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Abstract

This paper is the outcome of a community initiative to identify major unsolved scientific problems in hydrology motivated by a need for stronger harmonisation of research efforts. The procedure involved a public consultation through on-line media, followed by two workshops through which a large number of potential science questions were collated, prioritised, and synthesised. In spite of the diversity of the participants (230 scientists in total), the process revealed much about community priorities and the state of our science: a preference for continuity in research questions rather than radical departures or redirections from past and current work. Questions remain focussed on process-based understanding of hydrological variability and causality at all space and time scales. Increased attention to environmental change drives a new emphasis on understanding how change propagates across interfaces within the hydrological system and across disciplinary boundaries. In particular, the expansion of the human footprint raises a new set of questions related to human interactions with nature and water cycle feedbacks in the context of complex water management problems. We hope that this reflection and synthesis of the 23 unsolved problems in hydrology will help guide research efforts for some years to come.

Keywords hydrology, science questions, research agenda, interdisciplinary, knowledge gaps

1 Soliciting ideas for a science agenda for hydrology

"*Hydrology is in the same situation as many other sciences which through rapid growth and sub-division have suffered from lack of coordination of effort and incomplete correlation of results. [...] There is, in hydrology, as already noted, (a) a large mass of unassimilated data, (b) a mass of mostly uncoordinated results of research, and (c) a galaxy of unsolved problems.*" Horton (1931, p. 201). The calls of Robert Horton have been echoed by numerous other hydrologists since then (e.g. Dunne, 1998; Klemeš, 1986; Dooge, 1986; McDonnell et al., 2007; Thompson et al., 2013), changing in emphasis as new technologies and new societal challenges emerged, but the underlying theme of a need for better coordinating the hydrological research agenda has been surprisingly similar over almost a century (Sivapalan and Blöschl, 2017).

Science profits from a continuous process of self-reflection, and hydrology is no exception. David Hilbert gave a remarkable example of how identifying a research agenda has invigorated research (Hilbert, 1900). He launched a set of 23 unsolved problems in mathematics at the Second International Congress of Mathematicians held in Paris in 1900. The introduction of his speech reads as quite profound as it is poetic (Fig. 1): "*Who among us would not be tempted to lift the veil behind which is hidden the future; to gaze at the coming developments of our science and at the secrets of its development in the centuries to come?*" His set of 23 unsolved problems is widely considered to be the most influential one ever to be produced by an individual mathematician. Some of Hilbert's 23 problems have been solved in the meantime, for others the solution is still pending and, overall, they have greatly stimulated focused research in mathematics.

Following the example of Hilbert, a number of collections of unsolved problems have been compiled since then, such as the Millennium Prize problems of the Clay Mathematics Institute. Other disciplines, such as biology and ecology (Dev, 2015; Sutherland et al., 2013), have also followed suit.

A similar exercise could also invigorate research in hydrology, given the need for stronger harmonisation of research efforts and clearer articulation of the community's central research questions. As the societal problems related to water are becoming ever more complex, streamlining a community science agenda is more important than ever. There have been a number of previous initiatives to compile science agendas for hydrology or some subfield of hydrology. Some of these agendas were compiled at the national level (e.g. NRC, 1991; NRC, 1998; KNAW, 2005), others at an international scale (Kundzewicz et al., 1987; Sivapalan et al. 2003; Oki et al., 2006; Thompson et al., 2013; Montanari et al., 2013). Such initiatives are highly commendable and they influenced the progress of hydrology in various ways (Hrachowitz et al., 2013; Rajaram et al., 2015; Sivapalan and Blöschl, 2017). The focus of most of these initiatives was on assessing the status of the field and on developing and justifying a science plan in depth. Thus they were usually pursued by a relatively small group of people. For example, the Hydrology 2000 and 2020 foresight reports of the IAHS (Kundzewicz et al., 1987; Oki et al., 2006) involved 12 committee members each; the US National Research Council ”blue book“ (NRC, 1991) involved 19 committee members. It is now of interest to explore whether there is something to be learned by broadening the consultation process, given past successful community initiatives.

Motivated by the previous efforts, an open community process was initiated covering all areas of hydrology. The goals of the initiative identified during the process were:

- Increasing the coherence of the scientific process in hydrology (thus overcoming fragmentation) through providing common research subjects. This could, among other things increase the structure and coherence of the sessions at IAHS[1] , EGU[2] , AGU[3] and IAH[4] meetings.
- Energising the hydrological community through increasing the awareness that we do not fully understand many hydrological processes (thus overcoming complacency). We need more discovery science and outrageous hypotheses (Davis, 1926).
- Speaking with one voice as a community to increase public awareness and enhance funding opportunities for community projects.

This paper presents the outcomes of this exercise and reflects on the community input.

2 The process of community consultation

2.1 Overall approach and initiation of the process

The idea of compiling a set of unsolved scientific problems in hydrology was first aired at the IAHS Scientific Assembly in Port Elizabeth, South Africa, in July 2017. During the plenary session, attended by some 100 scientists, discussions took place regarding the initiative, the nature of the unsolved problems or questions and the consultation process.

From the beginning it was clear that hydrology is different from mathematics in a number of ways. Importantly, most hydrological problems, or science questions, cannot be stated with the same accuracy as in mathematics. This is because the boundary conditions and system characteristics are never fully known, while mathematics studies a well defined, closed system. Unlike mathematics, hydrological problems do not necessarily have objective, verifiable and general solutions. This is because hydrology is a landscape-scale science where repeatable experiments are rare and we rely on one-off observations. Also, part of the hydrological cycle occurs underground, and so cannot be observed directly. Lastly, hydrology is a cross-cutting discipline with a close link to practice. To account for these specifics of hydrology, three types of questions were identified:

- “Why” questions relating to phenomena (e.g. Why are there wind waves?)

[1] International Association of Hydrological Sciences
[2] European Geosciences Union
[3] American Geophysical Union
[4] International Association of Hydrogeologists

- “What” questions relating to processes or estimation (e.g. What is the effect of increased rainfall intensity on landslide probability?)
- “How” questions relating to methods (e.g. How can we estimate runoff in ungauged basins?)

The IAHS Commissions and Working Groups were engaged in providing inputs in terms of unsolved problems and procedure. Additional consultations were made with the hydrology sections of EGU and AGU, as well as with the IAH. Ideas on the process were also taken from similar exercises (e.g. Sutherland et al., 2013). Finally, the following steps were followed:

2.2 Seven steps

Step 1: Video launch

A video was published on YouTube on 14 November 2017[5] outlining the purpose of the initiative and the vision. Specifically it was requested that, to make tangible progress, the problems should:

- ideally relate to observed phenomena and why they happen;
- be universal (i.e. not only apply to one catchment or region); and
- be specific (so there is hope they can be solved).

The video also outlined the procedure and solicited input. The video was advertised through the IAHS mailing list (containing addresses of 8500 hydrologists across the world), social media and other channels. That video had been viewed about 1500 times by April 2018.

Step 2: Discussion via a LinkedIn group

The LinkedIn group IAHS – International Association of Hydrological Sciences[6] was established. All IAHS members were invited to join, and so were the sister associations and partners, and all hydrologists. The IAHS Commissions and Working Groups were tasked with contributing to streamlining the discussion and coming up with three unsolved problems each. The AGU Hydrology Section had a WebEx meeting with each of the Chairs of the 13 Technical Committees (TC). The TCs identified the three most important questions in their sub-groups, which were later published in the July 2018 Hydrology Section newsletter[7]. The Chairs of the EGU-HS SubDivisions (SD) were invited to discuss the initiative with their members and contribute to the LinkedIn group. With IAH, the heads of the scientific commissions and networks were asked to make up to three suggestions each, from which a list of 10 groundwater-related questions was compiled by the Executive and forwarded to IAHS. There was a lively discussion in the group (Fig. 2). A total of 83 contributions were posted as well as a total of 120 responses. The LinkedIn group was not only used to generate ideas but also to discuss some of them in terms of their relevance and focus. The questions varied widely. The IAHS president (the first author of this paper) encouraged “why” questions related to discovery science, but it was noted that the majority of the questions related to “what” and “how” questions. Additionally, the questions varied widely in terms of their specificity. The advice from previous exercises (Sutherland et al., 2013) pointed towards the value of more specific questions, or at least a more uniform specificity across questions. A question considered rather broad, for example, was “What are the main processes controlling transport and transformation of contaminants across scales?”, while a rather specific question suggested was “Why are the distances from a point in the catchment to the nearest river reach exponentially distributed?” The IAHS president gave feedback on his assessment of the specificity of the questions posted until then to be considered by the community.

[5] https://www.youtube.com/watch?v=jyObwmNr7Ko&feature=youtu.be
[6] https://www.linkedin.com/groups/13552921
[7] https://hydrology.agu.org/wp-content/uploads/sites/19/2018/07/HS-July-2018-Newsletter-Final.pdf

The LinkedIn group was also used to communicate the proposed procedure and seek feedback, although minimum discussion on it took place. One of the limitations of the group discussion was the introduction of login requirements, even for reading, which was not anticipated at the start and about which some colleagues expressed concern. As a response, input was also solicited through email, which was uploaded to the group.

