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From Engineering Hydrology to Earth System Science: Milestones in the Transformation of Hydrologic Science

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Abstract: Hydrology has undergone almost transformative changes over the past 50 years. Huge strides have been made in the transition from early empirical approaches to rigorous approaches based on the fluid mechanics of water movement on and below the land surface. However, progress has been hampered by problems posed by the presence of heterogeneity, including subsurface heterogeneity, at all scales. The inability to measure or map the heterogeneity everywhere prevented the development of balance equations and associated closure relations at the scales of interest, and has led to the virtual impasse we are presently in, in terms of development of physically based models needed for hydrologic predictions. An alternative to the mapping of heterogeneity everywhere is a new Earth System Science view, which sees the heterogeneity as the end result of co-evolutionary hydrological, geomorphological, ecological and pedological processes, each operating at a different rate, which help to shape the landscapes that we see in nature, including the heterogeneity that we do not readily see. The expectation is that instead of specifying exact details of the heterogeneity in our models, we can replace it (without loss of information) with the ecosystem function that they perform. Guided by this new Earth System Science perspective, development of hydrologic science is now addressing new questions using novel holistic co-evolutionary approaches as opposed to the physical, fluid mechanics based reductionist approaches that we inherited from the recent past. In the emergent Anthropocene, the co-evolutionary view has expanded further to involve interactions and feedbacks with human-social processes as well. In this paper, I present my perspective of key milestones in the transformation of hydrologic science from Engineering Hydrology to Earth System Science, drawn from the work of several students and colleagues of mine, and discuss their implication for hydrologic observations, theory development and predictions.

Key words: *Hydrologic Science, Scale, Heterogeneity, Variability, Earth System Science, Catchments, Co-evolution.*

எப்பொருள் யார்யார்வாய்க் கேட்பினும்
அப்பொருள் மெய்ப்பொருள் காண்ப தறிவு

In whatever matter and from whomever heard,
Wisdom will witness its true meaning.
Thirukkural, Verse 423 (Thiruvalluvar, c. 132 BC)
Translated by GU Pope, 1886

1. Introduction

Hydrology has undergone an almost complete transformation over the past century, from its empirical origins in the early 20th century to become a fully-fledged and key component of Earth System Science by early 21st century (Chow, 1964; Sivapalan and Blöschl, 2017). In this paper, I use the precious opportunity given to me by the European Geosciences Union, as part of my 2017 Alfred Wegener Lecture, to reflect on the evolution of the field, both as interested observer as well as a participant and a student of hydrology for the past 50 years.

I hope that the issues I raise, and the trends and milestones I recognize in the evolution of the science that I recount here, resonate with the experiences of many readers, even if they might not fully agree with my interpretations of the events and/or their antecedents. This is one person's view of the vast landscape that hydrologists have collectively traversed, so perspectives abound. This is also not the first commentary of its kind: indeed, my thinking during my formative years has been guided by the writings of Vit Klemeš and James Dooge, including their classic papers (Klemeš, 1983, 1986; Dooge, 1986). Their writings have provided unique perspectives on the field of hydrological science and its evolution over the past several decades. I hope that by re-telling this story through the prism of my own observations and experience I might be able to provide fresh impetus to early career hydrologists and new entrants to the field, and encourage them to reflect on and chart the course of their own future education and research.

2. Engineering Hydrology: Legacies of the past to new beginnings

My earliest introduction to hydrology and later work experience is probably similar to those of many hydrologists of my generation, i.e., 1970s vintage, especially those coming out of engineering schools. Going back in time, fifty years ago hydrology was mostly non-existent as a subject of study in many engineering schools (certainly not in Sri Lanka where I grew up). Most water-related education was then centered on fluid mechanics, e.g., open channel or river hydraulics, with a strong focus on applications to irrigation or hydraulic engineering. In 1972 when I walked into a hydrology class at the then University of Ceylon (later Sri Lanka), it was taught by a recent convert from fluid mechanics, who had received specialist training in hydrology.

