Scale, Complexity and Variability in Catchment Hydrology: The Need for Classification

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Abstract: The goal of science is to organise knowledge. Clearly then, the role of scientific hydrology is to organise hydrological knowledge. Catchments are complex natural entities, and so there is a great deal of knowledge, much of which is difficult to organise. The notions of scale, complexity and variability have helped to impose some order on the great variety of observed catchment behaviours. This paper reviews some of that research, summarising progress to date. Although elegant concepts and detailed findings have emerged from that research, the results do not usually support transfer of knowledge to other locations or times. Typically the findings are either specific to the study site, or have too many free parameters, to be reliably transferred. This is an inevitable consequence of studying diverse natural systems such as catchments. I suggest that the absence of a widely agreed catchment classification scheme is a key factor inhibiting the transfer of hydrological research results. The paper concludes with a suggestion for the development of a more appropriate and widely accepted classification of catchments, permitting an efficient and rational sub-division of catchment hydrology into manageable, interacting sub-disciplines.

Keywords: Scale; Variability; Complexity; Catchment hydrology; Classification

1. INTRODUCTION

The goal of science is to organise knowledge. Clearly then, the role of scientific hydrology is to organise hydrological knowledge. Catchments are complex natural entities, and so there is a great deal of knowledge, much of it difficult to organise. The notions of scale, complexity and variability all help to impose some order on the great variety of observed catchment behaviours. Here I review some of the progress made using these notions, and suggest that the results are often not transferable because there is no common context in which to place the work. Further progress might be made if an appropriate classification scheme for catchments, based on understanding of physical controls on hydrological response, were to be developed and widely adopted as a tool for putting research results in context.

2. SCALE

The importance of temporal scale has been understood intuitively by hydrologists for many decades: for example, hydrologists do not confuse storm rainfall with annual rainfall. The situation with respect to spatial scale is much less clear. Obviously, there is the almost trivial knowledge that larger catchments usually catch greater volumes of precipitation. But how much of that science have we codified regarding the differences between small and large catchments? The effect of catchment area on hydrologic response is not trivial [Dooge, 1986], and neither does it fully explain hydrologic phenomena. Put simply, although large catchments can be viewed as collections of small catchments, this perspective is incomplete. New features are present at larger spatial scales that are not apparent or meaningful at smaller scales. For example, a regional scaling approach to flood frequency may be successful at spatial scales from 100 to 100,000 km^2, but not necessarily at smaller scales, where additional basin characteristics can be needed to make reliable flood estimates [McKerchar, 1991]. It may also be inadequate at larger scales where spatial differences in climate may alter the scaling markedly. If available, a classification of the flood-influencing aspects of climate (perhaps in tandem with a classification of geomorphology) would help identify such changes in scaling.

Many aspects of the hydrological cycle have been studied using spatial and temporal scaling as ways of compressing information. Statistical models of storm occurrence and within-storm structure are an example of this compression in the time domain. As a more sophisticated example, storm precipitation can be understood as a space-time cascade [Seed et al., 1999], allowing phenomena at scales from seconds to hours and metres to kilometres to be both conceptualised and simulated. Scaling descriptions are also available for some other phenomena relevant to catchment hydrology, such as soil structure [Tyler and Wheatcraft, 1990], vegetation and landforms [Nikora et al., 1999], and river networks [Nikora et al., 1996]. These descriptions are limited, as with any abstraction, but they do identify patterns which can be recognised and re-used (a key step in dealing with complex systems). They also provide quantitative descriptions of how scale affects each phenomenon, which are essential for tasks such as engineering prediction. A significant limitation of these descriptions that they do not connect one phenomenon to another, nor do they provide connections to the dynamic response of the catchment.

