Hydrologic synthesis: Across processes, places, and scales

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[1] Hydrologic synthesis, I believe, is needed in at least three respects: across processes, where the challenge is how to represent complex interacting dynamic systems including feedbacks between system components; across places, where the challenge is how to synthesize the plethora of case studies around the world in the past decades; and across scales, where one is interested in the general characteristics of processes as a function of space and time scales for the same site or an ensemble of sites. Seeking explanations for patterns, puzzles, and paradoxes is the way toward synthesis, and this should be pursued through two approaches. The first is to engage in more complex model building, but model complexity may ultimately limit the practical applicability of these models. The alternative is to seek more parsimonious avenues to synthesis. One of them is classification and similarity concepts which, generally speaking, can be profitably used when the processes are not fully understood. This often is the case in hydrology. Among the key unresolved issues and research challenges in hydrology is separating the predictable and the unpredictable. Synthesis, I think, needs to focus on the patterns of predictability. There is also an important, alternative, role of models in water resources management using models as communication tools. The best model then is not the most accurate one but the one that serves best the purpose of reaching a consensus among the players.

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[2] Calls for synthesis in hydrology have been numerous and eloquent over the past century. *Horton* [1931, p. 201] noted that "the most immediate needs for the advance of the [hydrological] science are ... research to provide connective tissue between related problems" and the point has been made many more times after that in various contexts. Of course, a clever choice of limited system boundaries has always been the hallmark of scientific progress as it allows to isolate problems one can understand with the data and concepts at hand. However, for many problems the system boundaries span a multitude of processes and scales and these problems tend to be the important ones today. Hydrologic synthesis is hence more urgently needed than ever.

[3] Hydrologic synthesis, I believe, is needed in at least three respects: across processes, places, and scales. The synthesis of processes is the most obvious one. Here the challenge is how to represent complex interacting dynamic systems including feedbacks between system components. In the past decades hydrology has made a lot of progress in interfacing with other Earth sciences. Coupled atmospheric–hydrologic models, for example, are at the verge of being routinely used in numerous countries but as one moves further away from the physical sciences background of traditional hydrology, integration becomes more difficult. Chemical, biological, economic and social processes span a spectrum of processes that, in that order, tend to be increasingly harder to synthesize with hydrology. At the surface the difficulty is related to scientific jargon but more importantly it is related to the paradigm in each of the disciplines and the prevailing paradigm, in turn, is related to patterns of predictability. Physics strives for universal laws governing ideal systems and the level of predictability is high (at least for some systems) while in biology the focus is on contingency and complex historical factors and predictability is much lower. The social sciences, it could be argued, extend even further along the axis of complex interrelationships and low predictability particularly if political processes are involved. It is exactly this synthesis across processes that is needed for managing today's water resources.

[4] The second level of integration is that across places. Here the challenge is how to synthesize the plethora of case studies around the world in the past decades and this is directly related to the patterns of predictability. From the 1960s, there have been numerous national and international programs, initially on experimental catchments, to examine similarities and differences across different climatic and hydrological conditions. These programs have provided valuable insights but generalizing the findings beyond the areas of interest has always been difficult. Each aquifer, catchment, and river reach, in fact, each episode, seems to have particularities that cannot be specified in full detail. Each field study is by their nature unique in both space and time and they cannot be repeated under exactly the same boundary and initial conditions, a notion *Beven* [2000] terms uniqueness of place. Unlike other natural sciences it is nature that does the experiments [*Dunne*, 1998]. In an

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attempt to account for local particularities hydrologists almost always resort to calibrating model parameters to make the models work in any one location. Calibration usually works well, as biases tend to change significantly with location but tend not to change much over the timescales we are interested in because much of the bias is related to unknown subsurface characteristics. However, it is clear that if one calibrates parameters to compensate for the real uncertainty this is likely a "quick fix" which may jeopardize the realism of the model. Obviously, a much better strategy would be to allow for the uncertainty in an explicit way rather than to seek a best fit of the model to the one realization of hydrologic response available.