Hydrology education in those days covered three key topics: infiltration and runoff generation (e.g., SCS curve number method), the unit hydrograph method to runoff routing, and the flood

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frequency curve approach to flood estimation (Linsley et al., 1958). The focus of the training was on estimation, especially flood estimation (event scale, recipe style) and the approach was lumped and empirical. Compared to now, these were relatively much simpler problems, framed directly at the catchment scale, and formed the *bread and butter* of engineering hydrology, not just in Sri Lanka, but all over the world. The three building blocks of engineering hydrology were indeed legacies of three different previous eras in the growth of the field up until the 1970s (Sivapalan and Blöschl, 2017): empirical era (flood frequency analysis), rationalization era (SCS curve number method) and systems era (unit hydrograph method). These methods remain relevant to this day, very much the core of engineering hydrology, judging by the popularity of advanced textbooks such as Chow et al. (1988), which is still widely used for the training of hydrologists in engineering schools.

For some of us who have received training in mechanics – solid mechanics, fluid mechanics, soil mechanics etc. – the hydrology being taught and practiced using the traditional estimation methods might have appeared strange and even mysterious. In the early days, I remember being frustrated that I could not make much physical sense of the cookbook treatment of the hydrologic estimation process, unable to connect it to fundamental fluid mechanics principles. Yet, there was also wide appreciation for these otherwise simpler methods that efficiently solved practical problems of that day and age. In fact, even today's standard engineering practice would still be impossible without these simpler approaches.

There was also a profound fascination. How is it possible that something so inherently complex, as hydrology is, still comes out as so simple (apparently) in practice? Over the years, there was a grudging realization that perhaps hydrology is more than about fluid mechanics (Yevjevich, 1968). Indeed, the search for simplicity in amongst the enormous mechanistic complexity has been a constant theme in hydrologic research over the last 50 years (Rodriguez-Iturbe and Valdes, 1979; Sivapalan, 2003; Savenije, 2017). The answer to this question, we now know in hindsight, is tied up with the issue of scale (both space and time) and the objects of our study, catchments, being not simple physical (or mechanical) objects but complex ecosystems (Gaál et al., 2012), consisting of component parts that have co-evolved together over time, and are thus co-dependent (Dooge, 1986; Davies, 1992). I return to this theme throughout this paper.

3. Spatial heterogeneity and scale: promise of Newtonian mechanics

While the simple black box methods of engineering hydrology did solve practical problems efficiently, they had limitations when extrapolating to circumstances beyond those from which they were developed. For example, what is the effect of antecedent wetness on runoff generation (Mein and Larson, 1973)? How does one account for the nonlinearity of catchment response to the size of rainfall events (Minshall, 1960)? How does one deal with the climatic and geologic controls when extrapolating flood frequencies to ungauged catchments (IACWD, 1982)? Also, new and more complex problems were emerging, such as the effects of land use changes on streamflows and flooding, and increased concerns about river water quality, which demanded application of more process physics (Woolhiser, 1973). There was increasing realization that only a recourse to fluid mechanics and process physics will help address such questions, bring about needed improvements to the methods and make them applicable more generally.

Hydrologists thus began to open up the black-box to explicitly capture space, and to characterize water movement in catchments through application of physical (fluid mechanics) principles. The physically based models that were starting to be developed at the time were based on Newtonian mechanics valid at the laboratory or hydrodynamic scale (e.g., Richards equation, St. Venant equations; Chow et al., 1988), and not at the scale of a catchment. For example, Darcy's law embedded in the Richards equation is based on a local equilibrium assumption to warrant a well-defined potential, implying that internal mixing in the pore spaces is faster than external disturbance; but this is only possible at small scales (Or et al., 2015). This also brought with it the enormous challenge of specifying the (highly heterogeneous) parameter values to go with the equations to represent the landscape heterogeneity, (e.g., subsurface soils, surface features such as micro-topography, macropores, rills and the stream channel network, and vegetation cover), and the complexity of the resulting flow processes (Freeze, 1974). These problems are at the heart of the scale issue, which remains a major challenge in hydrology in spite of considerable progress made to date, of which I will discuss more later.