The availability of data made possible the relatively comprehensive scaling studies referenced above, e.g. RADAR for rainfall, accurate digital elevation data for topography. Using long streamflow records on some rivers, a large body of literature also exists on temporal scaling of catchment hydrology, particularly with respect to flood and low flow events [McKerchar, 1991; Pearson, 1995]. A key application of this knowledge is 'classical' flood frequency analysis, where one examines past flood events to estimate probabilities of (future) extreme events, rather than to explain why particular temporal scaling phenomena occur. The emergence of derived flood frequency [Eagleson, 1972], where models are used to route estimates of extreme rainfall, will eventually change that viewpoint radically. Flood frequency can now be considered as a phenomenon that has causes that can be investigated, comprehended, and used for flood estimation. This opens the possibility of looking at impacts of climate change and land-use change on flood frequency, provided we have sufficient confidence in the models. However, this approach is not yet widely used in practice, because our understanding of flood generating processes at the catchment scale remains limited, and practical descriptions of space-time rainfall are just emerging [Seed et al., 1999].

2.1 Spatial Scaling: Data

Regarding spatial scaling of catchment hydrology, rather less progress has been made. The immediate limitation is the lack of multi-scale spatial hydrology data that is suitable for the task. Although regional and national streamflow recording networks do provide data at a wide range of scales, interpretation of this data is confounded by the large differences in other factors than spatial scale (e.g. dominant runoff generation process). Existing measurement techniques for streamflow, soil moisture, water table position and evaporation are all poorly suited to the reliable collection of multi-scale spatial data. The reasons for unsuitability are usually the prohibitive costs and logistics associated with deploying locally-sensing instruments at enough locations to cover a domain of interest with a dense sampling network. This does not prevent the techniques being used, but has limited their applicability. Remote sensing remains a technique with the potential to revolutionise spatial scaling. Remotely sensed data has appropriate support, spacing and extent [Blöschl and Sivapalan, 1995] for spatial scaling studies. Once this data is calibrated to sense the 'signal' from hydrological variables (c.f. the 'noise' of atmospheric conditions or surface roughness), we can expect radical changes in hydrology.

The spatial scaling studies by Rodriguez-Iturbe et al. [1995] and Woods et al. [1995] (and some others like them) are unusual in that the support and spacing of the measurements are equal [Blöschl and Sivapalan, 1995]. Each measurement covers a defined area, and each area abuts all its neighbours. The entire study area is exactly covered by the measurements. This differs from studies that have incomplete spatial coverage, such as those with point observations of soil moisture, or most of those with streamflow data. To use partial coverage data in a spatial scaling study, assumptions are required about spatial variability between measured locations. This limitation is an important motivation to develop more effective spatial measurement techniques [see the examples in Grayson and Blöschl, 2000].

Once more effective measurement techniques have been developed, and a clear pattern of spatial scaling emerges at some experimental sites, there will remain the question of how to transfer that knowledge. It is not enough to understand experimental sites; we also need to know which places are similar to those sites. However, no general technique exists to select experimental sites that are known to be representative of a larger area. Again, classification could be a useful technique to make maximum use of knowledge.

2.2 Spatial Scaling: Models and Theories

As an alternative strategy in the absence of good spatial data, the last twenty years have also seen a large number of modelling and theoretical studies of spatial scale. Much of this work is summarised in the proceedings of four specialist conferences on scale problems in hydrology [Rodriguez-Iturbe and Gupta, 1983; Gupta et al., 1986; Sivapalan and Kalma, 1995; Blöschl, 1997].