Step 3: Splinter meeting at EGU

A Splinter meeting was scheduled for Friday 13 April 2018, at the EGU General Assembly in Vienna, and widely announced in order to maximise the input from the community in the consultation process. Attendees were encouraged to consult widely. The EGU-HS SD Chairs were asked to provide the input and point of view of each EGU-HS community. The meeting was attended by about 60 scientists. The initial plan for the Splinter meeting was to go through the existing set of questions, brainstorm additional questions, identify and merge questions, and set priorities. It turned out that the participants only partly overlapped with the contributors to LinkedIn, so most of the time of the meeting was spent on brainstorming additional questions. At the end of the meeting a total of about 260 candidate problems had been received through the LinkedIn group, email and the Splinter meeting.

Step 4: Vienna Catchment Science Symposium (VCSS)

On the following day, Saturday 14 April 2018, the Ninth VCSS was dedicated to the UPH initiative and attended by about 110 scientists. The meeting started with a short round of statements by panellists from IAHS, AGU, EGU, IAH and the hydrology community at large. Subsequently, the participants broke up into four parallel discussion sessions of 105 minutes. To this end, the IAHS president had divided the candidate problems into four groups:

(1) Floods and droughts; Hydrological change; Humans and hydrology

(2) Snow and ice; Evaporation and precipitation; Landscape processes and streamflow

(3) Scale and scaling; Modelling; Measurements and data

(4) Water quality; Groundwater and soils; Communicating hydrology; Engineering hydrology

Each of the four parallel sessions received one group of candidate problems to sort, merge, split, reword and prioritise. It was noted that the grouping was not final and should not have a bearing on the final outcome of the unsolved problems. The sorting, merging, splitting and rewording was left to the groups led by moderators and assisted by scribes who recorded the group decisions. It was suggested that questions of comparable specificity would be of advantage, and duplication should be avoided. For prioritising the lists, a method inspired by Sutherland et al. (2013) was adopted. As a start, discussions were held about which questions were unlikely to make it to the final list and should be excluded. Subsequently, the questions were ranked into ‘gold’, ‘silver’, ‘bronze’ and ‘remove’ in order of decreasing importance, by majority voting of the participants present at each session (Fig. 3).

These sessions were repeated twice more, and each time the participants were asked to change sessions, so that the four groups consisted of different combinations of people. Also, new moderators were asked to chair the sessions. The three rounds of sessions were considered essential, as the sorting, merging, splitting, rewording and voting was an iterative process. Only the gold and silver questions were retained for a plenary session with an additional round of voting (by all participants) for gold, silver or removal from the list. The idea was to whittle down the 260 questions initially proposed to a more coherent and smaller set of most important questions. The process resulted in 16 gold and 29 silver questions, which were then posted on the LinkedIn group and the IAHS website.

Step 5: Synthesis and addressing biases by a small working group

The synthesis process was inspired by that of Thompson et al. (2011), which recognised that two complementary classes of activities are required in synthesis: (a) *generative activities* in which new questions are generated, and (b) *consolidation activities* in which the questions are prioritised, revised, merged and put into the context of the literature (Fig. 4). Steps 2 and 3 involved the generative activities, while Step 4 consisted of consolidation activities. During the VCSS a small working group, involving representatives and members of IAHS, IAH, EGU and AGU, was appointed to consolidate, interpret and synthesise the questions, as well as address potential biases in their selection. Biases may have arisen from the composition of the participants at the VCSS due to differences in the visibility of the process in different subareas of hydrology. Additionally, the voting may have been affected by the specificity of the questions, with more general questions receiving more votes than more specific ones. The working group therefore consolidated the questions with a view to minimising bias. In this process, a few candidate questions (from the set of 260) that were not ranked gold or silver were reintroduced. The working group also merged questions for unifying the level of specificity and reducing their number. The decision of whether 23 (following Hilbert) or another number of questions would be appropriate was left open during the VCSS (Step 4) and the working group decided on 23, in line with the initial call in Step 1. In consolidating the questions (Supplementary material, Table S1), the intention of the symposium group in terms of gold and silver categories was adhered to by giving higher weight to gold questions than to silver and other questions. The working group also pooled the questions into seven themes for clarity and communication, but without changing the contents. As a result of the synthesis process, the working group proposed a set of 23 questions and prepared a draft of the present manuscript.

Step 6: Final consultation process

It was agreed at the outset that all scientists actively contributing to the process of community consultation should be offered co-authorship of the final publication. This was to recognise the individual contributions and to signal responsibility for the final outcome of the process. The manuscript draft including the 23 questions was sent to all 230 potential co-authors. At this stage, no final poll was conducted, but consensus among all co-authors was sought.

Step 7: Publication in *Hydrological Sciences Journal* (*HSJ*)

Finally, this manuscript was submitted to *HSJ* and peer reviewed by three referees. The review process resulted in some modifications of the manuscript to enhance its clarity, but the set of unsolved problems was not modified.

2.3 Limitations of the process

An initiative such as this, of course, has limitations (Sutherland at al., 2011). Most importantly, it is likely that there are remaining biases due to non-representativeness of participants. The Splinter meeting and symposium were held in Europe, which may have reduced the number of participants from other continents and more generally from countries where travelling abroad is difficult. The organisers were aware of the potential for biases and worked on reducing them from the beginning, e.g. through electronic communication. Also, 11 of the 13 members of the working group were from Europe, while the remaining two members were from North America, possibly reflecting biases in the associations themselves. Additionally, some subfields of hydrology were perhaps not well represented. It was noted during the LinkedIn discussion that there were relatively few questions related to groundwater, and an effort was made to get more groundwater questions through representatives of the IAH. Also, there were not many questions on rainfall processes and ecohydrology. The members of the working group did represent all subfields of hydrology well. Finally, some scientists noted that the discussion through LinkedIn may have formed a potential barrier as registration was required, with which some people might not have felt comfortable. For this reason candidate questions were also accepted through email.

3 Outcomes

The 23 unsolved questions are presented in Table 1. They are listed by theme but not in rank order.

3.1 Time variability and change

The questions on time variability and change mainly revolve around detecting, understanding and predicting changes in the water cycle due to human and natural causes during the Anthropocene. Questions 1, 2 and 3 specifically relate to climate change. Even though climate change has been on the 'radar' of hydrologists since the late 1970s (e.g. Lettenmaier and Burges, 1978) and the subject of major hydrological programmes since the late 1980s (see, e.g. Gleick, 1989), there are still many unresolved fundamental issues remaining that are high-priority for hydrologists. Question 1 is related to whether the hydrological cycle is accelerating (i.e. increasing fluxes and smaller residence times) and whether abrupt transitions from one regime to another (tipping points) have occurred or will occur in the hydrological system. Even though longer data records and more accurate models are becoming available, regime changes in complex systems are notoriously difficult to identify (e.g. Ditlevsen and Johnsen, 2010). Questions 2 and 3 are more practical and focus on cold places and dry places, respectively, where climate change impacts on hydrology and society are potentially largest and certain types of regime shifts have been identified (e.g. Karlsson et al., 2011; Mazi et al., 2014).

Question 4 relates to land-cover/land-use changes and their effects on hydrological fluxes, a topic that has been on the hydrological agenda for many decades, as illustrated by the early establishment of experimental catchments studying the effects of forests on streamflow, e.g. Emmental in Switzerland in 1900 (Strele, 1950), and Coweeta in North Carolina around 1930 (Douglass and Hoover, 1988). This question is of practical interest for water and land management, and of theoretical interest related to the question of how water, vegetation and soils interact across multiple time scales – despite almost 500 paired watershed studies to date, results of forest harvesting and afforestation are largely unpredictable (McDonnell et al., 2018). Changes in aquifer recharge (Question 4) may have profound effects on the management of groundwater. The Panta Rhei initiative of IAHS on change in hydrology and society (Montanari et al., 2013; McMillan et al., 2016) and numerous other programmes and studies on change in hydrology around the world (e.g. Destouni et al., 2013) are a reflection of the observation that hydrological change remains an important research issue.

3.2 Space variability and scaling

Question 5 was a merger of six silver questions that were all very similar in terms of understanding the nature of spatial variability of hydrological fluxes. The angle was slightly different from the perspective of PUB (Predictions in Ungauged Basins; Hrachowitz et al., 2013; Blöschl et al., 2013). While PUB sought to explain spatial variability and similarity by the co-evolution of the landscape with hydrological processes, Question 5 gives equal emphasis to why there is homogeneity, i.e. a *lack* of spatial variability in these hydrological characteristics.