A key development in this line of reasoning was Peter Eagleson's 1970 book titled Dynamic Hydrology (Eagleson, 1970), which provided a bold theoretical framework for a new hydrology based on the consistent and rigorous application of fluid mechanics principles, i.e., Newtonian mechanics, along with an appreciation of an organized structure behind soil, land surface and vegetation heterogeneity. Eagleson's treatment of hydrology was a major departure, a paradigm shift, away from the lumped, black-box treatment practiced until then.

Another major milestone was the computer implementation of the *coupled* governing equations by Allan Freeze (Freeze and Harlan, 1969) that framed the catchment hydrologic modeling problem as a boundary value problem. Progress in this area was advanced by the increasing availability of digital terrain information on topography, soils, vegetation etc. and computational tools that allowed them to be processed and visualized (Band and Wood, 1988). These data allowed the natural heterogeneity of landscapes to be captured in a more realistic way. Also, it was exciting that new runoff generation mechanisms such as saturation excess overland flow and shallow subsurface stormflow were being discovered in the field (Hewlett and Hibbert, 1967; Dunne and Black, 1970; Beven, 1981) and could now be faithfully replicated in models using the newly available spatial information, e.g., digital elevation models (DEMs) (Beven and Kirkby, 1979; Freeze, 1980; Band and Wood, 1988).

Heterogeneity: To resolve or to parameterize?

The Freeze and Harlan modeling paradigm has remained in force to this day, and several formal models have been developed based on the paradigm, such as the SHE model and variants of the same (Abbott et al., 1986). Due to data limitations and limits on computing power, early modeling efforts were restricted to small catchments, and their goal was limited to generating process understanding, and not so much to make predictions in real catchments (Stephenson and Freeze, 1974; Freeze, 1974). Their adoption and use in real world applications did not take off for a long time because of their enormous data needs and insufficient computing power and also concerns about the appropriateness of the process physics that could be included in the models at the model element scale (Beven and Binley, 1992; Grayson et al., 1992).

As computing power increased many-fold and the landscapes began to be mapped at increased resolution for soil, vegetation and topographic characteristics in many parts of the world, there has been a revival of sorts in recent times, with several models being developed and beginning to be applied to *larger* (e.g., meso-scale) catchments using more realistic data. Two (of the many) examples include the FIHM model developed at Penn State University (Kumar et al., 2009), and the PAWS model developed at Michigan State University (Shen and Phanikumar, 2010). These modeling efforts are expanding and I will not be surprised if, before long, such models are used not just to reproduce field observations but also, as in the case of Freeze (1980), to discover and explain previously unobserved phenomena.

In recent times, as part of climate change studies, modeling has been extended to continental and global scales to serve as the land-surface hydrology components of regional or global climate models. Because of the large scales, spatial resolution of these models in the past tended to be very coarse, of the order of hundreds of kilometers (e.g., bucket model, Manabe, 1969). However, progress is continually being made to improve the resolution from hundreds of kilometers to hundreds of meters, helped along by increased computational power and availability of terrain information at finer resolutions (e.g., Community Land Model, Oleson et al., 2013). There is now a new thrust to improve the resolution of these models to 30 m for the whole globe (note: 30 m is the resolution of terrain information globally available), under the theme of "hyper-resolution modeling" (Wood et al., 2011; Bierkens, 2015; Wing et al., 2017). Concerns and debates about the appropriateness of the physics used in these models, including the appropriateness of constitutive relations being used (Loritz et al., 2017), and the resulting uncertainty in predictions, have not gone away, however (Beven and Cloke, 2011; Wood et al., 2011; Clement, 2011).

