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Perceptions of scale in hydrology: what do you mean by regional scale?

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Abstract The discipline of hydrology has a long history of research in the practical and theoretical aspects of scaling and scale issues, but little effort has been focused on hydrologists' perception of the scale terms. What exactly do hydrologists mean when they use the terms "pore scale" or "regional scale"? The application of hydrological research requires clear communication, both within the discipline, and with a broader audience. Quantitative and qualitative data on hydrologists' perceptions of scale were collected using voluntary written surveys and face-to-face interviews. The results suggest that most hydrologists do not consistently define scale terms in the literature, and that this is a minor impediment when interacting with other disciplines and stakeholders. Yet, surface water and groundwater hydrologists agree, within one to two orders of magnitude, on the length scale for most scale terms. Most respondents suggest that the hydrological community needs to better define the length scale of scale terms. In the short term, hydrologists could more frequently and consistently clarify their own length scales whenever a scale term is used. A common and consistent language of scale for hydrological researchers could better enable communication, research, teaching and outreach.

Key words scale; perception; communication; surface hydrology; subsurface hydrology; interdisciplinary

Perceptions de l'échelleen hydrologie: qu'entend-on paréchelle régionale?

Résumé Il y a une longue tradition en hydrologie dee recherchesur les aspects pratiques et théoriques des questions de mise a l'echelle et d'échelle, mais on s'est peu préoccupé de la perception de ces termes par les hydrologues.Que veulent exactement dire les hydrologues quand ilsparlent « d'échelle porale » ou « d'échelle régionale »? La diffusion de la recherche hydrologique nécessite une communication claire, tant au sein de la discipline qu'en direction d'un public plus large. Des données quantitative set qualitatives concernant la perceptionde la notion d'échelle par les hydrologues ont été recueillies au moyen de questionnaires écritset d'entretiens. Les résultats suggèrent quela plupart des hydrologues n'interprètent pas uniformément la notion d'échelle dans la littérature et qu'il s'agit d'un obstacle mineur dans la communication avec d'autres discipline set les divers intervenants.Les hydrologues et les hydrogéologues s'accordent pourtant, à un ou deux ordres de grandeur près, sur la quantification de la plupart des échelles. La plupart des personnes interrogéespensent que la communauté hydrologique devrait mieux quantifier les termes d'échelle. A court terme, les hydrologues devraient plus fréquemment et plus systématiquement clarifier leurs propres échelles de longueur à chaque fois que le terme d'échelle est utilisé. Pour la recherche hydrologique, un langage commun et cohérent concernant les échelles permettrait d'améliorer la communication, la recherche, la pédagogie et la sensibilisation.

Mots clefs échelle; perception; communication; hydrologie de surface; hydrologie souterraine; interdisciplinarité

"The problem of scale does not arise only in hydrology. It poses difficulties for almost every science and is a key factor in our perception of the universe of which we are a part." (Dooge 1986)

1 INTRODUCTION

Issues of scale transcend all hydrological problems, and indeed problems in many disciplines. In hydrology, scale is defined as the time or length of a process, observation or model (Blöschl and

Sivapalan 1995). The transfer of information between scales is called scaling, and the problems associated with scales are called scale issues (Blöschl and Sivapalan 1995). Significant hydrological research effort has examined the mathematical, theoretical and practical aspects of scale issues (e.g. Klemeš 1983, Dooge 1986, Wood *et al*. 1988, Neuman 1990, Blöschl and Sivapalan 1995, Beckie 1996, Beven 1996, Bergström and Graham 1998, Sposito 1998, Zijl 1999, Blöschl 2001, Neuman and Di Federico 2003, Skøien *et al*. 2003, Sivapalan *et al*. 2004, Merz *et al*. 2009). However, in the broader hydrological literature, scale is often discussed in an arbitrary fashion, and scale terms are poorly defined or not defined at all. This paper explores whether such poorly defined terms may be an impediment to intra- and interdisciplinary research, teaching and outreach (Sivakumar 2012). In other disciplines, such as atmospheric science, the length scales of different scale terms are clearly defined.

