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Linking scientific disciplines: Hydrology and social sciences

R. Seidl [a,*], R. Barthel [b]

[a] USYS Transdisciplinarity Lab, ETH Zurich, 8092 Zurich, Switzerland
[b] Department of Earth Sciences, University of Gothenburg, 40530 Gothenburg, Sweden

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ABSTRACT

The integration of interdisciplinary scientific and societal knowledge plays an increasing role in sustainability science and more generally, in global change research. In the field of water resources, interdisciplinarity has long been recognized as crucial. Recently, new concepts and ideas about how to approach water resources management more holistically have been discussed. The emergence of concepts such as socio-hydrology indicates the growing relevance of connections between social and hydrological disciplines. In this paper, we determine how well social sciences are integrated with hydrological research by using two approaches. First, we conducted a questionnaire survey with a sample of hydrology researchers and professionals (N = 353) to explore current opinions and developments related to interdisciplinary collaboration between hydrologists and social scientists. Second, we analyzed the disciplinary composition of author teams and the reference lists of articles pertaining to the socio-hydrology concept. We conclude that interdisciplinarity in water resources research is on a promising track but may need to mature further in terms of its aims and methods of integration. We find that current literature pays little attention to the following questions: What kind of interdisciplinarity do different scholars want? What are social scientists' preferred roles and knowledge from a hydrology perspective?

1. Introduction

The integration of interdisciplinary scientific and societal knowledge plays an increasing role in sustainability science and more generally, in global change research (Grunwald, 2007; Kinzig, 2001). Many scholars have since advocated for collaboration among scientists from different disciplines to address the growing pressure of human behavior on environmental and human systems (Lang et al., 2012; Nature, 2015; Mauser et al., 2015). Interdisciplinarity performs a crucial function because problems in sustainability research are complex, interlinked, and solvable only by interactions among diverse scientific disciplines (Bammer, 2012).

However, such endeavors and the roles of the respective disciplines have not been established on a broad scale. Sometimes, what we think of as genuine interdisciplinarity, such as close cooperation and knowledge integration, might not be so interdisciplinary after all. Referring to climate change research, Bjurström and Polk (2011, p. 543) note, "Although a few fields and journals integrate a wide variety of disciplines, integration occurs mainly between related disciplines (narrow interdisciplinarity) which indicate an overall disciplinary basis of climate research. It is concluded that interdisciplinarity is not a prominent feature of climate research." We should thus carefully investigate what interdisciplinary research (IDR) actually comprises, what can be achieved realistically, and what is actually done in specific projects.

Interdisciplinarity is defined differently by various scholars. Klein and Newell (1997, p. 3) believe that interdisciplinary studies are motivated by questions or problems that are "too broad or complex to be dealt with adequately by a single discipline or profession." Importantly, interdisciplinarity draws on "disciplinary perspectives and integrates their insights through construction of a more comprehensive perspective" (Klein and Newell, 1997, p. 3). Multidisciplinarity also aims toward some form of collaboration but not with the same degree of cooperation as that of interdisciplinarity. Scholars basically agree on a certain progression from multi- to interdisciplinarity although not always for the same reasons (Rosenfield, 1992; Jantsch, 1947; Pohl, 2011). In multidisciplinary teams, "researchers work in parallel or sequentially from disciplinary specific base to address common problem," whereas interdisciplinary "researchers work jointly but still from disciplinary-specific basis to address common problem" (Rosenfield, 1992, p.1351).

Here we cannot delve into the details of this distinction for each author, but we stress that for our purpose, we perceive collaboration in multidisciplinary work as weaker than in interdisciplinary work. In this study, we face the challenge of distinguishing among

* Corresponding author.
E-mail addresses: roman.seidl@usys.ethz.ch (R. Seidl), roland.barthel@gvc.gu.se (R. Barthel).

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different degrees of collaboration on the basis of insufficient data and methodological means. Specifically, we cannot investigate the underlying degree of collaboration in each case due to indeterminacy in the given information. Thus, the methodological approach will necessarily reveal somewhat fuzzy results.

In the field of water resources, interdisciplinarity is considered crucial by different scholars (see, e.g., Brown et al., 2015; Lund, 2015). Articles highlighting the need for more inclusion of social/-societal aspects in hydrological modeling are becoming increasingly common because "good solutions for the wicked problems posed by sustainable water management will require wider interdisciplinary approaches" (Reddy and Syme, 2014). Recent developments in several areas of hydrological research have demonstrated the need to integrate aspects of human systems into hydrology, particularly hydrological modeling. For instance, although hydrological research has often perceived flooding as a purely natural or engineering problem, many researchers are beginning to view it as a societal issue since it concerns policies, risk zones, and societal adaptation behaviors (Gober and Wheater, 2015; Srinivasan et al., 2015). To this end, several authors have stressed the need for more interdisciplinarity in hydrology, particularly between hydrology and social science (topics and knowledge). Wagener et al.'s (2010) article entitled "The Future of Hydrology" discusses humans' impact on the Earth (especially water) and challenges faced by the hydrological sciences (HS). They advocate for increased collaboration with disciplines beyond the social sciences as well. "Hydrologists need to work much more closely with experts from other disciplines, geologists, soil scientists, biologists, geochemists, ecologists, and social scientists, among others, to understand how the system functions at a much more fundamental level, as well as at the holistic level" (2010, p. 6). Sivapalan et al., (2012) put forth the concept of socio-hydrology, linking societal issues to hydrology. A more recent series of comments in *Water Resources Research* adds to the basis for the development of socio-hydrology (e.g., Sivapalan, 2015; Pande and Sivapalan, 2016). Sivapalan (2015) mentions that one of the reasons why hydrology can no longer neglect the fact that societal issues are also driving factors for hydrological processes is the notion of the Anthropocene (see, Crutzen, 2002), a period characterized by humans' impact on the Earth. Some of the articles we found during our literature search criticize socio-hydrology. However, a rapidly increasing number of publications applying or discussing the concept of socio-hydrology illustrate the relevance that socio-hydrology is gaining in the research community. In a recent publication, Pande and Sivapalan (2016) review socio-hydrology's progress over the last four years.

Krueger et al., (2016) emphasize the point of using interdisciplinary endeavors, not only for the synthesis of disciplinary knowledge but also for a deeper discourse on the basic principles of someone's discipline. They call this "agonistic forms that challenge disciplinary foundations," referring to Barry and Born (2013). In their typology of IDR projects, Huutoniemi et al., (2010) distinguish among three dimensions related to three questions: *what* is integrated, *how* it is integrated, and *why* interdisciplinarity is employed. What does the vast freedom in designing interdisciplinary processes mean for the field of hydrology? In this article, we investigate potential answers to this question by examining HS, including water resources, and how this branch of science interacts with the social sciences and humanities (SSH).

To identify what role hydrologists believe SSH could and should play in hydrological research to more holistically investigate the human–water link, we conducted a survey among scholars working in the field of hydrology (in both academic and applied research). Furthermore, we review current research streams that incorporate interdisciplinary perspectives and evaluate their potential to improve interdisciplinary collaboration, linking to the current literature about interdisciplinarity. We then return to the dimensions put forth by Huutoniemi et al., (2010) and discuss our results.