Question 6 is the classical scaling question of how point-scale equations relate to catchment-scale equations. This issue has attracted a lot of attention beginning in the late 1980s when distributed hydrological catchment models came within the reach of many hydrologists (Gupta et al., 1986) and, similarly, in subsurface hydrology with the emergence of stochastic hydrogeology (Gelhar, 1986; Dagan, 1986). Since then, the interest has not wavered, but has gone beyond the sole treatment as a boundary value problem in the early days by including co-evolutionary ideas (Sivapalan, 2003; Savenije, 2018). Of course, the distribution and nature of flow paths is central to both questions 5 and 6, and this is what questions 7 and 8 address. Although the role of earthworms in water flow in soils was recognised early on (Darwin, 1881), it took a full century for the idea to become mainstream (Beven and Germann, 1982). Since then it was recognised that preferential flow tends to occur at all scales and in all compartments of the hydrological cycle, not just in soils, but the causes for this phenomenon are still unclear. It is curious how very little we know about the cycling of water underfoot, "The frontier beneath our feet" (Grant and Dietrich, 2017), even though the flowpaths, stores and residence times are so central to the understanding of the hydrological cycle (Sprenger et al., 2019). Much of this portion of the water cycle appears compartmentalized and the community still has a long way to go to include the velocities, celerities and residence time distributions of the catchment hydrograph (McDonnell and Beven, 2014).

3.3 Variability of extremes

The working group decided to keep extremes as a separate theme, as they are not fully captured by time and space variability. Extremes (floods and droughts) are unique in the dimension of "magnitude". Nature responds to extremes disproportionally (floods transport sediments, droughts kill plants) and so does society. Question 9 on the existence of and cause of flood-rich and drought-rich periods is a merger of three gold questions (related to the detection, attribution and characteristics of such periods, respectively), so is considered very important by the community. It is related to the Hurst phenomenon, which became of interest in the 1970s in the context of reservoir capacity design, treated mainly by statistical methods (Klemeš, 1974). The renaissance came with climate change, a decade ago, when a more process-based stance was adopted, singling out teleconnections as one of the possible causes, and the need for going beyond trend analyses was highlighted (Hall et al., 2014). On the other hand, land-cover/land-use change effects on floods and droughts (Question 10) are of continuous concern, and link well with the temporal variability theme and with questions 7 and 8 on flow paths.

Question 10 also links hydrological extremes with geomorphological processes, both along the river reaches and more generally in the catchment, e.g. rock falls and landslides due to permafrost melting, and hillslope changes with new or ageing land use/structures (Rogger et al., 2017). As is the case more generally in geomorphology, an interesting aspect here is how processes interact across space and time scales (Lane and Richards, 1997; Kirkby, 2006). Even though Question 11 is more specific than some of the other questions, it was retained because the common observation that rain-on-snow events often produce bigger floods than expected is a clearly defined and yet vexing phenomenon, and because of the important role of this kind of flood mechanism in many parts of the world (McCabe et al., 2007).

3.4 Interfaces in hydrology

Questions 12 and 13 deal with fluxes and flow paths across compartments (e.g. subsurface–surface) including their physical-chemical-biological interactions. These interface processes have had a tendency of "falling between the cracks" in hydrological research, partly because research is often organised by compartments and disciplines (Krause et al., 2017), but with the advent of the concept of a "critical zone" the awareness of their importance has increased dramatically, e.g. as illustrated by the establishment of Critical Zone Observatories by the US NSF (e.g. Anderson et al., 2008;

Rasmussen et al., 2011). Also, with the advent of hyper-resolution, global hydrological modelling (Bierkens et al., 2015), and data-driven comparative multi-catchment studies across continents (Orth and Destouni, 2018), there is a realistic chance to go beyond understanding groundwater recharge and other inter-compartment fluxes locally (which is still a daunting task) and address these issues at regional and continental scales. This includes groundwater discharge into the ocean (Question 13), which is clearly an under-researched area (Prieto and Destouni, 2011) and yet of great importance from a global water and ecosystems perspective.

Conceptually, much of the hydrological variability in time, space and of extremes arises from interfaces, as the internal mechanisms have a bearing on what one sees outside. The task for hydrologists is to open that black box, by acquiring a physically-based and universal understanding of the interfaces. A disciplinary interface is that with water quality, as much of the research is done by biogeochemists and biologists whose primary home is not hydrology. Question 14 addresses this interface, involving, for example, controls on the long-term spatio-temporal evolution of catchment water quality and the persistence of sources contributing to the degradation of water quality. Indeed, it has been a puzzling phenomenon that, for example, nitrogen sources linger such a long time in catchments even though emissions have been reduced for years (e.g. Ascott et al., 2017; Van Meter et al., 2018). Increased data availability and process-based theory are now paving the way to identifying (sub)catchments where such legacy sources are dominant in controlling water quality (Destouni and Jarsjö, 2018). It is also becoming clear that the topic of water and health is no longer just of importance to the water chemistry and microbial research communities, but also to the hydrological community (Question 15), as reflected, for example, by the recent launch of the *GeoHealth* journal by the AGU. Both advancements in microbial analytical methods and a move towards risk-based methods (as opposed to the traditional travel time-based methods) in drinking water management require a closer integration of hydrology with hydrogeochemistry and microbiology (e.g. Mayer et al., 2018; Dingemans et al., 2019).

3.5 Measurements and data

Many early hydrology books were mainly about hydrometry (e.g. Schaffernak, 1935). With the advent of remote sensing and digital data recording in the 1980s, there was a renewed interest in measurement methods and, more recently, there has been another boost of new technologies. These include non-invasive measurement systems for surface hydrological processes, e.g. with cameras and particle detection through image analysis, use of unmanned aerial vehicles, new tracer methods based on (micro)biota analysis (e.g. diatoms), and hydrogeophysics (Tauro et al., 2018). Clearly, the community recognises that not all the potential has been exploited so far (Question 16). The establishment of working groups on measurements, e.g. MOXXI (the Measurements and Observations in the XIst century, Working Group of IAHS), is a reflection of this recognition.

One aspect that has particularly defied progress is the measurement of large-scale fluxes (apart from discharge), and the measurement of subsurface fluxes at any scale. One potential path forward is the use of proxies, replacing few accurate data by many less accurate data, e.g. by using qualitative observations from lay persons or from data mining; however, it is not yet clear exactly what proxies would be of most benefit in a particular situation (Question 17). Similarly, it is not clear under what conditions one can infer past or future trajectories of hydrological systems from contemporary spatial patterns ("space-for-time" substitution). Similar statements apply to the conceptualisation and modelling of coupled human–water systems, which, in the past decade, has been dominated by stylised models using little data, yet a more solid data base. This has included the fusion of quantitative with non-quantitative data, as well as hydrological with other types of data (e.g. socio-economic, land-use; Pan et al., 2018), and seems essential for making further progress (Question 18) (see also Mount et al., 2016; Hall, 2019; Di Baldassarre et al., 2019). There are many datasets from local socio-hydrological studies throughout the literature. Compiling a database and performing a meta-analysis of these studies would be beneficial. An important element of our ability to reverse the current trend of decline of observation systems will be the ability to convincingly put a value on hydrological observation systems with open data (Question 17), perhaps building on novel developments in crowd-sourcing and Citizen Science, e.g. as reflected by CANDHY (the Citizen AND HYdrology Working Group of IAHS).

3.6 Modelling methods

Interestingly, there were relatively few modelling questions in the set of questions ranked as gold and silver. This may have been related to giving more visibility to “why” questions related to discovery science in the initiation of the communication process than to “how” and “what” questions related to modelling. Question 19 deals with the important challenge of developing hydrological models that can extrapolate to changing conditions (in particular vegetation dynamics) (Seibert and van Meerveld, 2016). Most hydrologists would probably agree that this will require a more process-based rather than calibration-based approach (Sivapalan et al., 2003), as calibrated conceptual models do not usually extrapolate well (Merz et al., 2011; Thirel et al., 2015). This would probably also include abandoning the use of potential evapotranspiration in modelling evaporation (Savenije, 2004).

An issue hydrology has been grappling with in the past four decades is model uncertainty (Pappenberger and Beven, 2006; Montanari, 2007). Although much progress has been made, in terms of both methods and awareness, Question 20 suggests that there is still work to be done, in particular on model structural uncertainty, which is more elusive than model input and parameter uncertainties (Kirchner, 2006). A more coherent framework of modelling uncertainty would certainly be desirable. During the symposium, one candidate question on whether development of a community model would be a suitable goal was discussed with much fervour, but it did not make it into the silver and gold lists. Apparently, the context-dependence or uniqueness of place (Beven, 2000) continues to be considered a relevant factor in hydrology, notwithstanding a range of modular models and model repositories that have been developed in the past decades (e.g. Clark et al., 2015, CSDMS, 2019).