Hydrological phenomena exhibit natural time–space scales, called process scales, but the finite number of samples leads to the necessity of observing hydrological processes over certain, specific observation scales (Blöschl and Sivapalan 1995). Blöschl and Sivapalan (1995) distinguish three different types of observation scales: extent or coverage of a data set; spacing or resolution of a data set; and integration volume of a sample. Dooge (1986) introduced nine different observational scale terms from molecular (10^{-8} m) to planetary (10^{7} m). To the best of our knowledge, Dooge (1986) is the only attempt to suggest observational scale terms for the hydrological community (Fig. 1). A smaller range of observational scales is accessible to humans directly through their unaided senses, from approximately one-tenth of a millimetre to a few kilometres. Klemeš (1983) suggests that we have the best grasp of hydrological processes occurring at these human scales (Fig. 1). The observational scales of hydrology have not previously been quantitatively or qualitatively examined. We do not propose a new understanding of the process scales of hydrological systems, but rather we explore the terminology used to define observational scales.

Other disciplines explicitly acknowledge the subjective and constructed nature of the concept of scale. Social theorists have a rich literature on how scale is socially constructed, reproduced and consumed (Marston 2000). This discourse is particularly relevant in relation to geographic terms such as local, regional or national scale, which have been naturalized to the point where they are no longer specifically constructed and defined for a given analytical purpose (Howitt 1998). Scale has also been conceptualized as having multiple facets, namely, size, extent, level, relation and resolution, whether these are noted explicitly or not (Howitt 1998, Gibson *et al*. 2000). In the present study, we focus on the facets of extent (see Gibson *et al*. (2000), Table 1, for definition) and size (see Howitt 1998, for definition).

In the past few decades, hydrology has significantly progressed in interfacing with other fundamental and applied sciences, though interaction becomes more difficult moving away from the physical sciences, the traditional realm of hydrology (Blöschl 2006). Yet increasingly, researchers are calling for interdisciplinary integration, catalysing new research and nurturing new educational models (Wagener *et al*. 2010). Effective communication is critical when attempting interdisciplinary research and collaboration. For example, Janauer (2000) indicates that efficient lines of research in ecohydrology start with mutual understanding of the concepts and scales associated with the different disciplines. Problems of scaling exist in both hydrology and ecology, and ill-defined terminology within each field leads to

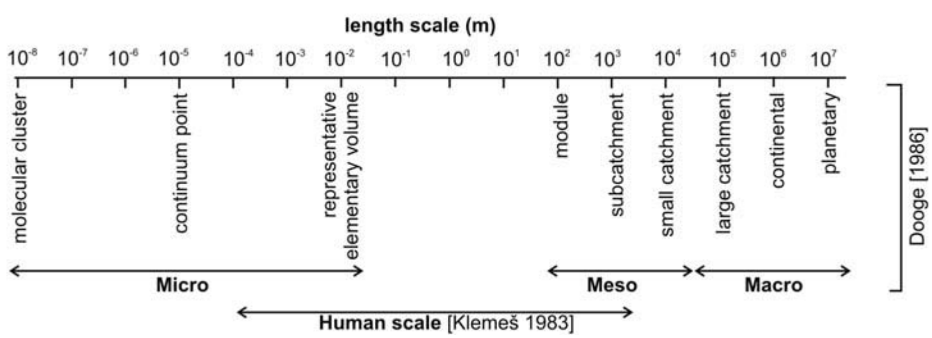

Fig. 1 The length scales of various observation scales.

Table 1 Written, open-ended survey completed by 147 respondents. Complete introduction and directions to the survey are in the Supplementary Material.