2. Literature search on collaboration between hydrology and social sciences in socio-hydrological studies

Measuring the degree of interdisciplinary (or even multidisciplinary) collaboration in an organization, a field of science, or a project and evaluating the modes and the quality of IDR are challenging yet tedious endeavors (Wagner et al., 2011). Approaches to these undertakings are commonly based on bibliometric indices, but there is agreement that such indices can only reveal general tendencies and that deeper analysis is required to detect and evaluate IDR (Strang and McLeish, 2015; Wagner et al., 2011; Rafols et al., 2012). Nonetheless, in this study's context, it is of interest to explore whether quantitative analysis of meta-data about journal publications could identify the modes and the intensity of *collaboration* between hydrologists and social scientists. We have therefore conducted a systematic literature review to investigate how such collaboration in socio-hydrology happens or is meant to happen. We want to determine the degree of collaboration in socio-hydrology as a "new interdisciplinary science of people and water" (the subtitle of Sivapalan et al., 2012), not to find flaws in the concept of socio-hydrology but to estimate its potential in the broader context of interdisciplinary collaboration across the boundary between natural and social sciences.

We point out that according to the cited rough definitions of inter- and multidisciplinarity, a clear distinction between the two is difficult to find. Particularly, it should be noted that the condensed content of a journal article usually does not allow a detailed evaluation of the actual modes of collaboration. Thus, what we can show at most with our quantitative measurement is the likelihood that any kind of collaboration took place, not whether it was multi- or interdisciplinary. Thus, for the purpose of presenting methods and results in relation to the literature analysis, we indicate multi- or interdisciplinarity, without nearer specification. Barthel and Seidl (2017) provide a more detailed discussion of the underlying problems.

2.1. Literature analysis: data and methods

The publications used in the analysis were selected using Scopus and Web of Science (WoS) (June 2016). We searched for publications with *socio-hydrology* (and different forms of the term) in the titles, abstracts, or keywords (Scopus) or listed as a topic (WoS). The search string in Scopus was SRCTYPE (j) AND PUBYEAR > 2011 AND TITLE-ABS-KEY (sociohydrology) OR TITLE-ABS-KEY ("socio-hydrology") OR TITLE-ABS-KEY (sociohydrologic) OR TITLE-ABS-KEY ("socio-hydrologic") OR TITLE-ABS-KEY ("socio hydrological") OR TITLE-ABS-KEY ("socio-hydrological").

We excluded conference papers, publications before 2012, and publications that *only* refer to socio-hydrology in engineered keywords (WoS: keyword plus, Scopus: Index keywords) because in such papers, the authors do not actually use the term *socio-hydrology*.

Our approach to evaluating the degree of multidisciplinary collaboration was inspired by approaches to measuring collaboration between disciplines through bibliometric analysis, based on the idea that the degree (and form) of collaboration between two scientific disciplines could be assessed by counting the number of mutual citations. Contrary to other studies (see, Wagner et al., 2011), we did not rely on journal and article classifications in the subject categories and the disciplines in WoS and Scopus, which we found questionable. The reliability of these classifications had already been questioned by many authors, and the resulting problems regarding the measurement of IDR had been discussed frequently (Hassan et al., 2014; Bensman and Leydesdorff, 2009; Pudovkin and Garfield, 2004; Leydesdorff and Opthof, 2010). As a second indicator of the degree of multi- or interdisciplinarity, we added an analysis of the composition of the author team and the disciplinary backgrounds of the individual authors.

2.1.1. Classification of article types

We classified the analyzed articles into four categories: research papers, reviews, editorials, and discussion/opinion papers based on categories chosen by the authors, assigned by the journals, and our own judgment. Distinguishing between research papers and discussions has been somewhat difficult as considerable parts of the articles classified as research papers are dedicated to discussions of the concept of socio-hydrology, likely because it is not well established yet.

2.1.2. Disciplinary composition of each publication's team of authors

The goal of this analysis was to identify whether or not an article was the result of any form of collaboration between hydrologists (or natural scientists in general) and social scientists. Ideally, that should become visible through a mixed author team comprising collaborators from either group. We determined the authors' disciplinary backgrounds based on (i) each author's publication record, especially by being listed as the first author, (ii) their personal web pages and information published on Research Gate or LinkedIn, for instance, and (iii) affiliations (although usually not indicative of their backgrounds). We assigned the authors to three categories of disciplines: those belonging to natural sciences, including engineering, computer sciences, and medicine (NASC); those belonging to social sciences, including arts and humanities and economics (SOSC); and scientists working in both fields and thus had a multidisciplinary background (MS). The author teams were subsequently classified into mono-disciplinary (all authors from either the NASC or the SOSC category), multi- or interdisciplinary (a balanced mix of authors from all categories), weakly multi- or interdisciplinary (e.g., one multidisciplinary author in an otherwise mono-disciplinary team), and single author. Furthermore, a tendency toward NASC or SOSC was determined for all but the teams with a completely balanced orientation.

2.1.3. Classification of cited references

The percentages of cited references in the NASC and the SOSC groups were determined by manually inspecting and categorizing each cited reference. For each reference, we assessed to which field (NASC or SOSC) it belonged, exclusively based on the cited publication's title and source. We discounted the number of cited grey literature (reports, manuals, data sets, etc.) when determining the ratio of cited social science/natural science references as it often remained unclear where they belonged.

2.2. Literature analysis: results

Up front, the classifications of the degree of collaboration that we found through the analysis of references and author lists contain terms that are strongly debated in the literature and used differently by various authors and in diverse contexts. Barthel and Seidl (2017) discuss our classification scheme in more detail. Here, we only point out that a mixed author team or a mixed reference list can at best show that different disciplines contributed or were drawn upon, not what the nature of the collaboration was (cross-, multi-, or interdisciplinary and whatever they meant). We decided to use the term *multidisciplinary* if contributions from both NASC and SOSC could be detected. However, even the multidisciplinary cases we found had different degrees of intensity. For example, we assumed that a collaboration of one author from NASC and another from SOSC indicated a higher degree of multi- or interdisciplinarity than a team of seven authors from NASC and one from MS. We classified the latter constellation as weakly multidisciplinary.

In total, 58 publications matched the selection criteria described in the previous section. The complete list of the identified articles and the individual classification results for the different indicators used are listed in the Supplementary material. Unexpectedly, 15 of the 58 selected journal articles mentioning the term *socio-hydrology* in their titles, keywords, or abstracts do not refer to the concept of socio-hydrology presented by Sivapalan et al. (2012). Caught by surprise, we contacted the authors of several of these publications, who confirmed that they had not heard of the concept (personal communication with, e.g., authors Erik Gawel and Markus Nüsser). We did not explore this interesting fact any further as it was outside the scope of this study, but we analyzed the 15 articles as a subgroup of their own. Fig. 1 shows the classification of all 58 articles into different publication types.

Fig. 2 shows the results of the classification of the author teams. Of the author teams for the 43 papers referring to Sivapalan et al., (2012), 32 are dominated by NASC authors, 2 are dominated by social scientists, 8 have balanced author teams, and 2 remained unclear with respect to the tendency toward NASC or SOSC. Of the papers classified as research articles in this category (see Fig. 1), 15 are written by NASC-dominated teams, 1 by an SOSC-prevalent team, and 3 by balanced teams. All of the single-author and mono-disciplinary papers are written by professionals from the natural sciences.

Fig. 3 shows the results of the analysis of the reference list for each publication. Of the papers with a mono-disciplinary reference list, 11 have an NASC orientation, and 9 are oriented toward SOSC. Of those that are only weakly multi- or interdisciplinary, 13 have an orientation toward NASC and 7 toward SOSC. In total, 18 papers are classified as multi- or interdisciplinary without a clear tendency toward either discipline. The subsample of research articles does not differ significantly from the full sample; the numbers of papers with NASC, SOSC, or multi- or interdisciplinary orientations are evenly distributed.