[5] The third level of integration is across space and timescales. Unlike in the integration across places case we are now not interested in comparisons between sites but in the general characteristics of processes as a function of scale for the same site or an ensemble of sites. Point scale equations can be straightforwardly extended to catchments, aquifers, reaches etc. provided the boundary conditions are known and the media characteristics are known spatially (e.g., uniform) at the scale of the equations. However, the challenge in the hydrological sciences is that hydrological systems are never completely uniform in terms of their parameters, fluxes and states, and are often not even approximately uniform. Although upscaling methods do exist, additional assumptions need to be made about the variability, both in space and time and, often most importantly, about the nature and locations of the flow paths but much of this information may be "unknowable". This is also one of the reasons why models generally need to be calibrated to the particular site of interest. Preferred flow paths are related to organized spatial variability in the subsurface. Organized nonrandom variability seems, in fact, to be a characteristic of many natural systems, including social systems, which complicates upscaling. It is then the outliers, such as macropores or extreme floods or droughts, that dominate system behavior. Fractal or self similar concepts have been proposed as a parsimonious model for scale transfer, and they are appealing as they do take outliers into account: rare events, long-term dependence and spikes, depending on the type of fractal. However, they are often based on a single relationship across many scales which may be less than satisfying when different causal processes operate at different scales as generally is the case in hydrology.

[6] What, now, are the exciting opportunities in hydrologic synthesis in the years to come? How can we synthesize across processes, places and scales? I think the surest way to foster synthesis across processes is to interpret process heterogeneities or patterns as puzzles and interpreting them through interdisciplinary viewpoints. The surest way to foster synthesis across places is to look for process heterogeneity across places, and find an explanation or description of the underlying patterns. Likewise, the surest way to foster research across scales is again seek explanations and descriptions of patterns across scales. It is patterns, patterns, and more patterns, all of them viewed as puzzles that require explanation, interpretation and quantification.

[7] Seeking explanations for patterns, puzzles and paradoxes is the way toward synthesis and this should be pursued in two ways. The first avenue is to engage in more complex model building, i.e., building all processes that are deemed relevant into a model or a suite of coupled models; accounting for all the local particularities of any site in a model; and representing the small-scale heterogeneities and organization explicitly in much detail. However, model complexity may ultimately limit the practical applicability of these models. In some cases this may be because of computer limitations but in hydrology the more typical case is that excessive model complexity will defy identification of the model parameters and it will be unclear whether feedback mechanisms (between processes, places, and scales) are represented well. Because of this, increasing model complexity may in fact decrease the modelers confidence in the model at some stage. In agent-based models of water related processes in catchments, for example, the behavior of any individual stakeholder may be represented well but the aggregated or group behavior simulated by the model may be grossly in error if a few individuals dominate. This is reminiscent of preferential flow in hydrologic systems where, similarly, the outliers tend to control system behavior. The challenge of excessive model complexity may be addressed by emerging measurement techniques that are able to measure spatial patterns of hydrologic dynamics [*Grayson and Blöschl*, 2000]. Remote sensing methods will continue to play an important role at large scales but there is a lot of value in down to earth measurements, perhaps more than is generally acknowledged. Novel measurement techniques that allow rapid measurement of spatial patterns, such as sled-mounted FM-CW radar for mapping snow depths, all-terrain-vehicle-mounted TDR probes for mapping soil moisture, and hydrogeophysical methods to identify properties and monitor processes governing water flow and solute transport in groundwater and vadose zones are becoming instrumental in understanding the interplay of processes at a range of scales.