Scale term	Length-scale in meters or feet (range or value)
Small scale	
Large scale	
Local scale	
Regional scale	
Site scale	
Pore scale	
Basin scale	
____ scale	
Subfield or research area (optional): ____________________	
State or province you live (optional): ____________________	

even more deviation when comparing the meaning of terms such as point scale, catchment scale, meso-, macro- or mega-scale, between disciplines. The importance of common understanding of scale terms and clear effective communication becomes ever more important as hydrologists attempt to better characterize coupled human–nature systems and participate in environmental management, given the connective and evolving role of water across a wide range of human and natural systems and a wide range of temporal and spatial scales (Gibson *et al*. 2000, Wagener *et al*. 2010, Sivakumar 2012).

Our objective is to examine the perception of scale in the hydrological community. Our research questions are: (a) what are hydrologists' perceptions of various scale words? and (b) do surface water and groundwater hydrologists have statistically different perceptions about scale terms? We used an exploratory, qualitative research approach to look for new patterns and insights. We collected and analysed quantitative and qualitative data on the perception of scale amongst practising surface water and groundwater hydrologists using a written survey and face-to-face interviews.

2 METHODS

Data were collected using two qualitative, exploratory research methods designed to assess participants' perceptions of spatial scale. The first was an exploratory written survey that asked open-ended questions (Table 1). The second was a set of semi-structured face-to-face interviews (Table 2 and Supplementary Material). An open-ended survey was used because the purpose was exploratory, and we did not want to presuppose a numeric range for answers. Face-to-face interviews were designed as a follow-up to probe respondents' perceptions of scales more deeply. Both investigations were entirely voluntary, tested on small pilot groups and designed following recognized survey and interview methodology (Miles and Huberman 1994, Wengraf 2001).

In the written survey, participants were asked to write the length-scale as a range or value in metres or feet for seven common scale terms, including "small scale", "large scale" and "regional scale", as defined in their research or hydrological subfield (Table 1). A comprehensive survey with all the scale terms used in hydrology was not possible. Some relatively common terms that were not included are hillslope scale, bench scale, reaction scale, plot scale, headwater scale, continental scale, watershed scale, microscale and mesoscale. Space was provided for participants to add any additional scale terms they felt to be missing from the list (Table 1). Participants were asked to leave terms blank if they are not used, and to put a strike through any terms they consider meaningless. Participants were given the option to identify their subfield or research area, in addition to their state or province of residence.

Written survey responses were collected at the GSA Annual Meeting in Denver, October 2010, during the Hydrogeology Section luncheon (hereafter referred to as GSA), as well as at the AGU Fall Meeting in San Francisco, December 2010, during luncheons for the Hydrology Section and Biogeosciences Section (hereafter referred to as AGU). The participants of each luncheon were all members of the Hydrogeology (GSA) or Hydrology (AGU) sections, and are all professional hydrologists, primarily from academia. Printed surveys were distributed to all participants at each luncheon, and the purpose of the survey was explained briefly. The AGU survey requested that any attendees who had completed the survey at GSA abstain from doing another.

Written respondents (n = 147) were categorized following the nomenclature of the AGU Hydrology Section technical committees (Table 3): surface water hydrologists (n = 30), groundwater hydrologists (n = 76) and other and undeclared (n = 41). Respondents from the AGU Hydrology Section luncheon were categorized based on their response to an optional question requesting that they identify

Table 2 Summary of questions and responses to oral, face-to-face survey completed by 18 respondents. Not all respondents answered all questions. Complete introduction and directions to the survey are in the Supplementary Material.