3. Survey among scholars working in the field of hydrology

In their highly recommendable discussions about the IDR between natural and social science, MacMynowski (2007) and Strang (2007) point out that determining and understanding differences among research concepts is an essential first step toward closer collaboration and the key to successful IDR. However, a couple of questions regarding the actual cooperation between the disciplines remain unanswered:

1. How should hydrological and social sciences be related?
2. What are hydrologists' expectations regarding what roles hydrology and social science should play in collaborative research?

To address these issues, we conducted a brief questionnaire survey to gauge hydrologists' ideas about the role of SOSC. The results may also shed light on how collaborative work can be designed in future socio-hydrological efforts.

3.1. Methods survey

The questionnaire comprised nine sections with different types of questions. The Supplementary material presents the full ques-

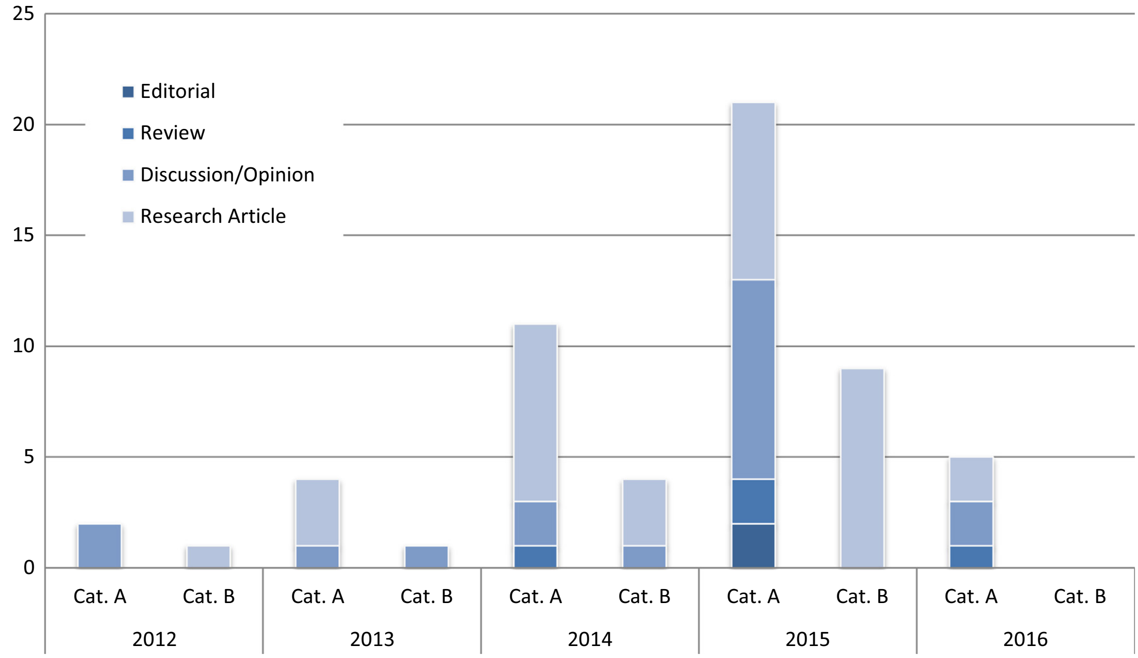

Fig. 1. Publication type. Category (Cat.) A: Articles that explicitly refer to the socio-hydrology concept introduced by Sivapalan et al. (2012). Cat. B.: Articles using the term socio-hydrology without referring to Sivapalan et al. (2012).

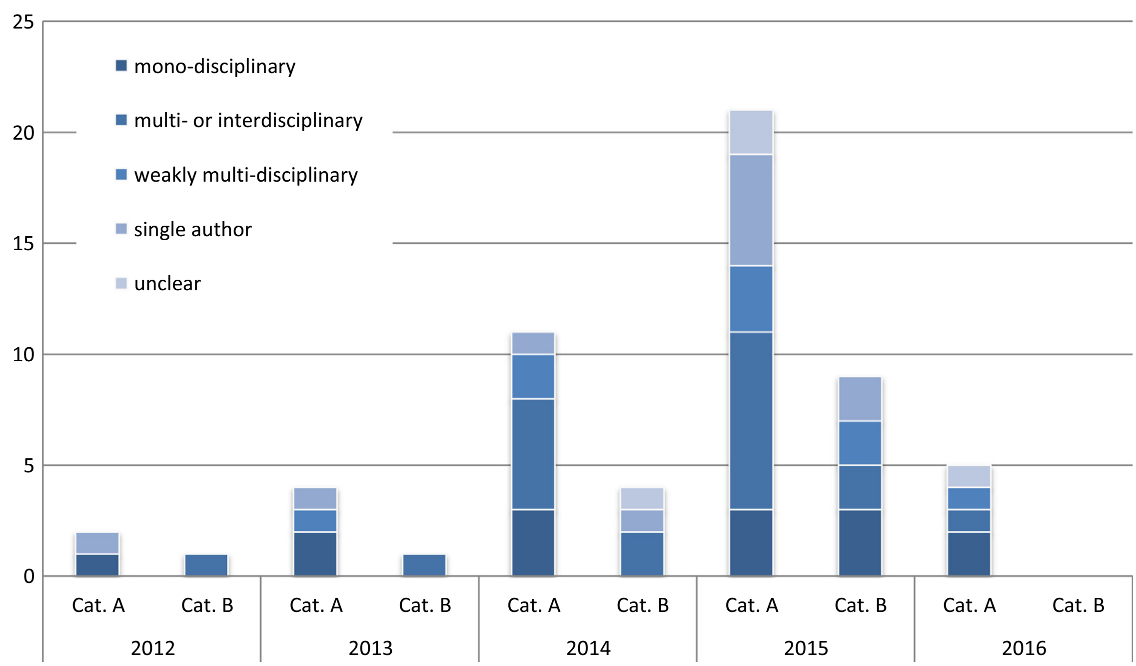

Fig. 2. Composition of author teams. Category (Cat.) A: Articles that explicitly refer to the socio-hydrology concept introduced by Sivapalan et al. (2012). Cat. B.: Articles using the term socio-hydrology without referring to Sivapalan et al. (2012).

tionnaire in text format. We adapted the questionnaire from an earlier study (see, Wäger et al., 2014).

The first and the second sections included questions about the contributions of SSH and HS, respectively. Each of these blocks consisted of 12 variables (i.e., statements that participants had to rate on a Likert scale ranging from 1 = "not at all" to 7 = "very much"). The third section asked the respondents to describe their perceived degree of integration and whether they saw the need for action to achieve better integration and improve cooperation between SSH and HS. These variables were followed by open questions to which the respondents could write their own answers. These questions focused on two subjects: "obstacles to better cooperation" and "incentives to make cooperation with SSH attractive." The fourth section asked respondents to rank the five given suggestions in terms of how likely they would "foster or improve cooperation between natural and social scientists." The remainder of the questionnaire asked about the respondents' demographic variables, such as disciplinary background, gender, age, work sector, and geographic area.