The Representative Elementary Area (REA) is an interesting case study in the role of theoretical scaling studies. Wood et al. [1988] suggested, on the basis of a modelling investigation, that a preferred spatial scale (the REA) might exist for the purposes of catchment modelling. The associated modelling strategy was to parameterise variability at scales smaller than the REA, and to explicitly resolve variability at larger scales. This strategy can be used at any spatial scale, but it is effective if the scale is chosen in a way that the parameterisation is generic. Since the seminal paper of Wood et al. [1988], several studies have investigated the question further, e.g., Blöschl et al. [1995]. They (and others) found that the REA may have a dependence on hydrological setting, or in some cases may not be well defined. The main limitation of the REA concept is that it does not explicitly recognise the multi-scale nature of hydrological variability [Seyfried and Wilcox, 1995]. As a result, the REA concept has not found wide acceptance in the hydrologists' theoretical 'toolkit'. The nature of variability changes with location, with scale, and with the hydrological response being studied. When one finds evidence of spatial scaling, it is important to also note the physical setting, the pre-conditions that contribute to the scaling. For example, the conclusions one reaches on the spatial scaling in steep, humid catchments might be completely different to those in an arid desert. Again, a classification scheme would help place such results in context.

2.3 Assessment

So have we made progress in spatial scaling of catchment hydrology? Although the hydrological community has not yet agreed on a set of characteristic spatial scales for catchments, the recent review by Blöschl and Sivapalan [1995] concisely summarises space and time scales associated with numerous hydrological processes. Their summary is a useful step in developing a common terminology for hydrology. It seems that hydrologists have also successfully defined terms such as 'local', 'hillslope', and 'catchment' [Blöschl and Sivapalan, 1995]. Several hydrologists working independently in the same landscape could be expected to agree on how to identify characteristic length scales for these three terms. However, it is not clear how useful this classification is; hydrologists do not have widely accepted techniques for each separate scale, and may choose scales differently depending on the science question being asked – whether it relates to floods, water balance, erosion, etc.

Table 1 gives a very simplified summary of some of this scaling research, classifying it according to whether hydrological causes or effects are considered, and whether the scaling is temporal or spatial. It can be useful to separate hydrological causes (e.g. climate, soil, vegetation, topography) and effects (soil moisture, streamflow, evaporation), even if that separation is context-dependent. (For example, at large scales soil moisture can influence climate, and climate can influence the development of soil and vegetation)

Table 1. Some scaling approaches for catchment hydrology - entries in italics are still developing, or not widely used.

	Hydrology causes	Hydrology effects	Linking cause and effect
Time	Storm occurrence and storm temporal structure	'Classical' flood frequency	Derived flood frequency
Space	River network structure	Representative Elementary Area	Geomorphic unit hydrograph
Space-Time	Space-time cascade models of rainfall	Regional flood frequency?	?

The entries in the table are examples of each category that are relevant to flood hydrology, and are not a comprehensive overview of hydrology. However, similar tables could be drawn up using examples from water balance, soil erosion, etc. In any case, the most challenging problems are those requiring considerations of both space and time scales, and linking causes to effects. These diverse and complex problems will almost inevitably be solved by breaking them into sub-problems. A coherent structure is needed so that the pieces of the problem can be re-assembled, and so that progress in one sub-problem is useful to others.

3. COMPLEXITY

Terms such as complexity and organisation imply a deep and rich set of connections among the parts of a system. These terms are suggestive of underlying, perhaps universal, regularity in the structure of a catchment. The possibility of generic knowledge provides a powerful motivation in the search for this structure. Given the diversity of catchments, it is important to recognise that any such connections in hydrology might well be generic within some class, rather than generic to every catchment for every hydrological response.

An example of this regularity is the GIUH (geomorphic instantaneous unit hydrograph) concept [Rodriguez-Iturbe and Valdes, 1979]. They postulate a direct link between river network structure and the response of a river basin to rainfall. In the GIUH, statistics of river networks are used to parameterise the variety of path lengths that drops of water can follow in a river basin. With a suitable runoff generation model to estimate how much of the rainfall contributes to storm runoff, the GIUH provides a concise summary of storm response. It uses information about the *essence* of catchment structure to infer response, an approach intermediate between assuming a single 'time of concentration', and the explicit modelling of river links.