An ostensible reason for going for finer resolution, is of course, since now we can do it, i.e., with data availability and computing power, why not, and also since the benefits of hyper-resolution modeling for both science and practice are increasingly becoming evident. For example, hyper-resolution models over regional or continental scale domains can track large-scale storm movements and the resulting impacts at scales relevant to human wellbeing, as well as generate insights about the large-scale teleconnections between or within regions (Fang and Shen, 2017). A more immediate reason, however, is that as one improves the resolution, the (fervent) hope is that all heterogeneity will disappear and the governing equations used will match the spatial scales of the processes one is trying to model (e.g., Clark et al., 2015, 2017; Peters-Lidard et al., 2017). In reality, of course, field evidence has strongly indicated that the heterogeneity does not disappear even if one goes to finer scales, and there is a limit to how far we can split the landscape to achieve any desired level of homogeneity and still maintain a continuum (Beven, 1989; Blöschl and Sivapalan, 1995). Besides, the presence of macro-pores and other preferred pathways (Beven and Germann, 1982), and explicit treatment of runoff phenomena involving concepts such as the "old water, new water" concept (McDonnell, 1990), present major challenges to traditional continuum representations of water movement on and particularly below the land surface based on Newtonian mechanics alone (Beven, 2006). One therefore reaches the alternative conclusion that, whatever grid scale one chooses, there is no alternative but to parameterize the effects of any remaining heterogeneity at the sub-grid scale.

The end result for spatially-distributed, physically-based models of catchment hydrology is that model development has been caught between two temptations (Hrachowitz and Clark, 2017): 1. split the landscape more and more down to the continuum (hydrodynamic) scale so that heterogeneity disappears as an issue (i.e., heterogeneity is completely resolved); 2. aggregate to some scale at which the effects of heterogeneity are taken care of through simplified treatments with process parameterizations that can account for the effects of all sub-grid heterogeneity. Advancing technological capability and increased process knowledge at small scales are the drivers towards the former option (Wood et al., 2011). Appreciation of scale effects, including expectation of simplicity through averaging (Sivapalan, 2003), concerns about predictive uncertainty (Beven and Cloke, 2011), and about the domination of techniques and other quick fixes (e.g., model-data assimilation) over the important search for hydrological understanding (Klemeš, 1986), are the key drivers towards the latter option. The issue of heterogeneity is not unique to hydrology, and applies to all environmental sciences, and approaches to mediate these alternative perspectives may draw inspiration from a quote from ecologist Simon Levin (1992):

> *"To scale from the leaf to the ecosystem to the landscape and beyond . . . we must understand how information is transferred from fine scales, and vice versa. We must learn how to aggregate and simplify, retaining essential information without getting bogged down in unnecessary detail. The essence of modeling is, in fact, to facilitate the acquisition of this understanding, by abstracting and incorporating just enough detail to produce observed patterns. . . the objective of a model should be to ask how much detail can be ignored without producing results that contradict specific sets of observations, on particular scales of interest".* ….. Levin (1992).

Levin's (1992) is an argument for "coarse graining", i.e., to formulate models with only the necessary degree of complexity, and an argument against attempting to resolve the enormous heterogeneity and complexity of hydrologic processes at progressively smaller time and space scales, which is echoed by hydrologist Thomas Dunne as well (Dunne, 1998).

Organized heterogeneity and preferred space scales: REA

Inspired by the organization that nature exhibits around a hierarchy of spatial scales, i.e., hillslope, catchment, region etc. (Blöschl and Sivapalan, 1995), there have been concerted efforts to identify whether a characteristic space scale, which reflects the spatial organization and can thus serve as the building block of distributed models, exists in catchment hydrology. This idea is similar to the continuum or REV concept used in groundwater hydrology with some degree of success (Bear, 1972; Hassanizadeh and Gray, 1979). The argument has been that aggregating the governing equations or process descriptions to this building block scale might lead to simplified (effective) lumped or continuum treatments, thus avoiding the need to split the catchment into smaller elements to capture the effects of heterogeneity. This way of thinking reflects the long-standing conviction, supported by observations, that in spite of the enormous complexity of hydrologic processes in landscapes, catchment scale hydrologic responses can often be described by simpler models with only a few parameters (Jakeman and Hornberger, 1993; Sivapalan, 2003). Dooge (1986) has argued that catchments are complex systems with some level of organization, and “simplicity out of complexity” is a useful property of such complex systems (Davies, 1992). When one opts for the parameterization approach inspired by this reasoning, one still needs to know the key features of the underlying heterogeneity, e.g., their statistical distributions or organizational structure (not necessarily the actual observed patterns). Furthermore, we also need to have information about cross-scale process interactions that might lead to the simplicity we desire (Hassanizadeh and Gray, 1979), and utilize efficient approaches them in models through appropriate model structures and parameterizations (Zehe et al., 2014).