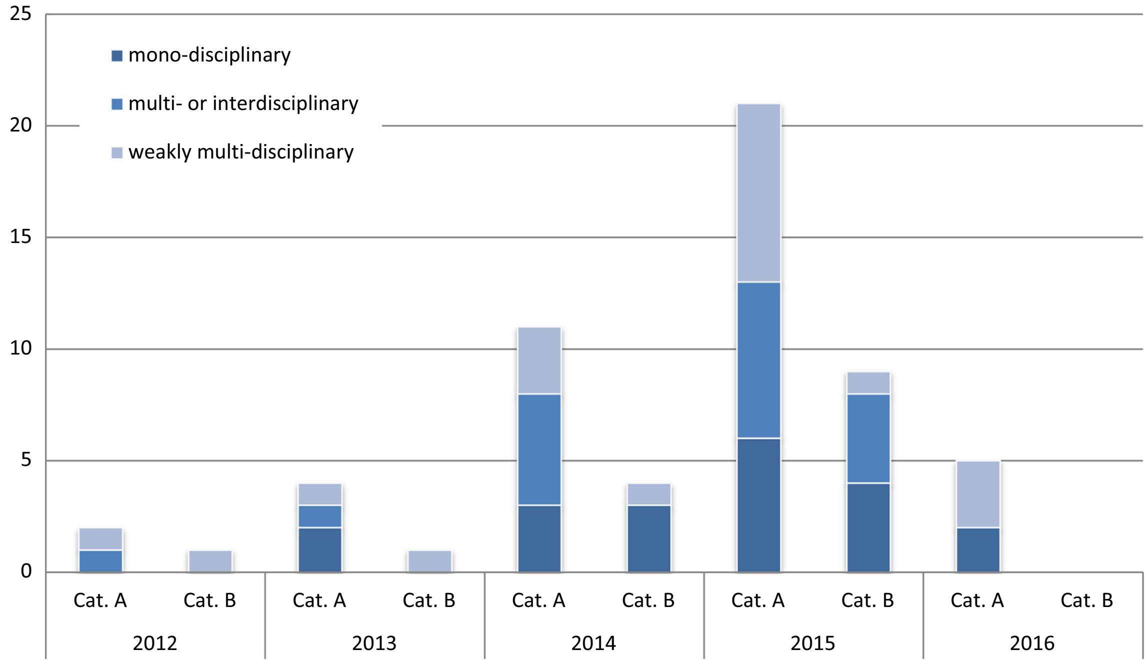

Fig. 3. Composition of cited references. Category (Cat.) A: Articles that explicitly refer to the socio-hydrology concept introduced by Sivapalan et al. (2012). Cat. B.: Articles using the term socio-hydrology without referring to Sivapalan et al. (2012).

In addition to the descriptive analysis of the results, factor analysis (alpha factoring using the Varimax rotation technique) was applied to reduce the complexity of the variables regarding expected tasks (roles of scientists; Section 3.3.2). Factor analysis is thus used to achieve "parsimony by explaining the maximum amount of common variance in a correlation matrix using the smallest number of explanatory constructs" (Field, 2009, p.629). The Varimax technique (as one example of the orthogonal rotation of factors) is used for data derived from a questionnaire, where the variables are not independent from one another. This technique "tries to load a smaller number of variables highly onto each factor resulting [in] more interpretable clusters of factors" (Field, 2009, p.645).

A *t*-test was also performed to compare the tasks that were expected to be completed by social scientists and by hydrological scientists (see Table 7). This test detects significant differences between the means of two variables. We used a dependent-means *t*-test (also called a paired sample *t*-test) when both sets of variables were filled in by the same participants.

Hierarchical cluster analysis (Ward method, measure interval = squared Euclidean distance, standardized values between 0 and 1) was used to identify subgroups in our sample. Since there were no significant differences between the demographic groups (sector and workplace) in a clear pattern, this analysis should help group participants with respect to their variables' ratings of the roles of SSH (Section 3.3.2). This technique identifies variables that should be merged to increase the overall within-cluster variance to the smallest possible degree, thus resulting in distinct groups of participants based on their ratings. For easier visualization of the clusters' profiles, we merged the variables into scales, using the structure suggested by the factor analysis. Specifically, the variables loading on one factor were combined by calculating their mean values, which is the standard procedure for developing scales. Three scales were thus calculated and checked for consistency, using Cronbach's α. All scores showed good ($\alpha > 0.80$) or acceptable reliability ($\alpha > 0.70$) and were not above 0.90, which would indicate unnecessary duplication across items (Streiner, 2003).

3.2. Sample description and demographics

The survey was administered as an online questionnaire and announced through the newsletters of the International Association of Hydrogeologists and the International Association of Hydrological Sciences. To further enrich the sample, we posted the questionnaire on the LinkedIn groups Hydrology International and The Geological Society of America (a hydrogeology subgroup), yielding 17 participants. We recruited additional participants by sending the survey link on February 26, 2016 to a selection of colleagues who published articles in *Water Resource Research* or other social science-oriented journals that address hydrological topics (such as *Applied Geography* or *Water Policy*). Potential participants' email addresses (2315 in total) were collected from Scopus (http://www.scopus.com). Of these, 169 completed the questionnaire.

Overall, the recruitment of participants was harder than expected; there should have been at least 10,000 potential respondents. We consider this a result of the study; interest in this topic appears limited at best. In total, 353 researchers responded to our (short) survey,[1] with 72% male and 28% female. The mean age was 46 years, ranging from 23 to 86. The majority of the participants (42%) were employed in Europe (see Table 1). Regarding sectors (Table 2), 251 participants worked in research and education fields (university, research center, etc.), 25 held positions in administration and management, and 34 belonged to the private sector.

Most participants had disciplinary backgrounds (Table 3) in hydrology. However, many participants ($N = 100$) had backgrounds in multiple disciplines, with 68 (20%) from SSH. Thus, as expected, our sample was relatively biased toward individuals who had a basic interest or considerable experience in cooperating with researchers from other disciplines.

Some participants mentioned working in more than one discipline. A combination of hydrology and engineering experience was the most frequent, followed by hydrology and social sciences

[1] Note that in some tables, the N is lower; this is due to missing values for the specific question.

Table 1
Locations of participants' workplaces.

Country (workplace)	Frequency ($N = 316$)
Africa	24 (8%)
Asia	45 (14%)
Australia/Oceania	18 (6%)
Europe	133 (42%)
North America	86 (27%)
South America	10 (3%)

Table 2
Sectors in which participants primarily worked.

Sector	Frequency ($N = 312$)
Administration and management in the public sector	25 (8%)
Private sector	34 (11%)
Research and education	251 (80%)
Other	2 (1%)

Table 3
Participants' main disciplines.

Discipline	Frequency ($N = 353$)
Hydrology/Hydrogeology, etc.	226 (64%)
Engineering	114 (32%)
Social sciences	62 (18%)
Humanities	6 (2%)
Other	25 (7%)
Hydrology/Engineering	84 (24%)
Hydrology/Social sciences + Humanities	21 (6%)
Engineering/Social sciences	15 (4%)

and engineering and social sciences. The disciplinary background had no significant impact on the ratings given by the participants.

3.3. Survey results

3.3.1. Current status of cooperation between SSH and socio-hydrology

We asked the participants about their opinions on two questions:

1. Is SSH integrated well enough into hydrological research/the field of hydrology?
2. Do you see a need for action to achieve better cooperation between SSH and hydrological research?

The last row (total number) in Table 4 shows the participants' answers (*yes*, *partly*, or *no*). The majority of the participants partly or fully agreed that SSH was *not* or *only partly* well integrated into hydrological research. Furthermore, most participants partly or fully recognized the need for better cooperation between the two sets of disciplines. However, of the 135 respondents who did not see enough integration, 4 saw no need to change anything, and 25 saw only a partial need to do so.