The question of spatial organisation in runoff generation has proved more elusive. The TOPMODEL concept [Beven and Kirkby, 1979] has proved a rich source for hypothetical studies, again because it summarises apparently complex topographic variability into mathematical forms which can be more easily combined with other assumptions. It has been suggested that TOPMODEL works equally well whether or not it uses local topographic data (given that some of the model parameters require calibration) [Franchini et al., 1996]. Other studies suggest that the relevant topographic probability distributions have a universal form [Willgoose and Perera, 2001], independent of spatial scale above a minimum scale. Hydrology is more complex than this. Even if topographic index distributions are universal and relevant, they are not sufficient to describe spatial variability of runoff generation. Other spatial variables besides topography are needed in runoff generation theory. If topographic theory is to be useful, it needs to be treated in the context of classes of climate, soil type and land cover.

4. VARIABILITY

The great challenge in catchment hydrology seems to be the diversity between catchments – classification is a technique for managing diversity. A detailed catchment investigation may yield well-defined relationships among rainfall, temperature, soil water, groundwater and streamflow. Yet there is no widely accepted technique for transferring these relationships to other catchments. Viewed in this way, spatial scale then becomes just one more potential source of variability between catchments. The difficulties in transferring results between catchments are ascribed to numerous causes including inadequate spatial data (particularly for soils, rainfall and evaporation), inadequate models (particularly for evaporation, storm runoff generation and subsurface discharge to streams), and inadequate modelling practices (model structure, calibration, and validation). Here we consider aspects associated with spatial variability.

Numerous investigations of spatial variability have been reported in the last 30 years, looking at the roles of spatial variability of climate, vegetation, soils and topography in determining spatial patterns of hydrologic response. All the data-driven studies of spatial variability share the limitation that other unmeasured sources of spatial variability are also present, making it difficult to identify clear cause-and-effect relationships. Perhaps the most progress has been made in paired catchment studies of the effect of land use on water balance. It has proved more difficult to examine the roles of varying precipitation, soils or topography in spatial catchment hydrology, because no methods are available to control the variability over large spatial scales. Those questions have instead been examined by simulation modelling, using sensitivity studies to determine the impact of spatial variability. As with the studies of spatial scaling, the results of these studies are limited by the validity of the assumptions. The advantage of using simulation modelling is that all the known quantified sources of variability can in principle be included.

Most studies of scale effects tend to concentrate on the effects of a scale change in the context of a single, stochastic source of variability, without including the possibility that new sources of variability arise at larger scales. Similarly, most studies of variability effects tend to consider that variability at a single spatial scale within the study area. The paper by Seyfried and Wilcox [1995] marks an important advance in this area, by describing how the nature of spatial variability may change with spatial scale and location. Seyfried and Wilcox [1995] argue for a deterministic description of spatial variability over a particular range of scales, denoted the 'deterministic length scale'. They gave a specific example in southwest Idaho, suggesting length scales ranging from a metre for the effects of individual shrubs to more than 10 km for frozen soil and snow distribution. The relative importance of these sources of variability changed with location, with some processes becoming more important at low elevations with more vegetation.

In a recent summary of six case studies on spatial patterns in hydrology, a Dominant Processes Concept has been proposed along similar lines [Grayson and Blöschl, 2000]. This is consistent with previous suggestions that runoff generation mechanisms (infiltration excess, saturation excess, subsurface runoff) are associated with certain combinations of climate, vegetation, topography and soils [Dunne, 1983].

5. CLASSIFICATION

Classification is the systematic arrangement of similar entities. Although it is often seen as simply an arbitrary grouping, it is the underpinning basis for many scientific fields. Its scientific value is clear when the classes correspond to a deep understanding of scientific structure. For example, in chemistry, the periodic table organises the elements to show that properties of the elements recur as atomic number increases. The same elements are also classified in other ways (e.g., conducting, non-conducting). At larger chemical scales, chemical compounds have their own classifications. These classifications are widely accepted by chemists. Catchments are more diverse than elements, but perhaps not much more diverse than compounds. How can the hydrological community develop useful, accepted classifications?

