Flood generation: process patterns from the raindrop to the ocean

CC1: 'Comment on hess-2022-2', Luca Brocca, 13 Jan 2022 reply

I read the "review" paper by Prof. Bloschl in less than one hour. Of course, it is written very well and it is really easy to follow the overall narrative from the beginning to the end (as to follow the rain drop from the soil to the ocean!).

However, I believe that the main questions are still there, they are highlighted but not addressed. How to move across scales? Are there physical relationships that can be applied across scales in hydrology?

Similarities across scales are evident (preferential flow in soils, river over landscape, atmospheric river, ...)...but how to exploit these similarities in our modelling?

Solving this issue will help in addressing a fundamental topic in recent time, how to perform high resolution hydrology? How to address the interactions between the water cycle and the human intervention?

I am aware that it's a very challenging topic and whoever will solve the problem will give an outstanding contribution to hydrology.

I am very interested to know the opinion of the author, and of my colleagues who will like to contribute.

Citation: https://doi.org/10.5194/hess-2022-2-CC1

Response to CC1:

I could not agree more with Luca Brocca’s observations, both regarding the open questions on scaling and the need for a more in-depth discussion of them.

How to exploit these similarities across scales, e.g. regarding preferential flow, in modelling? Truly a challenging topic which, I am afraid, I will not be able to do full justice in this paper. There exists a plethora of upscaling and downscaling methods (see, e.g., Blöschl, 2005), some of which account for connectivity, such as connectivity functions at the local and catchment scales (Western et al., 2001) and top-kriging at the catchment and regional scales (Skøien and Blöschl, 2007). The more general point in this paper is that the use of observed process patterns seems to me a key element in coming up with the structure and the parameters of such scaling methods. This means, rather than conjecturing the scaling relationships (which we do when, e.g., assuming that Richards equation applies to the catchment scale), the idea is to learn from observed patterns. From the patterns it is also possible to establish cause-effect relationships directly at the scale of interest, without resorting to scaling methods, when viewing hydrology through the prism of scale. In this case no upscaling methods are needed.

Reviewer RC1 has asked how applied hydrology could benefit from looking at flood generation patterns at different scales, and in the response I have provided a number of examples from my own work in the response, which could also help shed light on the scaling question posed here. I believe that flood design has benefitted from process patterns such as those in Fig. 6 (runoff generation) and Fig. 7 (flood types) through the flood frequency hydrology approach (Merz and Blöschl, 2008). Flood forecasting has benefitted from using observed snow and soil moisture patterns as well as preferential flow representations in the soil (Blöschl, 2008). And risk assessment of spring contamination has benefited from observed patterns of evidence on surface runoff (Reszler et al., 2018).

I will add these practical examples to the conclusions sections, but feel that an in-depth discussion of the topic – notwithstanding its importance – goes beyond what this paper tries to achieve. It would be worthwhile thinking about a follow up discussion or paper focusing more specifically on upscaling that builds on patterns.

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RC1: 'Referee comment on hess-2022-2', Anonymous Referee #1, 18 Jan 2022 reply

This is an inspiring paper. I was in the audience of the Dalton Medal lecture and I am delighted that Prof. Blöschl has accepted the invitation to put that talk on this excellent paper. Hereafter are some comments/questions/curiosities for which I would be grateful of knowing Prof. Blöschl opinions (and that may or may not result in minor additional discussion in the paper, even if they were not discussed in the medal lecture).

- The concept of the "digital twin" of the earth system is gaining more and more relevance in science, and not only, given the progress of technology (e.g., Machine-Learning) and of data availability. Does Prof. Blöschl think that a digital twin of the earth system (including hydrology) is possible? Hydrologists are starting to think of implementing a digital twin of the hydrologic system (see e.g., Rigon et al., 2022, https://hess.copernicus.org/preprints/hess-2021-644/). Rigon et al. (2022) suggest that the digital twin metaphor can be something more than the hyperresolution modeling paradigm mentioned by Prof. Blöschl, i.e., an infrastructure to connect different data/models/hypotheses. Can such a digital twin be the tool to bridge the gap between scales and to help hydrologists to learn about flood processes from patterns at all scales? Is this the tool to approach, as a community, the questions raised by Luca Brocca commenting on the present paper? Or, does Prof. Blöschl think that a **digital twin** of the earth system (including hydrology) is possible?