Table 4 clearly shows that across fields of work and countries, more participants see a need for action than those who think otherwise or believe that partial integration is already happening. Moreover, the participants from Europe see less need for action than those from Asia do, while Asian participants indicate a higher level of conviction (*yes* or *partly*) that integration has already happened compared to their European counterparts.

Table 5 shows how participants from different sectors rate the same variables. Those working in administration view the current state of integration as more positive and see less need for action than the other two groups. The response pattern of the participants working in research and education resembles that of the participants in the private sector (note the relatively small number of participants in the private and administration sectors).

3.3.2. Roles of SSH and hydrology

One question addressed the respondents' perceived roles as hydrology and SSH scientists: "As a hydrologist, what would you consider the contributions of SSH [or HS] to the field of sustainable use of natural resources (water)? Hydrologists could/should...." The participants were asked to assign a value from 1 ("not at all") to 7 ("very much") to each of the 12 statements (see Table 6 and the Supplementary material).

For the first investigation of the respondents' perceptions of the roles of SSH from a hydrology perspective, we conducted a factor analysis. Three factors were extracted (see Table 6) to group the participants' responses so that variables with similar meanings would load relatively high on a specific factor. We denoted the first factor (variables 1–4) as *integrated collaboration* because it represented aspects of collaboration, including how it was codesigned, how knowledge was exchanged, and how it was assumed that social scientists contributed to this task. We named the second factor (variables 5–9) *classic social science analyses* since it involved functions that were usually associated with social scientists and dealt with process reflection and moderation (note that variable 7 showed a somewhat ambiguous contribution). The third factor (variables 10–12) was labeled *translation and communication of findings* (*communication* for short) due to its relation to communication and the transfer of scientific knowledge and results to the public and potential stakeholders.

We adapted the variables shown in Table 6 to ask respondents about the role of hydrology from a hydrologist's perspective. We wanted to know what hydrologists expected of other hydrologists and to compare it with what hydrologists expected from SSH researchers. A comparison of the two resulting sets of variables

Table 4
Pattern of responses (in %) to the questions about whether participants see a need for action to achieve better disciplinary cooperation and whether SSH is already integrated enough, distinguished by workplace. The numbers of responses to each question differ since some respondents omit individual questions.

$N = 315–316$	Is SSH integrated well enough into hydrological research/the field of hydrology?			Do you see a need for action to achieve better cooperation between SSH and hydrological research?		
	Yes	Partly	No	Yes	Partly	No
Africa ($N = 24$)	13	46	42	83	17	0
Asia ($N = 45$)	13	67	20	89	7	4
Australia/ Oceania ($N = 18$)	11	39	50	72	22	6
North America ($N = 86$)	5	45	50	79	16	5
South America ($N = 10$)	0	70	30	80	20	0
Europe ($N = 133$)	7	49	44	62	30	8
Total number	24	169	135	235	72	18

Table 5
Pattern of responses (in %) to questions about whether participants see a need for action to achieve better disciplinary cooperation and whether SSH is already integrated enough, distinguished by sector ("other" omitted). The numbers of responses to each question differ since some respondents omit individual questions.

	Is SSH integrated well enough into hydrological research/the field of hydrology?			Do you see a need for action to achieve better cooperation between SSH and hydrological research?		
	Yes	Partly	No	Yes	Partly	No
Administration and management in the public sector ($N = 25$)	20	48	32	56	28	16
Private sector ($N = 33–34$)	9	50	41	79	18	3
Research and education ($N = 251$)	6	50	43	74	21	5

Table 6
Factor matrix for the variables related to the role of scientists from SSH.

Variables		Factor		
		1	2	3
1	Interact closely with natural scientists and engineers to interpret research results	0.743		
2	Critically review the implications of methodological assumptions in research about natural resources	0.677		
3	Exchange knowledge with natural and engineering scientists in the whole research process	0.663		
4	Codesign research about natural resources with natural and engineering scientists	0.660	0.348	
5	Study the social, economic, and cultural mechanisms affecting resource use		0.799	
6	Study the impact of human decisions and behavior on natural resource use		0.688	
7	Facilitate resource management (e.g., by studying barriers to the sustainable use of natural resources)	0.430	0.579	
8	Review the influence of specific interests and power on the design of resource management		0.538	
9	Reflect on the normative aspects of sustainable resource use	0.372	0.519	
10	Communicate the research results to the broader public			0.812
11	Translate the research results for decision makers/policy makers			0.694
12	Secure public acceptance of resource management			0.575
	Eigenvalues	2.52	2.44	1.86
	% of variance	20.98	20.34	15.52

Extraction method: alpha factoring. Rotation method: Varimax with Kaiser normalization. Rotation converged in five iterations. Values below 0.35 have been omitted (see, Costello and Osborne, 2005).

Table 7
Results of a dependent-means *t*-test for significant differences between ratings for the variables for SSH and hydrology perspectives, respectively. Higher mean values for the significant variables are in bold font. The factor structure is somewhat mirrored in the pattern of SSH and HS mean values (although for Factor 1, two variables are not significant).

Factor	Variables	SSH Mean	Std.	HS Mean	Std.	*t*-Value
1	Interact closely with natural scientists and engineers to interpret research results (ns)	5.3	1.62	5.4	1.54	0.99
1	Critically review the implications of methodological assumptions in research about natural resources (**)	4.9	1.63	**5.8**	1.19	9.44
1	Exchange knowledge with natural and engineering scientists during the whole research process (ns)	5.5	1.45	5.6	1.35	0.88
1	Codesign research about natural resources with natural scientists and engineers (**)	5.3	1.48	**5.6**	1.37	3.84
2	Study the social, economic, and cultural mechanisms affecting resource use (**)	**6.0**	1.22	4.4	1.76	−14.21
2	Study the impact of human decisions and behavior on natural resource use (**)	**6.0**	1.15	5.1	1.67	−8.62
2	Facilitate resource management (e.g., by studying the barriers to the sustainable use of natural resources) (**)	**5.7**	1.32	5.3	1.37	−3.88
2	Review the influence of specific interests and power on the design of resource management (**)	**5.4**	1.41	4.6	1.6	−6.75
2	Reflect on the normative aspects of sustainable resource use (*)	**5.2**	1.44	4.9	1.54	−2.54
3	Communicate the research results to the broader public (**)	5.5	1.5	**5.8**	1.22	3.1
3	Translate the research results for decision makers/policy makers (**)	5.6	1.58	**5.9**	1.22	3.37
3	Secure public acceptance of resource management (ns)	5.0	1.59	4.9	1.51	−0.91

Dependent-means *t*-test (99% confidence interval, 2-tailed), significance: $^{**}p < 0.01$; $^{*}p < 0.05$, ns: not significant.

(assumed/expected tasks of SSH versus HS) showed the differences between some variables but not all (see Table 7). A dependent-means *t*-test was used to compare the mean values of each variable pair (i.e., the role of SSH and that of HS) on the same topic (e.g., *communicate the research results to the broader public*). The results revealed significant differences. Particularly, the *study of socioeconomic issues* was more the role of SHH (mean value [*M*] = 6.0) than that of hydrology (*M* = 4.4). However, other roles were rated quite similarly; for instance, the *exchange of knowledge* was assumed to be a task for both SSH (*M* = 5.5) and hydrology (*M* = 5.6). Nonetheless, the *translation of results* was perceived more as a task for hydrologists (*M* = 5.9 versus *M* = 5.6) as was the *critical review of methodological issues* (*M* = 5.8 versus *M* = 4.9).