Do you consider yourself a:	7 surface water hydrologists, 4 groundwater hydrologists, 3 both and 4 other	
Did you complete the written survey?	11 Yes	
	7 No	
Do poorly defined scale terms impede your research, teaching or collaboration within hydrology or with other disciplines?	11 Yes	Why? – the impedance is minimal; just needs clarification – cannot transmit research findings or knowledge – publication and review within the discipline – difficult to communicate with stakeholders (× 2) – takes a lot of discussion – difficult to define and use terms
	6 No	Why not? – people have different ideas; just needs clarification – just accept that people define words differently and figure out what people mean – can come to common definition quickly even if terms are poorly defined – never thought about what they mean – scale terms are well defined in my research area
Do individual hydrologists consistently define scale terms in the literature?	18 No	Why not? – we do not have agreement or definition (× 5) – because we all have bias – we assume our bias is transferable to others – limited awareness of scale issues – people assume the reader understands (× 5) – people write for a small audience (× 2)
Does the discipline need to define the length scale of specific scale terms or should individual hydrologists define their own length scales?	10 Discipline defines	Why? – makes communication easier – would be helpful to have a standard (× 4) – save lots of arguments – could help the community synthesize – less assumptions about nomenclature
	4 Individual defines	Why? – universal definitions are impossible – not necessary – waste of time for the discipline to do this
Given that watersheds and basins are nested or fractal, should the discipline discuss their length scale?	4 Yes	Why? – as a nested system – easier to put data into context
	10 No	Why not? – need to specify every time – this is useless – context dependent (× 2)
Should groundwater and surface water hydrology use consistent scale terminology?	15 Yes	
	2 No	

their subfield or research area (Table S1). Participants from the AGU Biogeosciences Section luncheon who indicated affiliation with the Hydrology Section were categorized as surface water hydrologists. All participants from GSA were categorized as groundwater hydrologists (Table 3). Data were compiled for each category either as singular length values or ranges with maximum and/or minimum values. Approximately half of responses were singular length values and half of responses were ranges with maximum and/or minimum values. For responses provided as areas, the length scale was calculated as the square root of the area. The logarithm of each singular, maximum and minimum value was taken since responses varied over several orders of magnitude. For each scale term, the mean and standard deviation of each log-transformed value (minimum, singular and

Table 3 Number of respondents for written survey.

Category	*n*
Groundwater	76
(GSA meeting)	63
(AGU meeting, see Table S1)	13
Surface water	
(AGU meeting, see Table S1)	30
Other or undeclared	41
Total	147

maximum) was calculated and plotted. The difference in perception of different words between groundwater and surface water hydrologists was examined by testing whether the populations of log-transformed singular values were statistically different using *t*-tests and Kolmogorov-Smirnov tests.

Eighteen groundwater and surface water hydrologists were interviewed face-to-face at the AGU Fall Meeting in San Francisco, December 2011 (Table 2). Interviews consisted of nine questions that took respondents ~15 minutes to complete. Participants at Hydrology Section events were asked at random to voluntarily participate in the face-to-face interviews. Nine questions were designed to elicit both quantitative data (e.g. yes or no) and qualitative data (e.g. why or why not). Data summarized in Table 2 were drawn from notes taken during interviews as voice recording of the interviews was socially awkward.

3 RESULTS AND DISCUSSION

One simple first observation is that the science and practice of hydrology is concerned with a huge range of scales. The 19 orders of magnitude (10^{-9} m to 10^{10} m) identified by the groundwater and surface water hydrologists surveyed is decidedly greater than the eight orders of magnitude mentioned in Klemeš (1983) and Blöschl and Sivapalan (1995), but is more consistent with the 15 orders of magnitude (10^{-8} m to 10^{7} m) that Dooge (1986) indicates are the spatial scales of hydrology (Fig. 1).