3.7 Interfaces with society

The final theme deals with hydrology’s contribution to resolving societal problems, and with understanding the dynamics of water–societal interactions. Societal needs and technology, as externalities to the discipline of hydrology, have stimulated progress in hydrology tremendously (Sivapalan and Blöschl, 2017), and will likely do so in the future, as there is no shortage of grand challenges for another 100 years (Montanari et al., 2015; Bai et al., 2016), *inter alia*, in the context of the Sustainable Development Goals of the UN Agenda 2030 and beyond. Locally and regionally, much remains to be done to effectively communicate the confidence and uncertainty in hydrological predictions to decision makers and the general public (Question 21). Sister disciplines, such as meteorology, are already doing this successfully when issuing forecasts of precipitation probabilities, for example. We need to find a balance between optimism and realism that is in line with both societal expectations and what we can offer. Developments in social media offer new opportunities for hydrologists to put their message across to policy makers and the public (Re and Misstear, 2018).

At the global scale, one overarching challenge is the water–environment–energy–food–health nexus that involves identifying synergies and trade-offs between goals, sectors and stakeholders (Question 22; Liu et al., 2017). Much of the current research is done at the global scale (Bierkens, 2015), but it is likely that the issues will also become relevant at the regional scale, e.g. for the water sustainability of large cities (Pang et al., 2018). These interactions can not only be considered from a problem solving perspective, but also provide an opening for rich questions of discovery science that will feed back to other fields of hydrology, as hydrology continues to expand from an engineering discipline to an Earth system science (Sivapalan, 2018). In this context, we can learn a lot from the human–water interactions of ancient civilisations (e.g. Liu et al., 2014), provided the difference in the socio-political and economic systems can be accounted for (Question 23). The importance of the historical perspective comes from the inability to perform experiments on the interaction of people and water, which is reminiscent of the general difficulty of experimentation in hydrology. Question 23 particularly emphasises migration and urbanisation as key topics to focus on in human–water interactions.

4 Discussion

4.1 Knowledge gaps in hydrology

The working group both organised the questions for clarity and communication and helped further refine their presentation. From this, the group made four main observations on the knowledge gaps.

4.1.1 The fundamental questions remain the same

It appears that the community perspective on UPH is different from some previous blueprints in that it tends to favour continuity in the research questions rather than radical departures or redirections from the past. Even though the video launch of the process in Step 1 was headed "*To all hydrologists of the world: A Call to Arms! What are the 23 unsolved problems in Hydrology that would revolutionise research in the 21st century?*", the questions suggested, voted on and consolidated are not entirely revolutionary but reassuring. Sivapalan and Blöschl (2017) suggested that progress in hydrological understanding over the last century has been stimulated through repeated cycles of euphoria and disillusionment. From the results of the present survey, it does not look as if anxiety and an impending paradigm shift were in the air. They suggest we want to do a better job of what we are already doing.

International foresight reports in the past decades have been clear about the need to better understand hydrological fluxes, particularly in the presence of hydrological change. For example, as part of the "IAHS Hydrology 2000 report" Szolgay and Gottschalk (1987, p. 69) stated: "*In order to ensure the credibility of the present methods and of those to be developed on the same basis in the future, a much deeper understanding of the mechanisms governing hydrological, climatic and meteorological processes is required.*" The Dutch foresight report (KNAW, 2005) identified interactions between the hydrological cycle and ecosystems, landscape process, humans and climate change as key research areas, and heterogeneity and scale, measurement techniques, theories and uncertainties as methodological challenges. Dunne (1998) highlighted convergence of approaches, coherent theory, interaction of people, communication, improving measurement capabilities, and oversight as factors that would be instrumental for progress in hydrology. The "blue book" (NRC, 1991, p. 4) singled out 13 unsolved problems that revolved around heterogeneity, scale and feedbacks, and gave particular emphasis to geochemistry. A recent update (NRC, 2012) identified challenges and opportunities in three major areas: (i) the water cycle: an agent of change (involving changes and regime shifts in the water cycle due to climate and land use change); (ii) water and life (involving the co-evolution of ecosystems, geomorphology and water); and (iii) clean water for people and ecosystems (involving the interactions of contaminants with hydrological processes and ecosystems in the presence of heterogeneity and the water–energy–food–urbanisation nexus). There is a lot of similarity with the questions identified here, suggesting that the fundamental questions remain the same.

4.1.2 Variability and change

Much of the interest remains focused on understanding the causes of hydrological variability and extremes at all space and time scales in a process-based way. Progress is being sought through data analysis and modelling, but, apparently, modelling remains contentious because we have not fully addressed scale issues. Once they have been fully addressed, greater emphasis can be put on exploring phenomena that go beyond variability. An overarching theory of this, as a basis for modelling, however, is still elusive. Also questions of whether there are universal hydrological laws (beyond mass balance and Darcy's law), and universal models, remain unresolved (Sivapalan, 2006). Uncertainty in modelling has been mentioned, but there seems to be less concern about uncertainty *per se* and more about what models can tell us about the underlying processes. This is probably a healthy development, helping to advance the science of hydrology where the ultimate goal is to understand hydrological causality. Environmental change has been on the agenda for decades, but there seems to be a new emphasis on understanding more comprehensively how change propagates through the entire system. This implies propagation of compound events in space and time (e.g. teleconnections, time interactions), propagation through the hydrological compartments, and how the hydrological cycle may accelerate or decelerate. The challenges lie in linking short-term local processes (what we have mostly studied in the past) to long-term global processes, and *vice versa*. Also, the interest no longer resides only in providing scenarios of change (as only a decade ago), but in a rich fabric of experiments, data analysis and modelling approaches geared towards understanding the mechanisms of change.

4.1.3 Interfaces

There is a broad recognition that we need to learn more about interfaces in hydrology. These have traditionally been imposed as boundary conditions, thereby reducing complexity, but we now need to look at the more typical cases where we can and should not do this, as the interfaces couple rather than constrain system behaviour. These interfaces include those between compartments (e.g. atmosphere–vegetation–soil–bedrock–streamflow–hydraulic structures) in three dimensions, interactions between the hydrological fluxes and the media (e.g. soils, vegetation), and interactions between sub-processes that are usually dealt with by different disciplines (e.g. water chemistry, ecology, soil science, biogeochemistry). Linking these interfaces conceptually and in a quantitative way is currently considered a real bottleneck. Unless the community that specialises in these compartments comes together collaboratively, this bottleneck will remain. Vit Klemeš suggested that "*it is highly likely that instead of mastering partial correlations, fractional noises, finite elements, or infinitely divisible sets, the hydrologist would more profitably spend his time by studying thermodynamics, geochemistry, soil physics, and plant physiology*" (Klemeš, 1986, p. 187S). We believe these are certainly the pillars of progress, but it may be equally likely that progress will come from a more integrated treatment, connecting these processes across interfaces. The current, and future, focus on co-evolutionary thinking (in the co-evolution era 2010–2030 proposed by Sivapalan and Blöschl, 2017) will help in this endeavour.

4.1.4 Water and society

Interfaces with society are part of the integrated treatment. With the expansion of the human footprint, a new set of questions arises from the human interactions with nature in the context of complex water management problems. These are questions where hydrology can make important contributions, but they cannot be addressed by hydrology alone, and many core issues lie outside of hydrological science *per se*. Thus interdisciplinary collaboration will be essential. The traditional support that hydrology has provided to water resources management (Savenije and Van der Zaag, 2008) in its dual role of (i) quantifying hydrological extremes and resources relative to societal needs and (ii) quantifying the impact society has on the water cycle, is now broadened in a number of ways. First, these questions are complemented by more integrated questions of the long-term dynamic feedbacks between the natural, technical and social dimensions of human-water systems. While water resources systems analysis (Brown et al., 2015) has dealt with such interactions from an optimisation perspective on a case-by-case basis, much is to be learned by developing a generalisable understanding of phenomena that arise from the interactions between water and human systems. Thus, as socio-economic perspectives (Castro, 2007; Sanderson et al., 2017) are being integrated in these feedbacks, the interest is not only on decision support but also on the role of society in the hydrological cycle in its own right. Second, new topics seem to emerge where hydrology can play a more important role such as contaminants of emerging concern, microbial pathogens, or, more generally, the topic of water and health (e.g. Mayer et al., 2018; Dingemans et al., 2019), as well as spatial problems such as the interaction of migration and water issues. Third, the questions are broadened in terms of their spatial scales. There are important challenges in managing transboundary river basins and transboundary aquifers. Also, water is traded globally through the water–energy–food nexus, and it will be interesting to see what role hydrology can play in this nexus (Cudennec et al., 2018). While water governance is limited to the local and national scales, a global perspective is clearly becoming increasingly more important in the context of the UN Agenda 2030 and Sustainable Development Goals, the societal grand challenge of our time (Di Baldassarre et al., 2019).