- I will give this paper to my students for opening their minds on what is hydrology as a science. Even though it is touched here and there, the paper is less revealing of how "applied hydrology" could benefit from looking at flood processes at different scales. How has this journey through scales helped Prof. Blöschl to improve flood **design**, flood forecasting, flood risk assessment, etc.? How should common engineering practice evolve given the lesson learned (or to be discovered) by observing flood processes at different scales?

- On page 3 the debate about inherent and cognitive uncertainty is mentioned, and Prof. Blöschl suggests that "scaling work" can be an opportunity to resolve it (this is what I understand by the unification of concepts) and an opportunity to better estimate uncertainty (this is what I understand by the unification of tools and measurement techniques). Is this the meaning of the last paragraph on page 3? If so, it is to me unclear how the scale research is contributing to these issues. Would it be possible to give an example or two?

- The concept of "trading space for time", not explicitly mentioned here, is very much used in hydrology. I know this paper is about space and not time (not explicitly) but I am curious to know in what cases, based on his journey across spatial scales, Prof. Blöschl thinks that trading space for time is justified (e.g., flood frequency analysis, flood design under climate change, ...). For example, if flood generation processes result from the coevolution of climate and landscape, are we allowed to assume that the humid catchment A will behave like the dry catchment B 50 years from now?

- I am looking forward to the follow-up of this paper: an opinion on process patterns across temporal scales, from the instantaneous peak discharge to the long-term climatic flood behavior (e.g., Blöschl et al., 2020, https://www.nature.com/articles/s41586-020-2478-3). What could we learn from the temporal scales of floods? How would Prof. Blöschl streamline such a paper (just a curiosity of mine)?

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Response to RC1:

I would like to thank RC1 for the thought provoking questions and the opportunity to expand on them. Below I will share some of my thoughts, noting that the topic deserves fuller discussion, perhaps in the format of a future workshop.

The Digital twin concept (Rigon et al., 2022) is very relevant to the context of this paper. I would think that one can speak of “Weak Digital Twins” and “Strong Digital Twins”. In the weaker sense they are really hyperresolution models with the appropriate data assimilation and user interfaces, e.g. following the definition of Bauer et al. (2021, p. 80): “A digital twin of Earth is an information system that exposes users to a digital replication of the state and temporal evolution of the Earth system constrained by available observations and the laws of physics.” In the strongest sense, the connections between the physical and digital systems are fully implemented which goes beyond a user interface and, following the original idea from manufacturing, fully integrates water management processes, ideally with water-human feedbacks (Sivapalan et al., 2012). The perspective of Rigon et al. (2022), I think, is slightly more oriented toward science than to management and emphasises the potential of forging a more coherent science community, something I consider extremely important (Blöschl et al., 2019). So, in response to the question posed by RC1, a digital twin will perhaps not in itself resolve the scale issue, but it may help hydrologists do more coordinated research and thus also address the scale issue. I will add a comment in section 2 of the paper to refer to digital twins.

The question of how this journey through scales has helped improve flood design, flood forecasting and flood risk assessment is, again, a very good one. I feel very strongly about the synergies of theory and practice. Good science will lead to more accurate practical methods, and practice may provide data and direction for promoting science progress (Sivapalan and Blöschl, 2017). I believe that the scales perspective can indeed help practice. For example, flood design has benefitted from process patterns such as those in Fig. 6 (runoff generation) and Fig. 7 (flood types) through the flood frequency hydrology approach (Merz and Blöschl, 2008), which is also recommended in the German and Austrian flood estimation standards (DWA, 2012; ÖWAV, 2019). Flood forecasting has benefitted from using observed snow and soil moisture patterns as well as preferential flow representations in the soil (Blöschl et al., 2008; Blöschl, 2008). And risk assessment of spring contamination has benefited from observed patterns of evidence on surface runoff (Reszler et al., 2018). Again I will add a comment on my perspective on this in the conclusions section.