Figure 2 plots the mean and standard deviation of the minimum, singular and maximum values for each scale term and for each category of respondent (all respondents, groundwater hydrologists and surface water hydrologists). The mean minimum and mean maximum fall within the standard deviation of the singular values for all scale terms and all categories, except site scale for groundwater hydrologists. Therefore, Fig. 2 illustrates that there is reasonable agreement (within one or two orders of magnitude) for most scale terms. However, the standard deviation of most of the singular values is greater than one order of magnitude (Table 4), suggesting a definition of scale any more accurate than one order of magnitude is unlikely. For example, the term "pore scale" is interpreted over >5 orders of magnitude among hydrologists suggesting that multiple interpretations of pore are possible depending on disciplinary background and the research question at hand. The significant variability of the perceived value of each scale term may in part also be due to hydrologists limited understanding of different types of observation scales ("extent", "spacing" and "integration volume"), as discussed by Blöschl and Sivapalan (1995). This may be compounded by the difficulty of conceptualizing smaller (e.g. pore) and larger (e.g. basin) scales, which are outside of our direct sensory comprehension (Klemeš 1983).

There is reasonable agreement between surface water and groundwater hydrologists on the perception of many scale terms (Fig. 3). The singular value for surface water hydrologists falls within a single standard deviation of the singular value for groundwater hydrologists, and *vice versa,* for all scale terms except large scale. The similarity between responses from surface water and groundwater hydrologists was tested using a standard *t*-test and Kolmogorov-Smirnov test. An initial *t*-test indicates that the responses from both surface water and groundwater hydrologists is lognormally distributed at a 95% confidence interval for all scales except small scale for both groups. Small scale was not further analysed using parametric *t*-tests and is shown as n/a in Table 4. The null hypothesis of a second *t*-test (the means are not equal) was rejected ($p > 0.05$), for all scale terms except large scale. Similarly, the null hypothesis of the non-parametric Kolmogorov-Smirnov test (the distribution functions are not equal) was rejected ($p > 0.05$), for all terms except large scale. Therefore, the perception of scale is generally not statistically different between surface water and groundwater hydrologists.

Despite the general agreement on the lengths associated with particular scale terms, there is disagreement between groundwater and surface water hydrologists on which terms are meaningful (Fig. 4). Over 20% of surface water hydrologists consider "site scale" meaningless, whereas fewer (15%) consider "small scale" and "large scale" meaningless. In contrast, over 20% of groundwater