3.3.3. Differentiation of subgroups

To determine whether the participants could be grouped according to their ratings of the 12 variables (see Section 3.3.2), we conducted a cluster analysis of these variables. Three meaningful clusters emerged. Thus, the respondents were not homogeneous in the way they perceived the role of SSH. For ease of visualization, we aggregated the variables according to the three factors shown in Table 6. These scales have the following statistics: codesign of research, *M* = 5.3, *SD* = 1.28, Cronbach's $\alpha = 0.851$; classic social science analyses, *M* = 5.7, *SD* = 1.01, Cronbach's $\alpha = 0.831$; and communication, *M* = 5.7, *SD* = 1.29, Cronbach's $\alpha = 0.784$. Reliability analysis showed that all α values were high; thus, the scales were consistent.

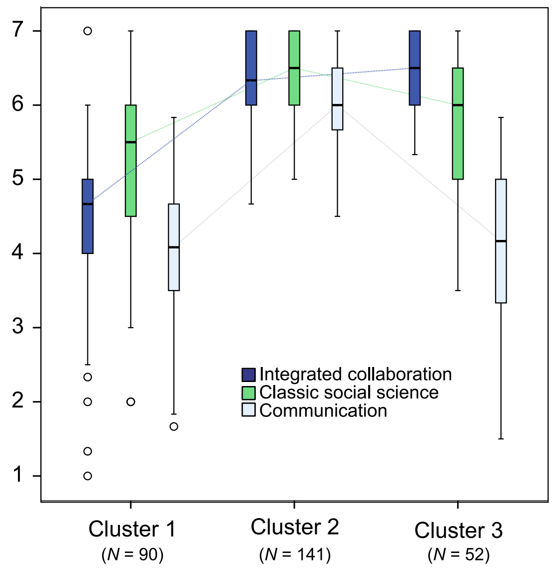

Fig. 4. Cluster ratings on the three scales on the roles of SSH from a hydrology perspective. The scales range from 1 ("not at all") to 7 ("very much"). Box plots show the median (—), quartiles (shaded box), and data range (whiskers). Outliers are represented as °.

The clusters significantly differed for all three scales. The first cluster (*N* = 90) showed critical reflection as relatively more important than communication or codesign of research for SSH, whereas the second cluster (*N* = 141) rated all three factors relatively high and equal (Fig. 4). The third and smallest cluster (*N* = 52) rated the three factors differently but revealed a different pattern than Cluster 1, with higher ratings for codesign, similar to Cluster 2.

3.3.4. Ranking of suggestions for better integration

The responses to the question "Is SSH integrated well enough into hydrological research/the field of hydrology?" revealed some room for improvement. We asked the participants who responded to this question with "no" or "partly" to indicate how integration could be improved. We proposed five options that the respondents had to rank (from 1 to 5). The question was as follows: *In your opinion, what would foster or improve cooperation between natural and social scientists the most? Please rank the following options in order.* The results (Fig. 5) of the ranking task indicated hydrologists' confidence about the integration of social science activities into their research. This finding matched the result of our comparison of the roles of SSH and HS (see Table 7).

The respondents seldom ranked peer acknowledgment of the collaboration between natural and social scientists as the most important or second in importance. Instead, interdisciplinary education was perceived as a long-term path to more integration and was ranked similarly to the idea that SSH research should consider aspects of HS. Moreover, increased acceptance by funding agencies was most often the least important option (ranked fifth 57 times).

4. Discussion

4.1. Results of the semi-quantitative literature analysis

Our semi-quantitative literature analysis aims to determine the extent of collaboration between hydrologists and social scientists in a clearly defined body of literature that refers to or deals with the concept of socio-hydrology introduced by Sivapalan et al. (2012). We performed this literature analysis after conducting the survey because we determined the need to compare the survey results with an independent, more objective data set. We wanted to find out whether our respondents' subjective perceptions, as well as the plans and visions expressed in some of the key papers we reviewed, would be matched by actual, quantifiable research activities.

We based our analysis on two main assumptions: 1) A publication presenting the results of the collaboration between hydrologists and social scientists is more likely to be written by

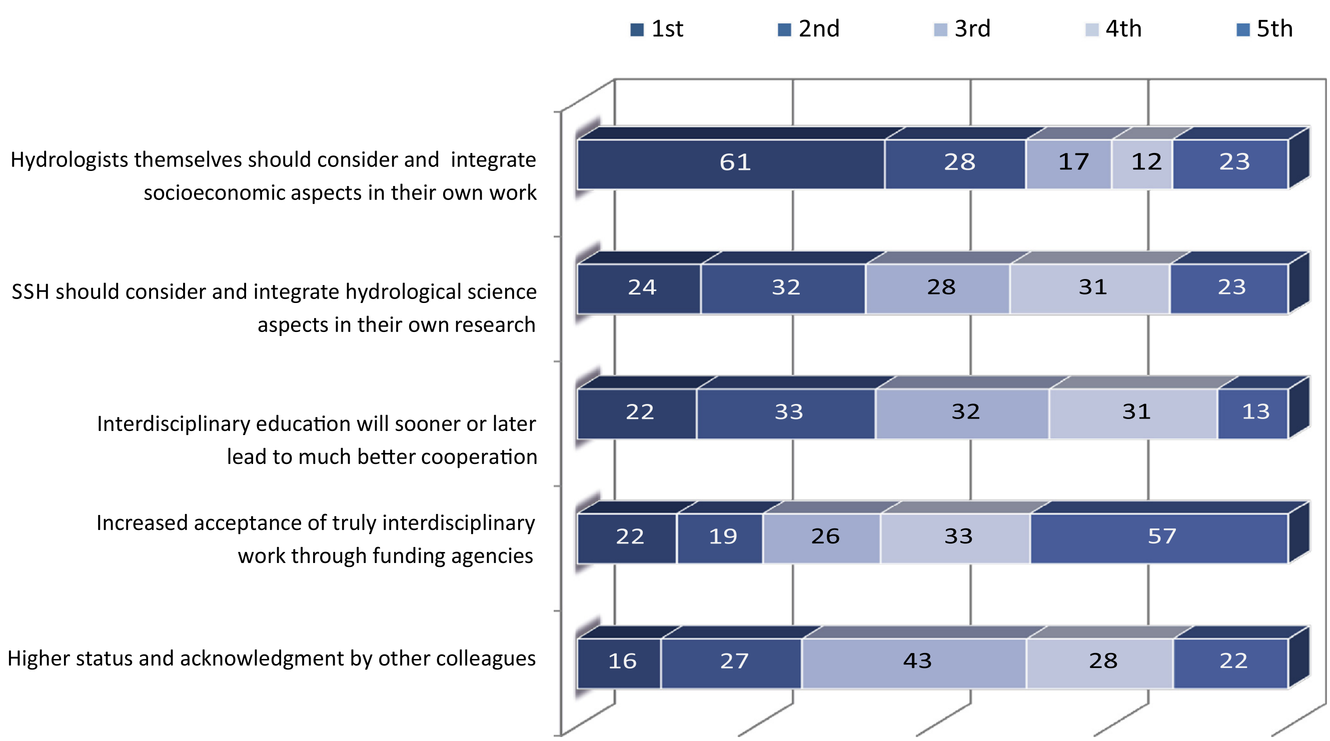

Fig. 5. Summative rank order of the five variables regarding how to improve cooperation (N = 287). Answers to the question "In your opinion, what would foster or improve cooperation between natural and social scientists the most? Please rank the following options in order." For instance, the variable "Hydrologists themselves should consider and integrate socioeconomic aspects in their own work" was ranked in first position 61 times.

a team of both groups than by single authors or mono-disciplinary teams. 2) Publications with multi- or interdisciplinary collaboration are more likely to include citations from both disciplines than from only one field.