[8] The alternative to complex model building is to seek more parsimonious avenues to synthesis. One of them is classification and similarity concepts which, generally speaking, can be profitably used when the processes are not fully understood and, alas, this is the case in hydrology. So, what is it that makes a hillslope and a catchment hydrologically similar and what makes two catchments similar? Contrasting different aquifers, catchments and river reaches based on their characteristics has been termed comparative hydrology [*McDonnell and Woods*, 2004] and the purpose is to learn from the similarities and dissimilarities. Can we find a taxonomy in hydrology even if we do not fully understand the processes in each of the case studies, can we find patterns of similarity? The classification approach may assist in the synthesis across places and help address the generalization issue that has haunted hydrology since the sciences began as it provides context on the boundary and initial conditions not usually known. It may also help with synthesizing across processes as has recently been suggested by *Merz and Blöschl* [2003] for regional flood processes. Characteristic scales could assist in classification in a similar way as in fluid dynamics; their potential has not yet been fully exploited in hydrology [*Skøien et al.*, 2003]. Perhaps classification based predic-

tions may not be as accurate as those based on complex models but classification promises to provide order in an otherwise seemingly random collection of case studies.

[9] The prevailing paradigm of hydrology, without doubt, is that of positivism, i.e., the view, that there is a truth out there and if enough data are analyzed in the right way we can understand and resolve even the most complex problems. In the synthesis process there is now a tendency of imposing this paradigm on other disciplines. There are emerging tools that allow us to integrate economic, social and biophysical data, and the positivistic claim is that good policies, decisions and practices would flow from them. However, it is important to remember that, while positivism has served the physical sciences well, there are alternative paradigms such as interpretivism that acknowledge the existence of multiple realities, depending on an individuals' interpretation. Perfect predictability, I would argue, is not necessarily the holy grail in a synthesis context and perhaps hydrology is more akin to the biological sciences than we would like to think. Clearly, once we integrate hydrological feedback effects with vegetation dynamics, biofilm and macrophyte dynamics in open waters, and microbial activity in the subsurface, predictability will be lower than what we are used to in traditional hydrology but even at the more modest level of water flow in hydrological systems, limits to predictability are an issue. *Zehe and Blöschl* [2004] recently adopted the concepts of microstates and macrostates from statistical mechanics to the prediction of hydrologic response. In their case, the microstates were the detailed patterns of initial soil moisture that are inherently unknown while the macrostates were specified by the statistical distributions of initial soil moisture that can be derived from the measurements typically available in field experiments. They showed that even if perfect knowledge on the processes is assumed, the level of detail with which one can measure the initial conditions along with the nonlinearity of the system will set limits to both the repeatability of experiments and the predictability of models. Among the key unresolved issues and research challenges in hydrology is separating the predictable and the unpredictable. Synthesis, I think, needs to focus on the patterns of predictability.

[10] A more realistic view of the capabilities of hydrological models, of what can be represented by quantitative models and what cannot, makes room for a new role of models to foster synthesis. Hydrological models are increasingly used to reach a consensus among parties on a particular matter [e.g., *Andersson*, 2004]. In catchment management studies, role games are becoming an important instrument. Here the purpose of an integrated system model is not to provide the best possible representation of reality but to assist actors in finding a consensus. The model then becomes a communication tool and the best model is not the most accurate one but the one that serves best the purpose of reaching a consensus among the players. The main strength of this type of approach is that it may enable synthesis of processes, places, and scales that are not incorporated in the particular model used. The synthesis is done by the players. The models will facilitate the dialogue if there is confidence in them, and stakeholders need to understand how the results are produced. There is hence a delicate balance in model complexity, simple enough to be transparent but complex enough to include the processes deemed important by stakeholders.

[11] I believe hydrology is at a stage of development where there is a lot of potential for synthesis through appreciation of alternative approaches stimulated by better communication. We need models of various types and complexities, but leaving it to the modeling community in a laissez faire way will not necessarily bring out synthesis. Perhaps we do not need more unified research approaches but we certainly need more focused research targets to trigger and encourage synthesis. The beacons that will drive the synthesis process are a strong research agenda at an international scale: (1) focusing on patterns of hydrologic dynamics in complex model building, (2) exploring alternative approaches such as classification to provide context, (3) identifying patterns of predictability, and (4) exploring alternative synthesis strategies revolving around communication.

[12] Synthesis may not materialize as a community model or a hydrologic theory but it may materialize as agreed patterns of predictability and help in consensus building among hydrologists. Complex system models clearly have their role in hydrology but alternative models and alternative model uses are equally valuable in hydrologic synthesis across processes, places, and scales.

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