4.2 Future directions

4.2.1 More high-risk/high-gain activities

Most of the unsolved problems identified here are questions that perhaps cannot be solved conclusively, but can likely be realistically advanced in the next couple of decades. This is in line with Hilbert's (1900, p. 254) recommendation on choosing unsolved problems "*A mathematical problem should be difficult so as to pose a challenge for us, and yet not completely inaccessible, so that it does not mock our effort.*" On the other hand, there were no really unexpected questions that came up in the process. Burt and McDonnell (2015) noted that hydrology has perhaps reached a stage, similar to geology in the early 1920s, where more daring activities (and outrageous hypotheses) were needed to inject a renewed sense of purpose. Davis (1926, p. 464) exhorted his fellow scientists thus: "*Yes, our meetings are certainly prosaic to-day as compared to those of the earlier formative period when speculation was freer and when differences of opinion on major principles were almost the rule rather than the exception. Our younger members may perhaps experience a feeling of disappointment, or even of discouragement at the unanimity with which the conclusions of an elder are received by a geological audience. … But to make such progress, violence must be done to many of our accepted principles; and it is here that the value of outrageous hypotheses, of which I wish to speak, appears.*" The statement is interesting as its publication coincides with the controversial discussion of Wegener's continental drift theory which, at that time, was not universally accepted. Thus. "*Yet I believe it the part of wisdom to view even* […] *the Wegener outrage of wandering continents* […] *calmly, as if they were all possibilities.*" (Davis, 1926, p. 464).

While the notion of hypotheses in hydrology has received renewed interests in recent years (e.g. Baker, 2017; Blöschl, 2017; Pfister and Kirchner, 2017), most of them are not outrageous. One of the few examples is the idea of an “active biotic pump transporting atmospheric moisture inland from the ocean” (Makarieva and Gorshkov, 2007) that has attracted numerous comments in *HESS* (*Hydrology and Earth System Sciences* journal). Another example is the idea of a “planetary boundary as a safe operating space for humanity” (Rockström et al., 2009). It is difficult to define what an “outrageous” hypothesis is, as some peers will consider them simply wrong, as was the case of continental drift theory which turned out to be correct. On the other hand, the opposite can also be true, as was the case of 19th-century aether theories (Schaffner, 1972). Davis’ suggestion of viewing such hypotheses calmly *as if they were all possibilities* is certainly a wise piece of advice (Baker, 1996).

In hydrology, the small number of outrageous hypotheses may be partly related to the funding system and the culture of reviewing, where reviewers generally require solid, proven methodologies in project proposals, rather than open-ended questions and speculative hypotheses. Similar observations apply to the review process of papers where the chances for a potentially transformative paper to be published are generally low (Koutsoyiannis et al., 2016). Perhaps, we should be more generous in reviewing such proposals and papers, giving outrageous hypotheses the benefit of the doubt. There are already a number of high-risk/high-gain initiatives around the world, such the ERC (European Research Council) Grants and the MacArthur Fellows Program, that encourage and fund this type of research. Both programmes target people of exceptional creativity whose work would benefit from greater freedom and support.

On the other hand, the more traditional bottom-up approaches based on deductive reasoning (Einstein, 1919; Baker, 2017) will likely continue to be important in addressing the unsolved problems. The focus is on deducing information from smaller scales and/or component processes, perhaps employing tools from other scientific areas (Klemeš, 1986). Such approaches should lead to modelling frameworks in which the scales are treated more rigorously, calibration of models becomes less relevant and extrapolations more reliable.

4.2.2 Generalisation and open data/models

From the very beginning, hydrologists have found generalisations to other areas difficult, as each aquifer, catchment and river reach, in fact, each episode, seems to have particularities that cannot be specified in full detail. Yet, the 23 questions are posed in a fairly universal way. Unlike other natural sciences, it is nature that does the hydrological experiments (Dunne, 1998) and these cannot be repeated under exactly the same boundary and initial conditions. Yet, a case could be made for using more (scale) experimentation in hydrology (Kleinhans et al., 2010). While calibration to individual catchments has served us well for practical predictive purposes, it has not been helpful for generalisation (Blöschl, 2006).

When reviewing project proposals and papers, reviewers generally consider both the suitability of the findings for the local situations and their value for the general body of knowledge, with a larger emphasis on the former (Koutsoyiannis et al., 2016); but perhaps we should give more emphasis to the latter, as in the timeless story of a stonecutter and a cathedral builder (Girard and Lambert, 2007) often used in promoting the vision of the whole over its parts. Or, in other words, building hydrological knowledge rather than fragmenting hydrological knowledge (Fig. 5). One contribution to this accumulation of knowledge is the area of model inter-comparison studies (WMO, 1975; Duan et al., 2006), while another is data-driven multi-catchment comparisons (e.g. Blöschl et al., 2013; Orth and Destouni, 2018).

Perhaps more importantly, the way we present the research findings in publications can contribute significantly to accumulating knowledge, by making them useful to the reader. This can be done through providing some degree of higher-level analysis of the results, both comparative (with other work) and synthetic (in terms of understanding) (Gupta et al., 2013), and by providing the data and the model code, preferably in public repositories. Indeed, as datasets used in publications are becoming more extensive and models more complex, it has sometimes become very difficult to assess the validity of a new theory or model prediction on the basis of the published material, and to build on it, because of a lack in reproducibility (Hutton et al., 2016). Most hydrology journals and research funders have therefore adopted an open data and open model policy, to allow peers – at least in principle – to repeat any published study (e.g. Data Citation Synthesis Group, 2014; Quinn et al., 2018), notwithstanding challenges with proprietary data and models in some countries. Koutsoyiannis et al. (2016) suggested that a change in culture is needed in linking research studies to each other, e.g. by establishing a jointly agreed protocol for meta-data. These would be archived along with published papers, as is already done in other disciplines (Moher et al., 2009). Open data/models can also be shared with pre-defined protocols for (numerical) experiments in "virtual laboratories" (Ceola et al., 2015), which may provide added value and incentives for sharing them.

4.2.3 Activities around more integrated questions

Lall (2014, pp. 5340–5341) expressed the need for more integrated questions across processes and scales thus: "*The planetary focus would entail the integration of capability to understand and predict local hydrologic processes into a context that brings climate, meteorology, agriculture, and social dynamics together into an exploration of what may be, and what is possible in a water networked world,* […] *the '*one water, one world*' concepts that I think are needed to excite the next generation of hydrologists to think broadly and holistically about the interactions between water, climate, and people and how we understand, study, and manage this resource.*" This comment addresses a serious issue in the hydrological community, i.e. fragmentation, which clearly came out of this scoping exercise. For example, during the VCSS in Vienna, different approaches to the same questions were discussed in the four rooms, using quite different language. This is likely an important line of action for the future: more integration within hydrology subfields, as well as with other water-related disciplines (biology, ecology, physics of fluids, fluid mechanics, chemistry, soil physics, physical geography, civil and environmental engineering etc.). These disciplines all deal with water, but there is often little communication with each other.

Similar to other fields (as observed by Horton, 1931, p. 201), the direction of hydrological research has branched out into new sub-disciplines of specialization. Figure 6(a) presents one view of how hydrology has branched out over the 20th century and the beginning of the 21st century. As a response to specialization in ecology, Graham and Dayton (2002) proposed enhancing the historical perspective on the evolution of ecological ideas. Numerous others have highlighted the need for closer cooperation within hydrology and with other disciplines, and suggested ways forward through interdisciplinary projects, consortia, summer institutes and doctoral programmes (e.g. McDonnell et al., 2007; Maidment et al., 2009; Sivapalan et al., 2011; Thompson, et al. 2011; Takeuchi et al., 2013; Carr et al., 2017). Dunne (1998) suggested that a slightly stronger coordination of research efforts would be beneficial to progress. There are large integrated research programmes at the national or continental scales (such as the EU Integrated Projects), but learned societies and university departments are usually structured by sub-disciplines. Activities such as the scoping exercise summarised here may assist in organising the community on a broader basis around major knowledge gaps rather than by the traditional sub-disciplines.

Most of the 23 questions require an explicit linkage of hydrological sub-disciplines. This need and opportunity for synthesis has important implications for how the community can organise itself in the future to benefit from and build upon the progress made so far. Figure 6(b) presents an alternative blueprint for organising the community in contrast to the current canalisation of sub-disciplines that is based on the themes identified in this exercise. In each of these domains, such as time variability, the focus of a symposium, or a session of a larger conference, may be on the unsolved problems identified here. This is not to say that other research questions should be excluded from the scientific discourse – they are equally valid; yet, this focus would help create a long-term, critical mass similar to that other disciplines are able to build, e.g. through large-scale infrastructure. Addressing the integrated questions will likely have a positive impact on other research questions in the field. A first step of organising the community in a more holistic way could be made by learned societies, such as IAHS, where little money is at stake (but substantial intellectual capital), and other organisations could follow suit. As the problems identified here tend to be universal, international cooperation is at the core of it.