The 58 analyzed publications contain around 4113 references and involve 204 authors, all of which were evaluated manually (i.e., we did not rely on the classifications provided by WoS or Scopus). We acknowledge that manual classification may introduce subjectivity and ambiguity into the results, but we are nevertheless convinced that the results indicate clear tendencies regarding the presence of multi- or interdisciplinary collaboration in an article.

The semi-quantitative study reveals several interesting findings. To a much higher degree than other hydrology articles, socio-hydrology publications are written by teams including scientists from fields other than the natural sciences. We cannot quantify the difference as we have not analyzed the author teams of other hydrology publications. However, readers may easily form their own opinions by searching the articles in *Water Resources Research* or *Hydrology and Earth System Sciences*, for example, where the vast majority of socio-hydrology articles are published. We estimate that 95–98% of all articles in these journals are written by mono-disciplinary teams (Barthel and Seidl, 2017). Similarly, the number of socio-hydrology articles citing equal numbers of SOSC and NASC references is much higher than that of typical hydrology articles that do so. We conclude that the connection between NASC and SOSC is much stronger in socio-hydrology than in almost all other branches of hydrology. Based on the relatively coarse indicators used, socio-hydrology seems to keep its promise to be the new interdisciplinary science of people and water, particularly with respect to collaboration. At the same time, we have learned that the issue of collaboration is a complex one. For example, the true roles of authors in a team can hardly be determined without performing a much deeper analysis, including interviews and surveys among authors. A cited reference may indicate everything, from adapting an entire concept to confirming a single bit of information to just acknowledging that other authors have conducted research in the same area.

What such deeper analysis may reveal becomes apparent upon closer examination of the contents of the articles with balanced author teams and references. In doing so, we have been unable to identify much of the anticipated interdisciplinary collaboration for the following reasons: 1) Many of these papers are discussions, opinions, or reviews and express plans and needs rather than presenting research. 2) Of the research papers, only four can be regarded as fully balanced with respect to author teams and cited references. Of these four (Kandasamy et al., 2014; Viglione et al., 2014; Elshafei et al., 2015; Wilson et al., 2015), two focus on NASC and do not use an SOSC methodology or SOSC concepts (Viglione et al., 2014; Elshafei et al., 2015), while the other two (Kandasamy et al., 2014; Wilson et al., 2015) do not use an NASC methodology. Thus, we regard these as attempts to create overlaps between hydrology and social science but not multi- or interdisciplinarity.

Our aim is to investigate where and how multi- or interdisciplinary collaboration between hydrology and social science actually takes place. We conclude that socio-hydrology in particular has progressed much further toward multi- or interdisciplinary collaboration than hydrology in general. Nevertheless, we could not detect a strong development of *interdisciplinary* collaboration, with some exceptions. In other words, socio-hydrology shows a higher degree of mutual recognition and exchange between hydrologists and social science disciplines, yet the interaction remains debatable.

4.2. Lessons learned from the empirical survey

As indicated in Section 3.1, our sample may be biased in several respects. First, the majority of respondents are employed in the research and education sectors, which probably does not reflect the actual distribution of professionals in hydrology among all sectors. However, in this study, we have focused on academic research. Second, many respondents report backgrounds in disciplines other than hydrology and seem to have relevant interdisciplinary backgrounds or work in environments that are already close to SSH. It is likely that those who have previously confronted interdisciplinary questions are more inclined to spend time answering a survey such as ours.

Basically, we find that the data can be grouped into three themes. The first theme involves the ideas of *codesigned research*, *close interaction*, and *knowledge exchange*. This theme indicates substantial contributions from both disciplines. The second theme entails *classic social science analyses*. The third theme comprises activities related to the *translation of research results for decision makers* and *communication of the results to the public*. Our sample shows that the second theme is perceived as more common in SSH, whereas the first and the third themes are more prevalent in HS.

Hydrologists' expectations about *who* should do *what* in integrative work reveal that they perceive the following roles as applied similarly by colleagues from both SSH and HS: *facilitate resource management*, *exchange knowledge*, *communicate the results*, *reflect on the normative aspects*, and *secure public acceptance*. However, the hydrologists also assume that SSH is more responsible for certain tasks, such as *studying the socioeconomic aspects and the impacts of human decisions on the environment*. Higher status and acknowledgment by colleagues do not seem to be major incentives for integrative work, ranking lowest of all the options. However, the statement "*Hydrologists themselves should consider and integrate socioeconomic aspects in their own work*" is rated most often as the most preferable. Funding agencies' increased acceptance of interdisciplinary work is also considered important.

These results can be interpreted to mean that hydrologists would like to learn from SSH and apply that knowledge themselves. In other words, they intend to *integrate* social science tasks into *their* field or into a new discipline, for instance, *socio-hydrology*. Loucks (2015, p.4792) addresses this challenge by posing (and answering) the following questions: "Should hydrologists be trying to predict human behavior? Should they be including nonhydrologic components in their hydrologic models[?] I suggest if we who have some expertise in hydrologic modeling do not[,] some other discipline will." He acknowledges some hydrologists' efforts to incorporate "economic or social components linked to hydrologic processes" Loucks (2015, p.4792) against the resistance of proponents of mainstream hydrologists.

We suggest that researchers interested in integrating disciplines should transparently specify how they intend to achieve this and what their mutual expectations are. In the case of socio-hydrology, this seems neither evident nor explicitly done. Overall, these results underscore the insights derived from the literature overview.

Generally, the participants do not think that SSH is well integrated into hydrological research, and the majority recognize the need for better cooperation between the two. However, not all of those who claim that integration is not currently taking place also believe that it may need improvement. Moreover, subgroups of the participants (clusters) differ with respect to the ratings. Particularly, cluster 1 differs from cluster 3 in the belief that codesigning research with SSH is less important. However, both clusters think that communication issues are less important in hydrology. Cluster 2 instead states that all three issues are of equal importance for hydrologists.

In future studies, it would be worthwhile to analyze actual interdisciplinary practices of colleagues working in the field of hydrology. This analysis would need a more qualitative approach, but researchers would gain more insights into how exactly hydrologists and engineers working in the field of hydrology collaborate with colleagues from the social sciences and the humanities. Moreover, it would be interesting to check whether the survey results on the nature of future collaboration improvement are valid. Researchers could investigate the reasons for the notions of how collaboration might proceed (e.g., ask deeper why hydrologists themselves should be immersed in social science methods and approaches). One reason might be the perceived lack of methodological rigor (i.e., quantitative analysis and modeling), but there might be other explanations.

4.3. Future developments of collaboration between hydrology and SSH

In this section, we discuss hydrologists' claims that they foster IDR against the background of genuine interdisciplinary literature and survey results.

Reddy and Syme state, "If hydrology is to continue to have a beneficial impact on the water resource and the community it needs to seek to place itself in partnership with social scientists. The obligation is mutual, social scientists can only provide benefit for water problems if they have access to sound hydrological knowledge" (Reddy and Syme, 2014, p.1).

However, fundamental assumptions about how to pursue and advance science have to be considered. As Wesselink et al. (2017) discuss in their comparison of socio-hydrology and hydrosocial research (a social science branch of human geography), a gap between both approaches is linked to socio-hydrology's focus on quantitative methods and computational modeling, whereas hydrosocial approaches concentrate on understanding and theorizing. In a similar vein, Sharp et al., (2011) distinguish between positivist and post-positivist approaches (see also, Connelly and Anderson, 2007) in water research. One example is *water demand*, which can be defined in a "positivist format as the average volume of water demanded from a water body per person per unit of time" (Sharp et al., 2011, p.504). From a post-positivist perspective, *water demand* would also comprise cultural issues (hygiene and convenience) and water abundance, which would influence expectations of availability.