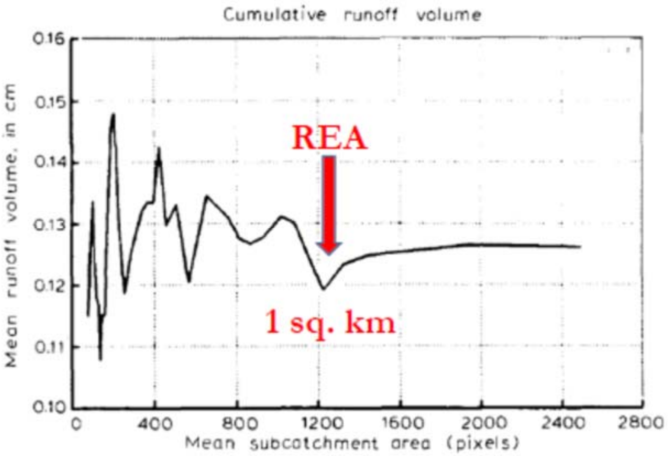

Figure 1. Mean event runoff volume as a function of mean subcatchment area (for the case of variable topography but uniform soils and precipitation). Taken from Wood et al. (1988).

Motivated by this reasoning, Wood et al. (1988) pursued this question in the context of runoff generation responses at the catchment scale. On the basis of spatial averaging of numerical simulation outcomes from a distributed rainfall-runoff model of hypothetical catchments, Wood et al. (1988) postulated that such a spatial scale could exist, which they called the representative elementary area (REA), and estimated its size to be about 1 km^2 (Figure 1). Subsequent field observations and simulations in New Zealand and Germany supported the idea with some reservations and further refinements (Woods et al., 1995; Didszun and Uhlenbrook, 2008). The claims about both the existence and size of the REA have been questioned by others, based on perceived limitations of the averaging approach used to resolve these questions (Fan and Bras, 1995; Blöschl et al., 1995). A further limitation of the REA of Wood et al. (1988) is that it focused on surface runoff volume, and not its timing. Robinson et al. (1995) explored the change of dominant controls on runoff timing (e.g., hydrograph dispersion) with increased catchment area, and showed that the scale at which the dispersion is maximally reproduced can be affected by whether (fast) surface or (slower) subsurface runoff pathways dominate. The significance of the existence of the REA, whatever its size, is that it is small enough to still account for relevant spatial hydrological variations, and yet large enough to avoid the overwhelming data and parameter needs of small scale (distributed) models. As a result, despite the reservations, the notion of using a representative watershed scale as the building block towards the development of distributed models (now at a sub-catchment scale) has remained as a working hypothesis for organizing our thought processes in respect of modeling.

Inspired by the possibility that adoption of such a representative scale might lead to simplified yet physically based hydrologic prediction models, Reggiani (1999) developed a new theory of hydrology around this building block, now named the representative elementary watershed or REW, which accounts for some of the limitations of the earlier REA concept. Reggiani's theory was expressed in the form of balance equations for mass, momentum, energy and entropy written down directly at the scale of the REW (Reggiani et al., 1998), and an accompanying constitutive theory (Reggiani et al., 1999) to ensure the theory gives rise to a determinate set of governing equations. Subsequently, Zehe et al. (2006) derived soil moisture characteristic (i.e., constitutive) relationships at the REW scale through the upscaling of corresponding point scale observations. Likewise, Lee et al. (2007) developed a set of closure relations for the many boundary fluxes for the catchment system – between different REWs and between different sub-regions within each REW – again, to account for the effects of sub-grid heterogeneity and process complexity, thus helping to complete the specification of the governing equations representing the catchment response.

