoir (and thus assessing its overall usefulness) may involve focusing the required knowledge of hydrological processes on specific issues. An understanding of social dynamics makes it possible to define the type of hydrological knowledge needed to address the question (e.g., focusing on the filling and emptying of the reservoirs in addition to the sizing of the dam spillway). The present socio-hydrological approach thus involves identifying research questions in an interdisciplinary and contextualized way from the onset, rather than incorporating the human factor within a predetermined frame and answering water management questions that may be out of context or even irrelevant.

These considerations lead us to discuss a second case study that combined hydrogeology and socio-anthropology near the village of Haffouz in Tunisia (Figure 1). The hydrogeological questions previously investigated in this area concerned the relationship between the surface water and groundwater and exchanges between aquifers to explain the fluctuation of the piezometry in a context of scarce and unreliable hydrological data. The purpose of mobilizing social sciences was to produce additional knowledge on the aquifer and pumping practices to help build a hydrodynamic model and highlight flow exchange processes. Farmers grew crops using water drawn from individual wells. Socio-historical field surveys showed that the way in which water was used had changed since the 1950s. After a period of gravity-fed irrigation with surface water, the farmers gradually shifted to groundwater, first withdrawn from the superficial aquifer and then from the deep aquifer, as piezometric levels had been dropping by $\sim$1 m/yr for several decades. A socio-hydrological survey was conducted to understand the relationship between changes in access to water and groundwater dynamics. Owners and users of wells were questioned about the history of their wells, the difficulties they faced in accessing water, and about their different water resources (i.e., surface, groundwater, and rainwater). The survey produced qualitative results in several areas: (i) the history of hydroagricultural practices and groundwater use techniques (Collard et al., 2015), (ii) the collection of current and past hydrological information (piezometric levels, water quality, reduction in runoff in the wadi and of discharges in wells and springs, etc.), (iii) local knowledge about groundwater pathways gathered through their observations and extensive experience with land and water use. This information led to hypotheses to model the hydrological processes based on stakeholder knowledge. The correspondence between these local perceptions of groundwater and the hydrological cycle yielded interesting perspectives for future research (see Bekkar et al., 2009, for a similar example in Morocco). In-depth interviews with irrigators, using sociological knowledge to guide the discussions and hydrological skills to interpret their answers, enabled the precise reconstruction of the stakeholders' perception of the subsoil and of their theories concerning the circulation of groundwater. When a well is dug or drilled, knowledge of the lithology of the strata encountered as well as of the water productive layers is widely shared among irrigators and local service providers (drillers, in particular) and stored in the collective memory to be applied in future decisions concerning wells and boreholes. Contrary to the common assumption that ordinary people cannot perceive the complexity of hydrological processes, the interpretations offered by some farmers proved to be very relevant. Some of these interpretations differed from those of hydrologists, notably on the connections between the wadis and the aquifers. When the interpretations of local people were tested in a hydrogeological model, they proved to be compatible with the hydrodynamics of the area and led to a considerable change in the hydrologists' approach to the area. Although qualitative, the hydrological data collected from the local stakeholders (variations in piezometric or salinity patterns, hydraulic connections between wells, recession of springs, etc.) are thus a potentially useful source of information for hydrologists. Finally, in terms of groundwater management, the fact that farmers are perfectly aware of a piezometric decline, and even of the depth of the aquifer and its recharge rate, challenges the mainstream discourse of Tunisian water managers advocating the need to educate farmers because their “unsustainable” practices are based on ignorance of what is at stake. Proposing scenarios to “raise awareness” among stakeholders of their limited resources thus does not seem very relevant. By contrast, the qualitative surveys allowed the identification of the constraints to their activities and the reasons behind their choices.

These two examples of socio-hydrological research yield several lessons for the analysis of the relations between water and society and the benefits of combining social and hydrological tools and approaches in field investigations. On the one hand, understanding the logic underlying local practices makes it possible to identify pathways for change. This, in turn, makes it possible to redefine research questions beyond their strictly hydrological context and, through better contextualization, also helps redefine the research object to be modeled. Furthermore, a deeper understanding of local water issues makes it possible to choose suitable specific temporal and spatial scales of observation, analysis—and possibly action. This requires setting aside approaches and analysis tools dictated solely by the hydrological discipline. Building on these first two lessons, socio-hydrological research makes it possible to match research questions and analytical abilities with the parties concerned, and to move beyond the conventional “decision support” approach for (poorly identified) “end-users” (see Shove & Rip, 2000, for an interesting discussion on the representation of scientists of the “users” of their research). It also requires considering water-society systems as contested arenas for social groups with different (often conflicting) interests, especially in the case of scarce resources like water in semi-arid regions (see Geertz, 1972, for an interesting analysis on how cooperation in Moroccan farmer-managed irrigation systems happens in an “agonistic sort of way”).

This highlights the need for reflexive research as favored, for example, by Lane (2014) or Vincent (2003), notably regarding the way in which hydrological expertise is usually built. Why, for instance, produce tools for the water administration, create projections or focus on a particular scale of analysis or management like the river basin scale? On the other hand, additional insight produced through social research often remains qualitative and (only) enables the production of an explanatory narrative of the situation observed and ultimately of what is at stake. To go one step further, one may then need to accept that this narrative can constrain the design of the model and that the hydrological model itself becomes (only) one element in the socio-hydrological approach rather than its end purpose.