As long as hydrologists assume the quantitative (positivist) approach as superior to other, more qualitative methods, the road toward more and better communication and collaboration between the disciplines appears bumpy (including basic philosophical assumptions of science, Connelly and Anderson, 2007; and communication challenges, Krueger et al., 2016; Bracken and Oughton, 2006).

Hydrology researchers will more frequently encounter representatives of SSH in the future, which will hopefully result in mutual inspiration. Socio-hydrologists may also consider existing research streams in hydrology that deal with inter- and transdisciplinarity (e.g., Giupponi et al., 2006). Moreover, the following provocative statements are presented here as food for thought to open up a discourse on the future of hydrologists' efforts to collaborate with other disciplines:

(i) Socio-hydrology is meant to be an *interdisciplinary* field, yet it does not refer to any protocols (or best practices) for doing interdisciplinary work. The term *interdisciplinary* is rather understood as incorporating aspects of SSH into hydrology.
(ii) Socio-hydrology has not acknowledged much previous work on integrated models undertaken by hydrologists and social scientists.
(iii) Socio-hydrology is still dominated by hydrologists, who have adopted a perceived hegemonic attitude toward *interdisciplinary* collaboration with social scientists.

What scholars who are familiar with the literature on interdisciplinary cooperation may miss in interdisciplinary endeavors in the field of hydrology (including but not limited to new concepts such as socio-hydrology) is the reflection on the collaboration process itself. Some researchers would expect to read more on ideas about how to accomplish the promised interdisciplinary collaboration, relating the current hydrological approach to key literature on interdisciplinary processes (Bammer, 2012; Wiek and Larson, 2012; Campbell, 2005; Carayol and Thi, 2005; Heberlein, 1988; Klein, 2013).

This observation is also evident in our analysis of socio-hydrological literature. Although collaboration or rather connections between hydrology and SSH are indicated by mixed author teams and mutual citations between the disciplines, the collaboration seems to stop there. Codesign of research may be attempted but not achieved.

Another example for such a development involves the field of ecology, which originally comprised human systems but has later mostly excluded these systems from ecological concepts. McIntosh (1985, p.319) discusses this issue: "If human factors are beyond ecological consideration, what then is human ecology? It is not clear whether ecology will expand to encompass the social sciences and develop as a metascience of ecology. The alternative is a more effective interdisciplinary relationship between ecology and the several social sciences." Additionally, Bradshaw and Bekoff (2001) discuss interdisciplinarity in terms of incorporating SSH elements into biophysical research (i.e., considering humans in ecosystem concepts), which resembles a rather instrumental notion of cooperation and assumes that the predominant perspective is that of the natural sciences. In a similar vein, socio-hydrology faces the risk of being accused of a hegemonic attitude. This would likely harm the potential of the otherwise highly welcome and timely concept. Therefore, we recommend highlighting its interdisciplinary manner more than before by detailing the methods and the processes of interdisciplinary work and referring to the appropriate literature, for instance. According to our literature overview, this undertaking has already or only partly been done so far.

Revisiting the three dimensions discussed by Huutoniemi et al., (2010)—the scope of interdisciplinarity, the type of interaction, and the different goals or functions of interdisciplinary work—we find that the third dimension (*why*) is addressed by socio-hydrology through the link to the concept of the Anthropocene and the importance of including humans' impact on the water cycle and geological processes. Specifically, the coevolution of human and ecological systems should be acknowledged and made a core topic of socio-hydrology.

However, the literature about socio-hydrology seldom explicitly states *what* is integrated; in other words, the scope of interdisciplinarity is unclear. Three factors emerge from the survey results that hint at areas where socio-hydrology should be careful in respecting the expectations from hydrologists (and SSH researchers, although we did not explicitly include this perspective in the survey).

Moreover, the literature is largely silent concerning *how* the integration will occur; rarely do we find hints about the architecture of integration or the methods used to arrive at a more holistic understanding of socio-hydrological systems and insights into coevolution (Pohl et al., 2007). Regarding *how* integration occurs, Klein (2008, p.119) highlights evaluation questions, including whether "known integrative techniques [have] been utilized, such as the Delphi method, scenario building, general systems theory, and computer analyses of stakeholders' perspectives" or whether there is "a unifying principle, theory, or set of questions that provides coherence, unity, or both." Again, the survey results show that most hydrologists think that they are able and eager to take the lead and integrate SSH methods and knowledge into their own work. Current approaches to socio-hydrology should deal with this claim and explain the hydrologists' methodological portfolios. Probably some hydrologists, currently hesitating to collaborate with researchers from the social sciences and to rely on their expertise and methods, may feel more confident if the discourse among hydrologists also covers the *how* question.

From the preceding discussion of the study results, we conclude that attempts at collaboration between hydrology and other disciplines need to mature further with respect to their aims and integration methods. We acknowledge that researchers have already made considerable progress, and we appreciate their efforts, particularly those that highlight the need to cooperate and address the coevolution of human and ecological (water) systems.

Highlighting some open questions regarding the conceptualization of interdisciplinary cooperation may provide a basis for further elaboration of the concept and help it receive wide attention among hydrologists as it deserves. The questions are as follows:

- What kind of interdisciplinarity do different scholars want to achieve in their attempts at collaboration between hydrology and other disciplines?
- A mutual understanding of what hydrologists and SSH do and how they should contribute to interdisciplinary collaboration has not been well developed yet. Thus, what are social scientists' preferred roles and knowledge within socio-hydrology research themes and projects?
- Collaboration between SSH and hydrology needs improvement, but how to do so is unclear. Thus, what knowledge integration measures may facilitate a more holistic research agenda for hydrology?
- How can the existing literature about inter- and transdisciplinarity, as well as successful examples from hydrology and other fields of environmental science, be better considered in socio-hydrology? We regard it as crucial that researchers now engaging with new integrative concepts acknowledge and consider the work of those who have conducted and published research at the interface between scientific disciplines and the interface between science and society over a long period. Thus, how can the existing literature about inter- and transdisciplinarity, as well as successful examples of hydrologists, be better considered in socio-hydrology?

We conclude that increasing interdisciplinary collaboration (as previously defined) between hydrologists and researchers from other disciplines, such as SSH, will inevitably result in friction and sometimes conflict. These typical problems may arise from interactions across disciplines, with misunderstandings due to discussions at different levels in various languages. These issues may lead to frustration for those involved. However, we emphasize that this phenomenon is not unusual or unexpected but a normal process that nevertheless should be taken seriously. Moreover, the challenges ahead for those attempting to link hydrology and other disciplines have been deliberated in key literature in other cross-disciplinary settings, which also presents the tools to surmount the challenges (Fischer et al., 2011; Campbell, 2005; Sievanen et al., 2012). One such tool is collaborative writing because scientific papers constitute the currency of natural and social sciences researchers alike (although there are some exceptions, for instance in sociology and especially the humanities, where books and book chapters still count for much; Pohl et al., 2015). Overall, this issue could be framed as an agonistic form of collaboration (Barry and Born, 2013), which would force colleagues from different disciplines to collectively work and decide on joint writing endeavors. As Krueger et al., (2016) highlight, this form of collaboration should become more frequent and be understood as a welcome challenge for disciplinary knowledge.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jhydrol.2017.05.008.

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