Regarding the concept of "trading space for time", I believe we can learn a lot about the time evolution in one catchment from comparisons with other catchments. Hydrology is not a unique case in the spectrum of science disciplines to use comparative methods. For example ethnologists learn about the cultural evolution of music by comparing different ethnicities at the same time (Schneider, 2006), and chronosequences are the classical case in Earth science (Walker et al, 2010). However, such a space-time similarity does not necessarily imply that the cases compared are exact carbon copies shifted by a fixed time of e.g. 50 years. The learning is more about the underlying cause-effect relationships. In the case of flood generation processes, for example, Perdigão and Blöschl (2014) have suggested, that trading space for time is possible provided coevolution is taken into account through characteristic celerities that reflect the spatiotemporal symmetry. In practical terms their study has shown that "the spatial sensitivity of floods to precipitation exceeds that over time, in such a way that, given a 10% spatial increase in precipitation, there is a corresponding 23% increase in flood peaks, whereas given a similar 10% increase in precipitation over time, the flood peaks increase only about 6%." They conclude further that "the interchangeability is found to be legitimate in regions with hydrogeological stability that have had the time to span the whole state space (thus enabling the ergodic hypothesis) or systems that, even not in equilibrium, are evolving at a similar pace (enabling the Taylor hypothesis). On the other hand, regions with transient hydrogeological activity do not comply with such hypothesis, therefore measures of coevolution or relative characteristic celerities have to be taken into account in the space-time trading." I should add that this is only one case study and an evaluation of whether these findings are more widely applicable is still needed.

The statement on the potential of scale research as a unifying framework was not specifically intended to relate to uncertainty but more generally to hydrology. The idea is to explore phenomena at commensurate scales (e.g. explaining regional scale flood patterns by regional scale climate and soil patterns, rather than soil preferential flow) and to establish cross scale links that may be similar, e.g., for floods and droughts (Blöschl, 2001, 2006). I will add an explanation to better bring out the idea of the quote. In fact, I believe that the entire paper is an example of how a scale perspective can help organise one's thinking and thus contribute to progress.

Scale issues in time have been the subject of Sivapalan and Blöschl (2015). There are plans for a paper on flood changes in HESS (Blöschl, 2022). A paper on how one could learn from the temporal scales of floods is still to be written and could revolve around the propagation of information between time scales. An example of how the seasonal and event scales interact is discussed in Sivapalan et al. (2005).

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RC2: 'Comment on hess-2022-2', Anonymous Referee #2, 26 Jan 2022 reply

This paper provides an excellent timely review on runoff generation processes at different spatial scales and their links, with a focus on flood phenomenon. The continuous spectrum of flood generation process is separated into 5 distinctively representative scales, i.e., pore, profile, hillslope, catchment, region, and continent, with a total of 10 order of magnitude. The inherent interaction at the lower scale leads to emergent behaviors at the high scale, which can be universally described as preferential flow and threshold behavior. The implications of scale transition for hydrological modeling are also deeply discussed. All in all, this review is of great importance to the hydrological community in both process and modeling fields. I recommend its immediate publication after some minor revisions to address the following comments.

- Introduction part, Ln33: the fatal flood event occurred in July 2021 in Henan Province of China is worthy to be mentioned, with a total death of over 300.
- Conclusion part, Ln366: 'connectivity' is considered to be universal at all scales which control where flow paths connect and thus the overall behavior of the system. However, it is not obvious at the continental scale. At this scale, the author revealed preferential path of atmospheric storm dominates the flood generation. How 'connection' presents itself at this scale is not obvious. More explanation will help readers for a better understanding.