5 Concluding remarks

This initiative has identified 23 unsolved problems through a broad consultation process, revealing a lot of continuity in the choice of research questions in hydrology. Most of the 23 questions require an explicit linkage of hydrological sub-disciplines. Providing common research subjects is therefore hoped to increase the coherence of the scientific process in hydrology, and thus accelerate progress, through increasing the critical mass of researchers working on any one science question and through increasing the scientific connectivity within hydrology. While the diversity of the hydrological community has sometimes been considered a barrier to progress, during this initiative diversity was felt by many as a strength, as – once unsolved problems are identified – diversity allows them to be addressed from different perspectives and by complementary expertise and methodologies. Applications of the science and fundamental research may reinforce each other rather than compete with each other. More high-risk/high-gain activities, generalisation and open data/models, and organising activities around more integrated questions have been identified as the three pillars for progress in hydrology, in the spirit of Lall’s (2014) "*one world, one people, one clime*". Left alone there is a danger of canalisation which is not good for science or practice. A number of activities are being planned to capitalise on the outcomes of this initiative, including organising sessions at symposia on specific unsolved problems as a starting point.

While the unsolved problems identified here are not likely to revolutionise hydrology in the sense of radical departures from the paths we have followed in the past, they can nevertheless lead to more coherence in our scientific pursuits in the future, and can indeed assist in the long-term quest to develop comprehensive new theories of hydrology. It is also reassuring that the UPH initiative is a proof of concept that this kind of broad consultation process is actually feasible, and is received well by the community. Attendance at the 2018 Vienna Catchment Science Symposium for the final voting was the highest in the 10-year history of the symposium series. Thus, equally important as the outcomes of this initiative is the *community-level learning process* of such a consultation, involving a large number of hydrologists and the four main learned societies in the field. This is a consultation that could and should be repeated in the future for the benefit of our discipline.

As a closing remark, we share the outlook of David Hilbert, who, in response to the Latin maxim “ignoramus et ignorabimus” (we do not know and will not know), coined a much more optimistic maxim, generally considering questions to be solvable unless proven otherwise. His maxim reads: “*Wir müssen wissen, wir werden wissen*” (“*We must know, we will know*”).

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Table 1. The 23 Unsolved Problems in Hydrology identified by the community process in 2018.

Time variability and change

1. Is the hydrological cycle regionally accelerating/decelerating under climate and environmental change, and are there tipping points (irreversible changes)?
2. How will cold region runoff and groundwater change in a warmer climate (e.g. with glacier melt and permafrost thaw)?
3. What are the mechanisms by which climate change and water use alter ephemeral rivers and groundwater in (semi-) arid regions?
4. What are the impacts of land cover change and soil disturbances on water and energy fluxes at the land surface, and on the resulting groundwater recharge?

Space variability and scaling

5. What causes spatial heterogeneity and homogeneity in runoff, evaporation, subsurface water and material fluxes (carbon and other nutrients, sediments), and in their sensitivity to their controls (e.g. snow fall regime, aridity, reaction coefficients)?
6. What are the hydrologic laws at the catchment scale and how do they change with scale?
7. Why is most flow preferential across multiple scales and how does such behaviour co-evolve with the critical zone?
8. Why do streams respond so quickly to precipitation inputs when storm flow is so old, and what is the transit time distribution of water in the terrestrial water cycle?

Variability of extremes

9. How do flood-rich and drought-rich periods arise, are they changing, and if so why?
10. Why are runoff extremes in some catchments more sensitive to land-use/cover and geomorphic change than in others?
11. Why, how and when do rain-on-snow events produce exceptional runoff?

Interfaces in hydrology

12. What are the processes that control hillslope–riparian–stream–groundwater interactions and when do the compartments connect?
13. What are the processes controlling the fluxes of groundwater across boundaries (e.g. groundwater recharge, inter-catchment fluxes and discharge to oceans)?
14. What factors contribute to the long-term persistence of sources responsible for the degradation of water quality?
15. What are the extent, fate and impact of contaminants of emerging concern and how are microbial pathogens removed or inactivated in the subsurface?

Measurements and data

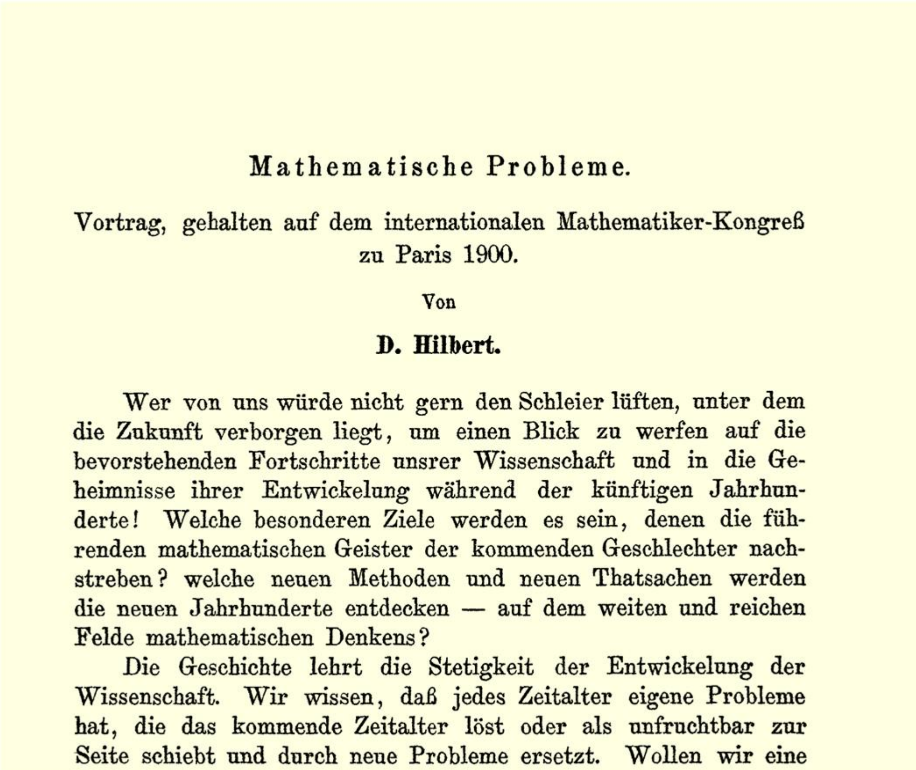
16. How can we use innovative technologies to measure surface and subsurface properties, states and fluxes at a range of spatial and temporal scales?
17. What is the relative value of traditional hydrological observations *vs* soft data (qualitative observations from lay persons, data mining etc.), and under what conditions can we substitute space for time?
18. How can we extract information from available data on human and water systems in order to inform the building process of socio-hydrological models and conceptualisations?

Modelling methods

19. How can hydrological models be adapted to be able to extrapolate to changing conditions, including changing vegetation dynamics?
20. How can we disentangle and reduce model structural/parameter/input uncertainty in hydrological prediction?

Interfaces with society

21. How can the (un)certainty in hydrological predictions be communicated to decision makers and the general public?
22. What are the synergies and tradeoffs between societal goals related to water management (e.g. water–environment–energy–food–health)?
23. What is the role of water in migration, urbanisation and the dynamics of human civilisations, and what are the implications for contemporary water management?


Mathematische Probleme.

Vortrag, gehalten auf dem internationalen Mathematiker-Kongreß zu Paris 1900.

Von

D. Hilbert.

Wer von uns würde nicht gern den Schleier lüften, unter dem die Zukunft verborgen liegt, um einen Blick zu werfen auf die bevorstehenden Fortschritte unsrer Wissenschaft und in die Geheimnisse ihrer Entwickelung während der künftigen Jahrhunderte! Welche besonderen Ziele werden es sein, denen die führenden mathematischen Geister der kommenden Geschlechter nachstreben? welche neuen Methoden und neuen Thatsachen werden die neuen Jahrhunderte entdecken — auf dem weiten und reichen Felde mathematischen Denkens?

Die Geschichte lehrt die Stetigkeit der Entwickelung der Wissenschaft. Wir wissen, daß jedes Zeitalter eigene Probleme hat, die das kommende Zeitalter löst oder als unfruchtbar zur Seite schiebt und durch neue Probleme ersetzt. Wollen wir eine

Figure 1. Left: First page of Hilbert's "Mathematical problems" (Hilbert, 1900). Right: David Hilbert around 1900. English translation[8] see Hilbert (1902).

[8] Who among us would not be glad to lift the veil behind which the future lies hidden; to cast a glance at the next advances of our science and at the secrets of its development during future centuries? What particular goals will there be toward which the leading mathematical spirits of coming generations will strive? What new methods and new facts in the wide and rich field of mathematical thought will the new centuries disclose?