The net advantage of the REW approach is that it ends up with the solution of a system of coupled ordinary differential equations (as opposed to a system of partial differential equations, which one obtains if they were to split a catchment into rectangular or triangular elements). Both Tian et al. (2006) and Lee et al. (2007) developed numerical schemes to solve these governing equations, thus forming a new generation of models based on the REW approach that parallel distributed models based on rectangular or triangular finite elements following the Freeze and Harlan paradigm. In this way Tian et al. (2006) and Lee et al. (2007) have contributed to a new class of models of intermediate complexity, resolving processes occurring at scales larger than the REW scale, and parameterizing those happening at smaller scales (Beven, 2012). Their potential as a new modeling framework has also been highlighted through several applications. For example, models based on the REW approach have been applied to real catchments, generating space-time predictions of the rainfall-runoff response for catchments in Australia (near Darwin, Lee et al., 2007) and in Oklahoma in the United States (Li et al., 2012; Tian et al., 2012). In recent years, these models have been extended to make distributed predictions of sediment and nutrient transport and export at the catchment scale and across the corresponding stream networks (Patil et al., 2013; Ye et al., 2012).

4. Catchments as ecosystems: Limits of Newtonian mechanics

In spite of this progress, the REW approach shares the as yet unsolved problem confronted by all other distributed models, which is how to derive or estimate parameters *a priori* at the scale of the chosen grid (in this case, the REW) without fully resolving sub-grid heterogeneity and process *complexity*, which was the problem in the first place. The spatial heterogeneity and the resulting cross-scale process interactions can introduce enormous complexity and richness to catchment hydrological responses. Processes can become even more complex when we extend the analysis to include multiple time scales. When we attempt to make predictions over longer time scales, i.e., longer than events (e.g., months or years), the media through which hydrologic processes operate (i.e., soils, topography, vegetation) may themselves change dynamically or transform permanently (e.g., time variant macroporosity due to life cycle of earthworms, Zehe and Sivapalan, 2009; soil swelling and cracking, Savenije and Hrachowitz, 2017). In other words they are not inert objects fixed for all time as is commonly assumed in deterministic models. Furthermore, if the hydrologic prediction problem is deemed a boundary value problem, as it often is, the location of the boundary and its condition itself are not fixed, but evolve dynamically as part of the water dynamics, the very dynamics we are trying to predict (see Figure 2). The end result is that the hydrologic response can no longer be described by Newtonian mechanics alone, and is now the emergent outcome of two dynamic, coupled processes: water flow itself and the changes to the media, both occurring over multiple time scales (Gaál et al., 2012). All of the complex spatial processes operate in the time domain as well.