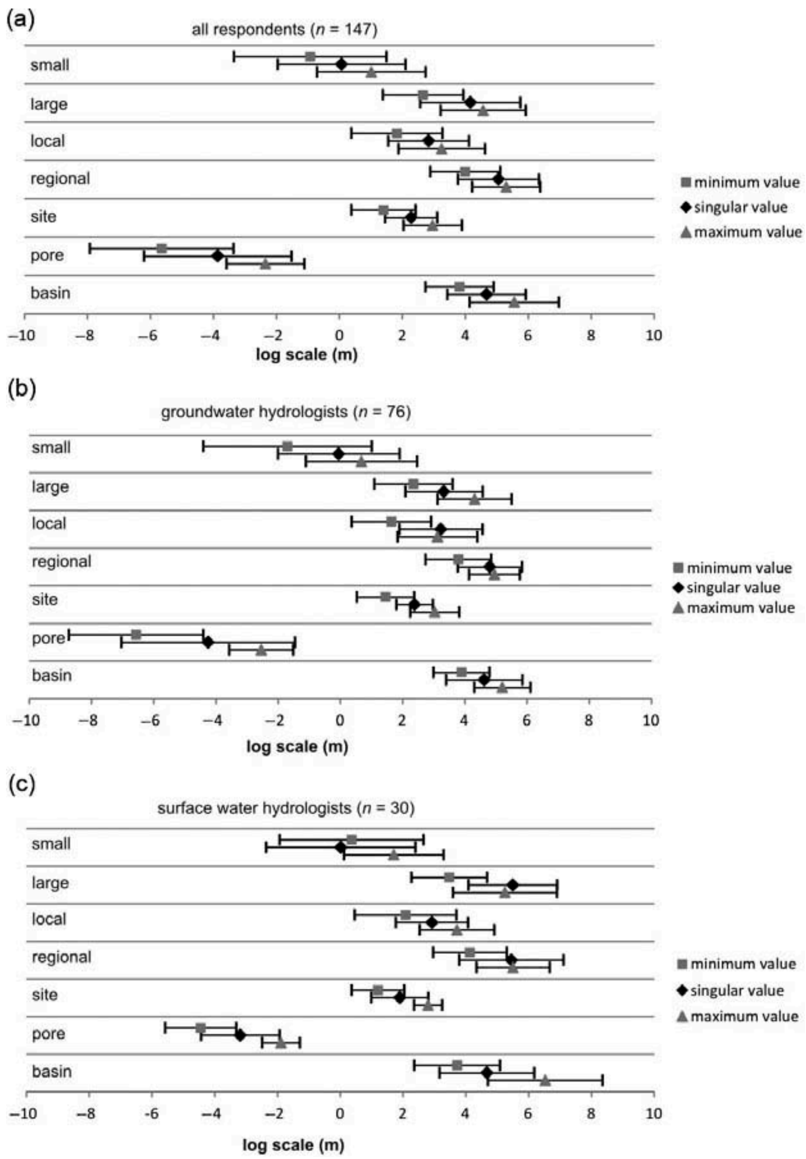

Fig. 2 Perception of scale terms among: (a) all respondents, (b) groundwater hydrologists and (c) surface water hydrologists. Data were compiled for each category as either singular length values or ranges with maximum and/or minimum values. Mean and standard deviation for the minimum, singular and maximum values are shown for each scale term.

hydrologists consider "small scale" and "large scale" meaningless, and less than 10% consider site scale meaningless, possibly because "contaminated sites" are a strong research thrust in groundwater hydrology. The remaining scale terms (local, regional and pore) are considered to be meaningless by less than 10% of groundwater and surface water hydrologists. The results of the face-to-face interviews suggest that hydrologists considered a scale term meaningless if the term was vague, rather than technically inconsistent or not part of hydrological research or practice.

The results of the face-to-face interviews (Table 2) are useful for understanding the underlying perceptions of scale within the discipline. Results for most questions were convergent although the sample size was small (n = 18), which is not unusual for more intensive interviewing methods. All respondents (100%) said that individual hydrologists do not consistently define scale terms in the literature. Reasons for not consistently defining scale terms included not having a common agreement for scale terms and the bias or assumptions of an individual scientist or small scientific community. Most respondents (65%) consider poorly defined scale terms an impediment to their research, teaching or collaboration within hydrology or with other disciplines. This

Table 4 The log-transformed mean and standard deviation of the "singular values" from Fig. 3. Units are metres, μ is the mean, σ is the standard deviation and p is the p-value. The t-test and Kolmogorov-Smirnov (K-S) test whether the perception of scale is different between groundwater and surface water hydrologists. For both tests and all terms analysed except large scale, shown in bold, the null hypothesis is rejected ($p > 0.05$), meaning the perception of scale terms is not statistically different between surface water and groundwater hydrologists. Small-scale data were not analysed (n/a) using the t-test because they are not log normally distributed.

Term	All respondents		Groundwater hydrologists		Surface water hydrologists		t-test	K-S test
	μ	σ	μ	σ	μ	σ	p	p
Small	0.1	2.0	0.0	2.0	0.0	2.4	n/a	0.7815
Large	4.2	1.6	3.3	1.2	5.5	1.4	**0.003**	**0.0295**
Local	2.8	1.3	3.2	1.3	2.9	1.2	0.522	0.941
Regional	5.1	1.3	4.8	1.0	5.5	1.7	0.201	0.8252
Site	2.3	0.8	2.4	0.6	1.9	0.9	0.082	0.4145
Pore	–3.9	2.3	–4.2	2.8	–3.2	1.3	0.258	0.5596
Basin	4.7	1.2	4.6	1.2	4.7	1.5	0.934	0.9711