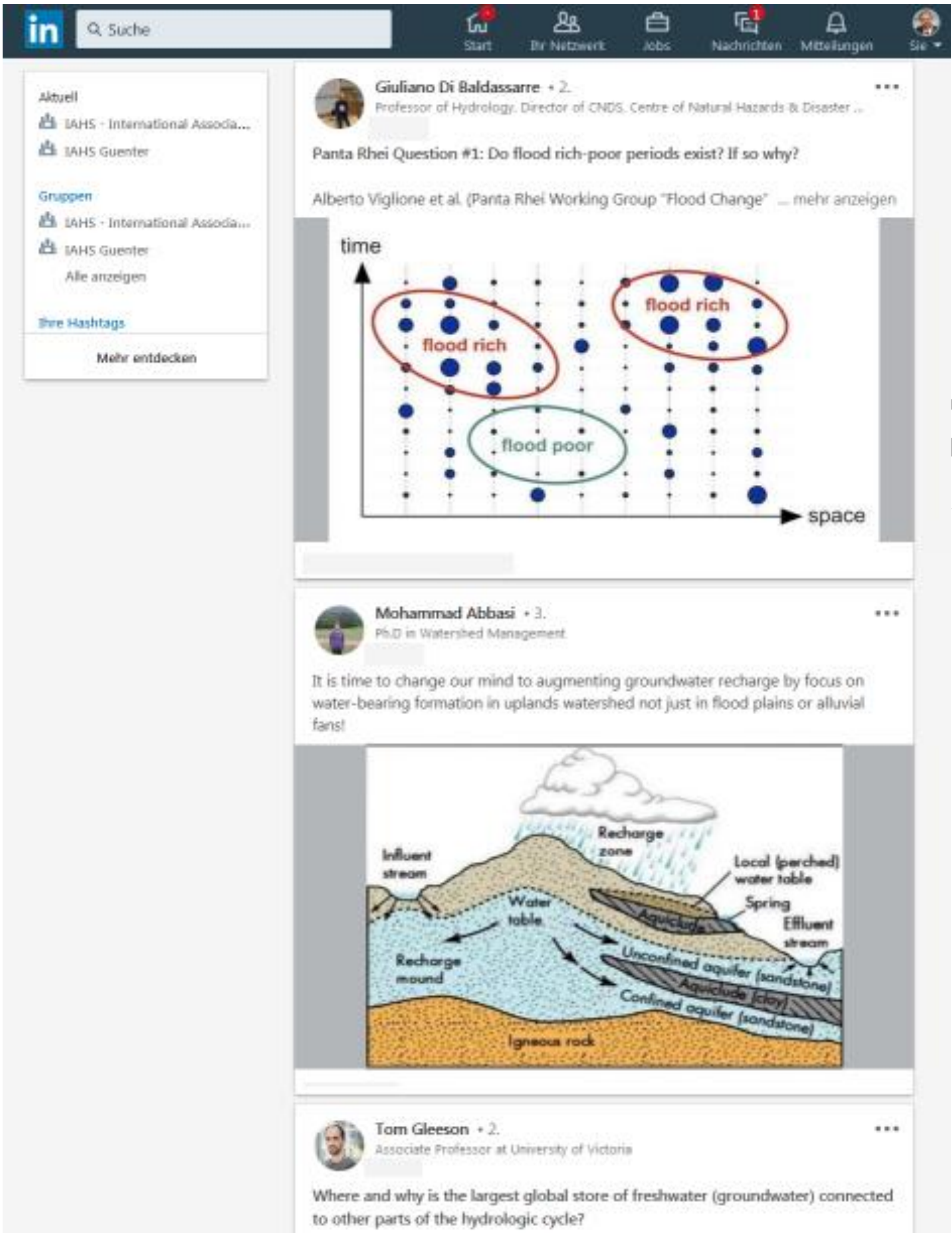


Figure 2. Example screenshot of the discussion forum on LinkedIn.

Figure 3. Bottom: Participants of the Symposium on 14 April 2018. Top left: voting in a break-out group. Top right: voting in the plenary session.

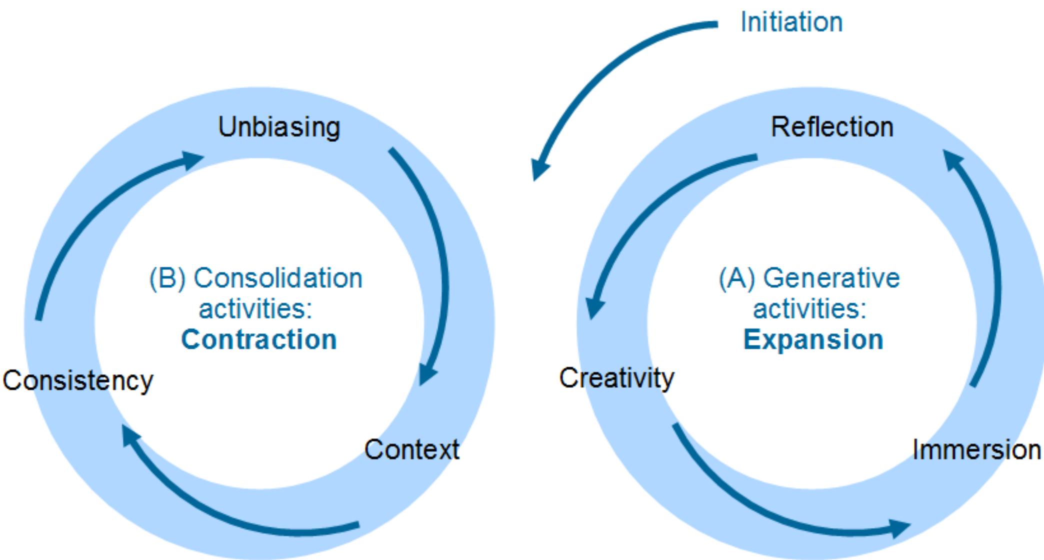


Figure 4. Conceptual diagram illustrating the underlying structure of the synthesis process. Modified from Thompson et al. (2011).

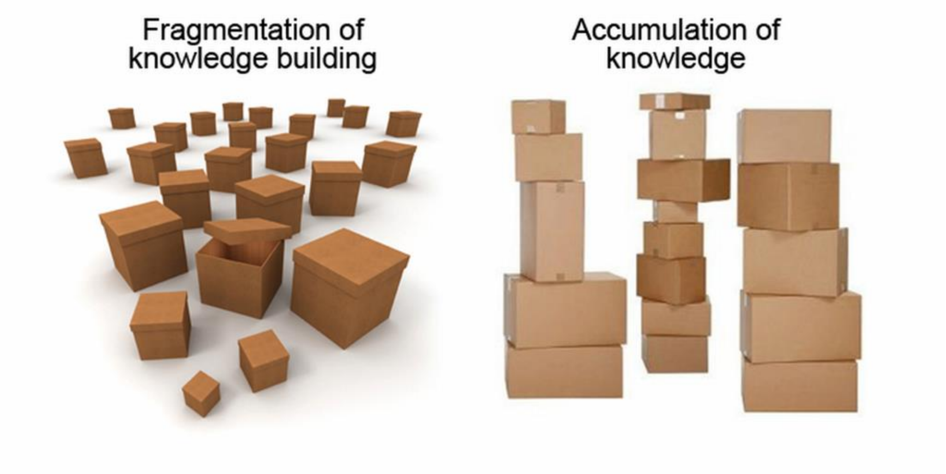


Figure 5. Accumulation of knowledge through generalisation and open data/models. From Gupta et al. (2013). Extending the model on the right, there should be links between the separate piles of knowledge reflecting the integrated nature of questions and knowledge.