In this respect, the proposed approach is comparable to a form of negotiation between different disciplines, going back and forth many times during the course of the research process, including the formulation of the research question and the place this question ultimately takes in the research framework.

6. Discussion and Conclusion: Confronting the Social and the Hydrological Rather Than Incorporating the Former in the Latter

The approach presented here contributes a way to handle the specificity of a given situation of dynamic relations between water and society to current conceptual and methodological advances in the field of socio-hydrology. This is a useful way to feed knowledge into foresight exercises, to understand the consequences of specific social interactions for a hydrosystem, as well as to analyze local problems and assess the likely impact of development interventions on the water cycle and water uses (including the construction of new infrastructure). It associates formal computational models with empirical inductive fieldwork and social science approaches. The objective of such an undertaking is to explore and forecast social and water dynamics simultaneously, putting interdisciplinarity at the heart of the investigations from the beginning, including in designing observation protocols. Each step is “negotiated” across all disciplinary points of view throughout the research process. A negotiation perspective was already identified in the past to enable “new (and often wider) problem definitions and perceptions” in (participatory) development processes (Leeuwis, 2000, p. 947), but we argue that such a perspective is also pertinent for interdisciplinary research as it helps to deal with conflicts between prospects, epistemologies and viewpoints. Most attempts to “integrate” social dynamics and hydrological dynamics on the basis of predetermined frames and with the same conceptual tools have led to deadlocks as soon as local cultural, social and political patterns have to be taken into account. The research (as well as development) issues that arise from the field and that make it necessary to include the "social" in hydrological analyses will not necessarily find a solution through modeling. Consequently, the pragmatic solution designed to respond to the difficulties actually encountered in the implementation of such research is to confront social analyses with hydrological analyses and to consider hydrological models as an important, but not exclusive or final, piece of the puzzle.

In sum, the approach presented in this paper starts with an interdisciplinary dialog around observations and measurements made in the field. Negotiations take place throughout the research process between researchers from different disciplines regarding the research objects. This results in building a shared view of water-related problems and allows researchers to break with mainstream views and/or common sense discourse and redefine the situated water-related problems. Each discipline investigates the underlying factors in the given context with its own tools. Joint production of exploratory models is a way to organize the "negotiation" between these partial explanations, as proposed in various group modeling approaches (see Voinov & Bousquet, 2010, for a comprehensive review). The negotiation can also be opened up to all or some of the actors represented, thereby creating a link between social simulation and participatory modeling (Barreteau et al., 2013). Technically, from a modeling point of view, situated action theory (Suchman, 1987) paves the way to finding constructive outcomes or spin-offs to these negotiations. Finally ways of better understanding or reinterpreting the observed problems are proposed, potentially including models and new narratives as a support for decision making. The conceptual representation is not of hydrological entities and social entities interacting together in a positive or negative way but the combination of entities, each with their social and hydrological aspects, that lead to the actual situation.

The literature on interdisciplinarity between social and physical sciences explores these challenges and can be referred to here. The necessary balance between disciplines in the practice of research (MacMynowsky, 2007) relies on the importance of agreeing on the meaning of the concepts used (Lele & Norgaard, 2005), as illustrated earlier with regard to the concept of "social dynamics," on the need for joint reflection prior to starting the research, when the issues to be dealt with are being defined, and giving hydrology or modeling the final word, or not. (Wesselink et al., 2016). Therefore, in line with Mostert (2018), we suggest adding a grounded component to socio-hydrology, in which the field, with its social, cultural, political, ecological, and physical components, consistently challenges the research choices. The research questions originate in the field, the perspectives of each discipline start from and interact through the field and the results are relevant to the field. This obviously translates into very situated results and, hence, into modest theoretical ambitions and limited capacity to reproduce or extrapolate conclusions. Nevertheless, some of the results obtained shed light on more theoretical questions such as the scale of observation to be adopted, the question of the accuracy of parameters, and the need for reflexivity. To implement this stance, decades of inductive works (e.g., grounded theory; companion modeling, see Barreteau et al., 2003, 2014) provide a basis to be adjusted to the specificity of the socio-hydrology agenda and extend the negotiation arena from interdisciplinary to transdisciplinary through the involvement of stakeholders and users in the emergence of new knowledge.

This methodological choice has, for example, led us to reconsider the conceptual approach to social dynamics: a much wider range of considerations need to be included than simply changes in population, crop choice, or technology. While "behavior" (understood as multiple choices in the face of a predefined situation) can be incorporated in modeling, wider socio-political analysis is required to complement modeling by both early scoping exercises and the coconstruction of scenarios or narratives (Gidley et al., 2009). This inductive empirical nature of the approach can help minimize predetermined frames and hence favor different ways of structuring detailed field data and/or descriptions of water and society. The advent of new organizing principles would then allow the accumulation of knowledge from prior field studies.

The plurality of methods is now well acknowledged as suitable (at least) in the domain of social-ecological systems and common pool resources (Poteete et al., 2010). The addition to socio-hydrology we suggest here is part of the same movement. Learning from empirical and inductive approaches to water-society relations may challenge administrative or scientific approaches at higher levels (for example the basin level) that aim to provide a general understanding of water-society relations, and then to further improve them. The results of such approaches may also constitute explicit frames to put forward for discussion (or even negotiation) in a more grounded field approach. The modeling tools, whatever their (potentially hybrid) formats, are then of interest to explore the consequences of contingent knowledge, but also to provide enhanced information to water users in order to collect their feedback.

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