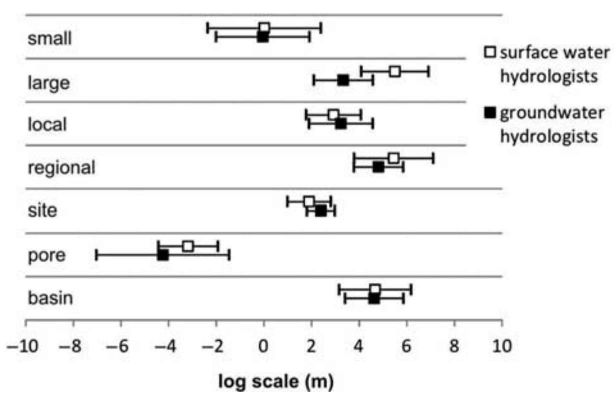

Fig. 3 Comparison of perceptions of scale between surface water and groundwater hydrologists. The mean and standard deviation of the "singular values" from Fig. 2 are shown.

impediment is generally considered minor and fairly easily resolved by discussion between colleagues, but some considered this a more significant impediment to communication with stakeholders or colleagues outside of hydrology or the physical sciences. This impediment may be more significant for publications because one cannot clarify a misunderstanding as easily with an author as one can when speaking.

The results of the face-to-face interviews are also useful for recommending how the discipline could proceed. Most respondents (71%) suggested the discipline needs to define the length scale of specific scale terms, rather than individual hydrologists defining their own length scales. The purpose of clearer definitions would be to make communication easier and more effective and to help with synthesis of hydrological data. Most respondents (88%) said that groundwater and surface water hydrology should use consistent scale terminology, since they are strongly coupled. However, most respondents (71%) suggested the discipline should not discuss the length scale of watersheds and basins since these are nested or fractal, and their scale is context-dependent. Therefore, the discipline could proceed towards more universal definitions of scale terms that are applicable to both groundwater and surface water hydrology, but exclude terms for fractal entities such as basin or watershed.

Interpretation of the survey results should consider the limited number of respondents given that ~7000 AGU members list the Hydrology Section as their primary affiliation and the GSA Hydrogeology Section has ~1350 active members. In addition, some of the written survey results are physically implausible. Over 10% of the surface water hydrologists reported singular or maximum values for basins that are larger than the Nile or Amazon river basins. We suspect that these physically implausible answers might not have been reported if the hydrologists had taken more time to consider their answers, possibly with reference materials, but this was not possible in the venue of the written surveys.

4 CONCLUSIONS

Important conclusions about current perceptions and future directions can be drawn from the two analysed surveys.

Most respondents suggest that hydrologists do not consistently define scale terms in the literature