The Dominant Processes Concept [Grayson and Blöschl, 2000] seems useful at relatively small scales, where one can use unambiguous descriptions of environmental conditions (rainfall, vegetation etc). The prospect of being able to determine dominant processes *a priori* is appealing, although the research tasks are challenging. The concept would be more powerful if it also included a component of spatial scale, along the lines of Seyfried and Wilcox [1995]. That is, in a given environment, one might predict at several scales the dominant source of spatial variability and the associated dominant processes.

Using this approach, one might find in an arid alpine environment that vegetation is dominant at the one metre scale, other variables at intervening scales, and snow distribution at 10 km [Seyfried and Wilcox, 1995]. However, the dominant factors in a more temperate environment might be very different: perhaps soil hydraulic properties dominate at one metre, topography at 10 metres, and rainfall at 10 km. Of course, one can immediately imagine many different spatial hierarchies, each specific to a particular physical setting. Unless the physical settings are classified into well-defined and widely agreed categories, and the hydrological question of interest is made explicit, we are really no better off.

Classification systems already exist for some elements of catchment hydrology, such as climate, weather systems, soils, plants, and fluvial geomorphology. A variety of local hydrological classifications also exist, but are not complete or consistent enough to unify hydrology science.

Here I suggest two environmental descriptors that together cover a useful range of hydrological environments. One descriptor addresses the relative availability of water and energy. Spatial patterns in water-short places will be controlled by quite different processes to those in water-rich locations. One might classify catchments according to whether the average annual climate is Dry, Balanced (average precipitation similar to potential evaporation), or Wet. A second independent descriptor should address the dominant state of stored water in the catchment. Water held as snow or ice responds to a different set of environmental factors than water held below the ground surface, which is again quite distinct from open water bodies (e.g. lakes, wetlands).

Within each combination of the categories of climate and water state, a particular hierarchy of dominant processes can be envisaged, such as that proposed by Seyfried and Wilcox [1995]. They identify dominant length scales from field data in a climate which is dry, and where water is stored as both snow and subsurface water. In contrast, Dunne's [1983] diagram showing dominant storm runoff processes appears relevant to a wide range of climates, provided that neither snow/ice nor open water dominate the hydrology. A hierarchy of processes might include features controlled by factors such as climate (e.g., seasonality), geology, vegetation, soil and topography.

A classification like that suggested above needs widely agreed, easy to use definitions of Dry, Wet etc to classify particular catchments. As an example, using as a climate dryness index Ep/P, the ratio of average annual potential evaporation to average annual rainfall, the values of that index can define Dry as regions with Ep/P>1.5, balanced as 0.75<Ep/P<1.5 and humid as Ep/P<.75. Similarly one might define (i) a snow/ice class on the basis of the whether the daily mean air temperature is below zero degrees for more than half the year; (ii) an open water class defined if the fraction of the region covered by lakes and wetlands exceeds a threshold such as 20% (a task well suited to existing remote sensing capabilities), and, failing any better approach, (iii) subsurface water storage as the remaining unclassified area.

6. CONCLUSIONS

A system as complex and varied as the natural catchments of the globe requires a classification scheme to place our knowledge in context. Hydrological knowledge gained in one environment may be applicable to some other locations, but this knowledge cannot be applied indiscriminately. Studies of scale and variability have begun to identify patterns in hydrologic response, but knowledge transfer is hampered by the lack of a widely agreed, soundly based classification of hydrological systems, designed for the purpose. The suggested classification on the basis of climate dryness and type of catchment water storage (snow/ice, subsurface, open water) is not intended as a final statement on this classification. Instead it may be a stimulus for further thought on how hydrology might organise itself to cope with the extraordinary richness and complexity of global hydrology.

7. ACKNOWLEDGMENTS

This work was funded from New Zealand's Public Good Science Fund (contract C01X0010). My thanks to Richard Ibbitt, Rodger Grayson and Siva Sivapalan for commenting on a draft manuscript.

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