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Response to RC2:

I would like to thank RC2 for the kind assessment and the comments.

The July 2021 in Henan Province will be included in the introduction.

The connectivity at the continental scale would indeed profit from further clarification. The superposition of the polar and the subtropical jet stream over the Western Mediterranean, which often Vb cyclones, I would interpret as a „connection“ of atmospheric process (Hofstätter et al., 2019). Another example are precipitation characteristics related to atmospheric rivers (Kim et al, 2021). I will add an explanation of the argument to the paper as follows: “It appears that connectivity is also important at the continental scale, e.g. through preferential pathways of flood-generating cyclones; in the particular case of Vb events through the connection of the eddy-driven polar jet stream and the subtropical jet stream over the Western Mediterranean; and through the role of teleconnections (e.g. as quantified by the Northern Atlantic Oscillation (NAO) and Arctic Oscillation (AO) indices in affecting flood-relevant cyclones (Hofstätter et al., 2019). Another example of connectivity in the atmosphere are atmospheric rivers (Kim et al, 2021).“

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RC3: 'This is essential reading for all starting PhD students in hydrology', Anonymous Referee #3, 26 Jan 2022 reply

This paper represents a major contribution to the issue of spatial scale and scaling, but with a focus on flood generation.

One can think of this as a continuation of the highly cited and authoritative review paper by Bloeschl and Sivapalan (HYP, 1995). It builds on the earlier review, but has gained in terms of richness through the substantial work that the author has done subsequently, especially in the context of the Flood Change project funded by the ERC. In this way, it has reinforced many of the key messages in the previous review paper.

The paper is presented in a narrative way, with no jargon in a lucid style (no preaching either), and thus will appeal to graduate students starting to specialize in hydrology and Earth sciences. I would consider this essential reading for starting graduate students.

In spite of a lot of progress over the last few decades, hydrologists continue to misunderstand the role of time and space scales and do much of their work oblivious to challenges and promise of scale interactions. This is holding back progress in many areas, especially modeling.

I support publication of the paper in its present form. However, one or two reviewers mentioned that they would like to see more discussion of a formalization of these ideas in the form of frameworks and analysis approaches. I think this is a useful suggestion. However, such a formalization was already present in the 1995 review paper, which this paper built on. What was missing in the earlier paper, and in this paper too, is a focus on timescales. Perhaps there will be an opportunity to do something along these lines in the future, whereby both space scales and timescales are both considered together.

That could be in the future - for now, this paper can be published in its current form

Citation: https://doi.org/10.5194/hess-2022-2-RC3

Response to RC3:

Many thanks for the thoughtful assessment of this paper.

A discussion of a formalization of the scale and scaling ideas in the form of frameworks and analysis approaches is of course important, perhaps building on Blöschl and Sivapalan (1995) and the present paper but, given its focus, a formalization would go beyond what this paper tries to achieve. It would, however, be worthwhile thinking about a follow up discussion or paper focusing more specifically on upscaling that builds on patterns.

Yes, a focus on timescales was missing in Blöschl and Sivapalan (1995), and it is missing in this paper too. As pointed out in my response to reviewer RC1, scale issues in time have been the subject of Sivapalan and Blöschl (2015). Traditionally, hydrologists were more concerned with scale issues in space because of the lack of spatial information, while time series of hydrologic fluxes have been available for a long time. More recently, the situation has changed a bit, both because of the availability of spatial satellite data and the increased importance of hydrological change, so scale issues in time are definitely becoming very relevant, in particular when the interactions with human activities are involved.

A joint consideration of space scales and timescales is important and there has been some work on it (see, e.g., Skøien et al., 2003; Blöschl et al., 2015) but I fully agree that, given the important science questions and the data availability, there is now an opportunity for deepening our understanding of space scales and timescales considered together.

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