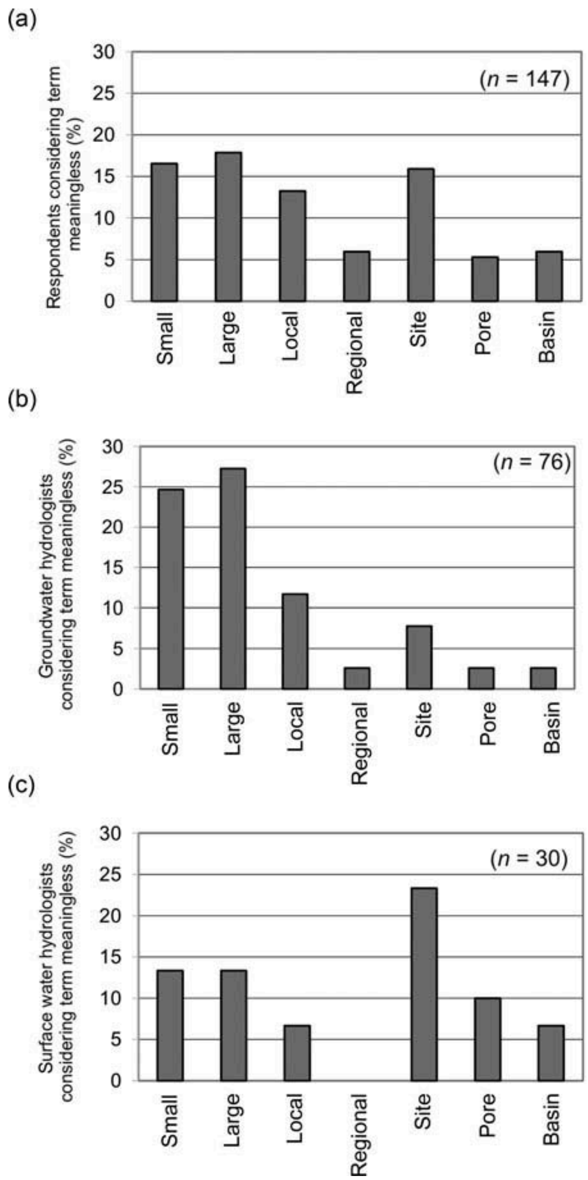

Fig. 4 Percentage of respondents considering given scale terms meaningless among: (a) all respondents, (b) groundwater hydrologists and (c) surface water hydrologists.

and that this is a minor impediment to their research, teaching or collaboration within hydrology, or with other disciplines and stakeholders.

Even though all respondents suggested that individual hydrologists do not consistently define scale terms in the literature, there is reasonable agreement across the discipline on the perceived length scale for most scale terms (Fig. 3). Most hydrologists agree, within one to two orders of magnitude, on the length scale for most scale terms. One to two orders of magnitude may be the entire range of scales for some research fields within hydrology (such as contaminant hydrogeology), which may render this discipline-wide agreement of length scales operationally meaningless within a research field. However, this unrecognized agreement of perceptions is useful for the discipline since, overall, it examines processes over ~19 orders of magnitude (Figs 1–3).

Most respondents suggest the hydrological community needs to better define the length scale of specific scale terms. Results from the written survey could be used as the basis for these discussions and Fig. 3 suggests that this process may not be as difficult or impossible as some hydrologists assume (Table 2). Guidelines for this process include definitions that apply to both groundwater and surface water hydrology, but exclude terms for fractal entities such as basin or watershed.

In the short term, we suggest that hydrologists can more frequently and consistently clarify their own length scales whenever a scale term is used. The most effective and simple method is clarifying the singular length scale or range of length scales in brackets following the first use of a scale term in a paper. For example, "small-scale (10–20 m) observations were conducted over the entire hillslope-scale (100 m) study area". This data could then be collated to become another quantitative basis for future scale definitions.

Commonly agreed upon terms and their meaning within the discipline of hydrology could facilitate intra-disciplinary research, as well as communication with other disciplines and the general public. We echo other researchers (e.g. Janauer 2000, Sivakumar 2012), in calling for more strict definition of scale terminology, and more explicit accounting for scale as a variable in analysis (e.g. Marceau 1999). The application of hydrological sciences and water resources management increasingly requires stakeholder engagement and a participatory approach. High-level communication skills are necessary for these processes, and one of the basic elements for meaningful communication is a common language known moderately well by all participants (Dooge 1997). With a common set of scale terms for groundwater and surface water hydrologists, the process of communication with each other and with others outside of the discipline is greatly simplified.

An obvious extension of this research is the inclusion of more disciplines, both within the natural and social sciences. This could help to identify barriers to communication, as well as commonalities which may promote mutual understanding between disciplines. The perception of timescales is another avenue of potential research—it is well acknowledged that there is an intrinsic relationship between space and time (Klemeš 1983), and because of this relationship we often refer to "the scale" of a process, implying both spatial and temporal scales (Blöschl and Sivapalan 1995). However, upon closer examination of many hydrological processes, it is clear that there are many subtleties in the space–time relationship, and it would be worthwhile to explore hydrologists' perception of this topic.

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SUPPLEMENTARY MATERIAL

Supplemental data for this article can be accessed at http://www.tandfonline.com/10.1080/02626667.2013.797581.

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