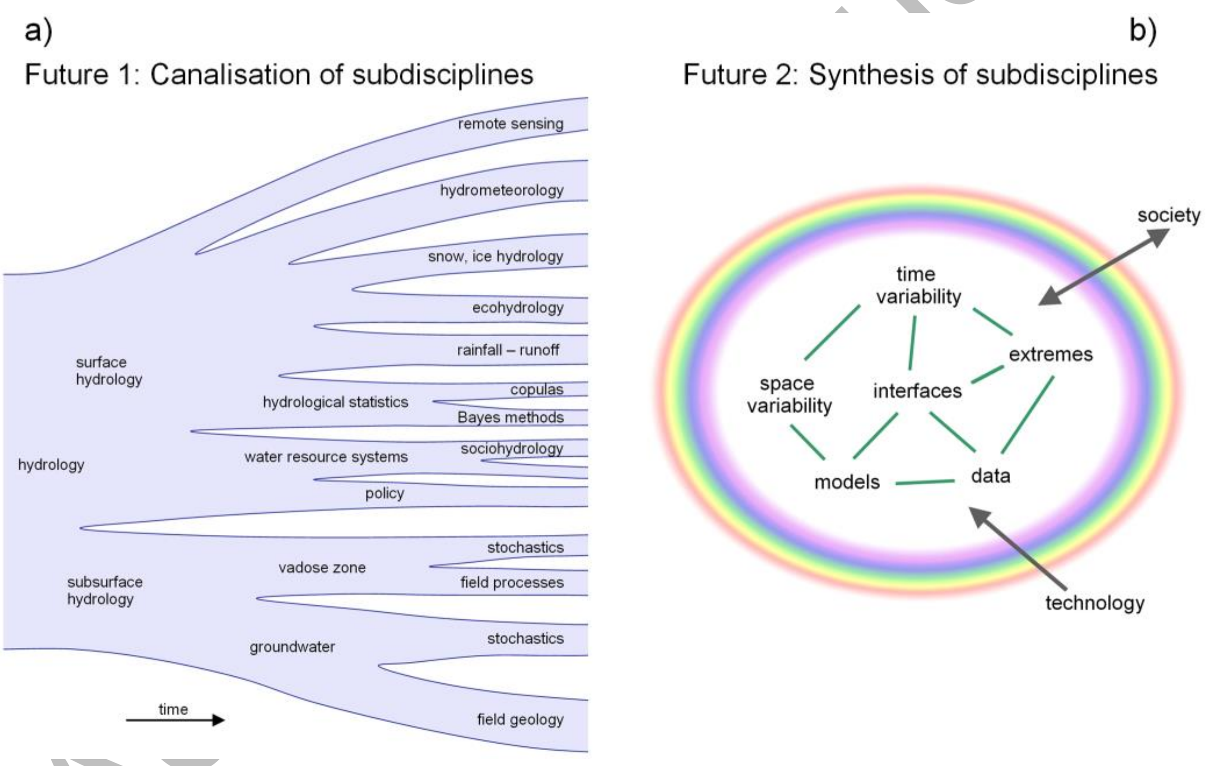


Figure 6. Two alternative visions of hydrological research. (a): Future1: Prolongation of the canalisation of sub-disciplines in the past century. (b) Future 2: More integrated vision of interconnected sub-disciplines.

Electronic supplement

Table S1: Mapping of questions resulting from the voting process to the questions consolidated by the working group (Table 1).

Questions as an outcome of the voting process Gold Silver Moved up from raw list New	Consolidated questions
Time variability and change	**Time variability and change**
Is the hydrological cycle regionally accelerating/decelerating under global warming? Can we identify tipping points of hydrological systems due to changes in climate and/or human impacts. .. regime changes	1. Is the hydrological cycle regionally accelerating/decelerating under climate and environmental change and are there tipping points (irreversible changes)?
When will we run out of glacier augmentation (to runoff and groundwater) and what will happen to those catchments? (until and after) What is the hydrologic effect of thawing permafrost	2. How will cold region runoff and groundwater change in a warmer climate (e.g. with glacier melt and permafrost thaw)?
Understanding the dynamics of temporary rivers / Why, when and how do rivers dry up?	3. What are the mechanisms by which climate change and water use alter ephemeral rivers and groundwater in (semi-) arid regions?
What are the effects of natural and anthropogenic soil disturbances on heat and mass fluxes at the land-atmosphere interface? What are the impacts of climate and environmental change on aquifer recharge?	4. What are the impacts of land cover change and soil disturbances on water and energy fluxes at the land surface, and on the resulting groundwater recharge?
Space variability and scaling	**Space variability and scaling**
Why are evapotranspiration rates spatially homogeneous despite differences in controlling mechanisms? Why is soil-water content so variable in space and time? Why do changes in the snow fall regime have a very different impact on stream flow in different catchments? Why is aridity (according to the Budyko Curve) the main controlling factor in the partitioning between runoff and evapotranspiration? How can we identify the similarities between catchments? Why are reaction coefficients for the same process heterogeneous in time and in space across different soils, streams, lakes, catchments, groundwater bodies…?	5. What causes spatial heterogeneity and homogeneity in runoff, evaporation, subsurface water and material fluxes (carbon and other nutrients, sediments), and in their sensitivity to their controls (e.g. snow fall regime, aridity, reaction coefficients)?
Why do dominant hydrological processes emerge and disappear across scales? Why is hydrology simple at the catchment scale despite being complex at smaller scales? What are the emergent hydrological laws at catchment scale? How do constitutive relationships and their parameters change with scale?	6. What are the hydrologic laws at the catchment scale and how do they change with scale?
Why is most flow preferential and what are the consequences?	7. Why is most flow preferential across multiple scales and how does such behaviour co-evolve with the critical zone?
Why is stream water so young when ground water is so old? Why do streams respond so quickly to rainfall, with storm flow that is so old? What is the fate and lifetime of evaporated water from land surfaces?	8. Why do streams respond so quickly to precipitation inputs when storm flow is so old, and what is the transit time distribution of water in the terrestrial water cycle?
Variability of extremes	**Variability of extremes**
Why do drought and flood rich/poor periods exist? Why do we see long term cycles and correlations in hydroclimatological variables? What is the cause of the Hurst phenomenon?	9. How do flood-rich and drought-rich periods arise, are they changing, and if so why?

Are the characteristics of extreme events changing and if so why? Floods and droughts How to reconstruct paleohydrological phenomena during the Holocene and why did they happen? How do extreme floods and droughts around the world teleconnect with each other and with other factors?	
How do geomorphic processes interact with floods and droughts? Why are some catchments more sensitive to land-use/cover change than others? What is the role of changing land use/land cover change patterns on in-situ and downwind droughts and floods?	10. Why are runoff extremes in some catchments more sensitive to land-use/cover and geomorphic change than in others?
What are the controls on and consequences of (e.g. streamflow, groundwater recharge, evaporation, soil moisture etc.) the spatial and temporal patterns of snow and ice in catchments? Why and when do rain-on-snow events produce exceptional runoff?	11. Why, how and when do rain-on-snow events produce exceptional runoff?
Interfaces in hydrology	**Interfaces in hydrology**
Groundwater-surface water interactions / regional What are the processes of groundwater-surface water interactions, including the role of the hyporheic zone (e.g. in contaminant fate and transport), and the dependencies of different ecosystems? Why is the connectivity between hillslopes and streams so heterogeneous and dynamic?	12. What are the processes that control hillslope-riparian-stream-groundwater interactions and when do the compartments connect?
What are the processes in the unsaturated zone, which have significant impacts on groundwater recharge and composition? What are the storages and fluxes of groundwater across boundaries (oceans, atmosphere and inter-catchment fluxes) at different scales?	13. What are the processes controlling the fluxes of groundwater across boundaries (e.g. groundwater recharge, inter-catchment fluxes and discharge to oceans)?
What controls long-term spatio-temporal evolution of catchment water quality? What factors contribute to the persistence of sources contributing to the degradation of water-quality? What are the dominant processes controlling the fate of material fluxes in catchments over different spatial and temporal scales?	14. What factors contribute to the long-term persistence of sources responsible for the degradation of water-quality?
What is the extent, fate and impacts of contaminants of concern (EOCs) in groundwater? How are microbial pathogens removed in the subsurface?	15. What are the extent, fate and impact of contaminants of emerging concern and how are microbial pathogens removed or inactivated in the subsurface?
Measurements and data	**Measurements and data**
How to reduce uncertainty in large-scale hydrological fluxes using novel technologies/remote sensing? How can we accurately measure subsurface properties, states and fluxes at a range of scales in space and time?	16. How can we use innovative technologies to measure surface and subsurface properties, states and fluxes, at a range of spatial and temporal scales?
How can we convincingly put a value to hydrological observation systems with open data to reverse the current trend of decline of observation systems? What are the consequences of choosing between a large number of less accurate observations vs a few more accurate measurements? Working with different data sources / big data Under what conditions can we substitute space for time in hydrology?	17. What is the relative value of traditional hydrological observations vs soft data (qualitative observations from lay-persons, from data mining etc.), and under what conditions can we substitute space for time?
How to extract information from available data on human and water systems in order to inform the building process of socio-hydrological models?	18. How can we extract information from available data on human and water systems in order to inform the building process of socio-hydrological conceptualisations and models?
Modelling methods	**Modelling methods**
How do we adapt hydrological models to be able to extrapolate to changed conditions.	19. How can hydrological models be adapted to be able to extrapolate to changing conditions, including changing vegetation

What is the sensitivity of hydrologic models to vegetation dynamics?	dynamics?
How to disentangle and reduce model structural/parameter/input uncertainty in hydrological prediction?	20. How can we disentangle and reduce model structural/parameter/input uncertainty in hydrological prediction?
Interfaces with society	**Interfaces with society**
How to communicate (un)certainty to decision makers and general public How can we improve flood and drought forecasting on different lead times? Why are drought and flood risk assessments ineffective? (social)	21. How can the (un)certainty in hydrological predictions be communicated to decision makers and the general public?
Water-energy-food nexus Water quality – ecosystem health – human health nexus Water sustainability of large cities	22. What are the synergies and tradeoffs between societal goals related to water management (e.g. water-environment-energy-food-health)?
How strong is the impact of hydrological change on the migration of people worldwide and what is the effect of migration on hydrologic change? What is the role of water in the collapse of ancient civilizations and the implications for contemporary water management?	23. What is the role of water in migration, urbanisation and the dynamics of human civilisations, and what are the implications for contemporary water management?