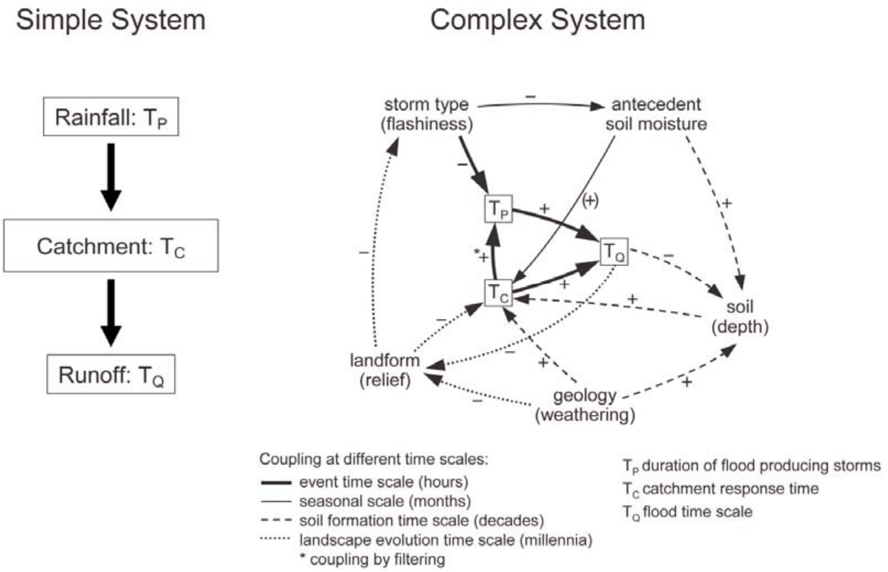

Figure 2. Simple and complex system representations of time scales contributing to floods. Interactions of multiple time scales makes the response an emergent outcome of a complex system. Taken from Gaál et al. (2012).

The most obvious example of a catchment subsystem that evolves dynamically is vegetation, which is directly involved in the crucial process of evapotranspiration. Vegetation adapts itself dynamically over multiple time scales in response to changing climate and hydrology, even as it has an impact on the hydrology. Also, over much longer time scales it can modify the environment around it (e.g., soil structure, macro-pores and topography, to name a few). In this way the temporal dynamics of vegetation can also indirectly impact runoff generation processes. As well as evolving with the dynamic hydrology, such biologic activity renders the system even more internally dynamic. The adaptations of vegetation and their modifications of landscapes may be governed by biological or ecological processes, and cannot be captured by universal descriptions based on Newtonian mechanics that focus on flow processes alone; presently their effects on flow can only be described by empirical, place-based relationships. As in the case of spatial upscaling problems discussed before, it is always tempting to ask the question whether the *temporal* organization of a catchment's hydrologic response, arising from vegetation adaptations to the multi-scale temporal variability of climate and hydrology, and the resulting landscape modifications, could also be averaged to produce a simplified description of catchment response. This question is explored next by highlighting different examples of vegetation (and even landscape) adaptations to natural climate variability and hydrology.

Adaptation Strategies by Vegetation

Understanding vegetation adaptation processes is a rich and multifaceted problem, but here I will use examples from my own modeling experience to illustrate the point about simplicity in spite of complexity, and how this might arise as a result of vegetation adaptations. Many existing catchment models, including the ones mentioned before, approximate evapotranspiration rates by vegetation (e.g., forests, grasses etc.) as if they function like agricultural crops, i.e., they transpire at a potential rate (e.g. potential evaporation) when the soil is wet, and reduce their evapotranspiration rate when soil moisture falls below the saturation value. In reality, this is not normally the case under native vegetation, and such approximations can lead to serious discrepancies since evapotranspiration is a large fraction of annual water balance in most places around the world (Sivapalan et al., 1996; Thompson et al., 2011a). This was highlighted in the Darling Range region of south-west Western Australia during field experiments carried out by Silberstein et al. (2001).

South-west Western Australia experiences a strong Mediterranean climate, with warm dry summers and cold wet winters. Field measurements made by Silberstein et al. (2001) in a forested catchment in this region showed that daily evapotranspiration rate (bare soil evaporation plus transpiration) was roughly 2.5 mm per day during a 2-week period in the wet winter part of the experiment. Remarkably, when the experiment was repeated 6 months later during a 2-week period following a very dry summer, the evapotranspiration rate turned out to be very much the same, about 2.5 mm/day every day. The assumption that trees, like agricultural crops, might reduce their transpiration rates during dry periods (due to their experiencing water stress) was found not to be the case. It turned out that native Eucalyptus trees in this part of Western Australia have adapted to the strong seasonality effects (hot dry summers and cold wet winters) by growing dynamic deep roots that tap into a groundwater aquifer that is over 30 m deep. Indeed, it was found that tree roots remained always in contact with the deep water table even when the latter fluctuated between summer and winter and between years. The net result is an apparently constant transpiration response by the vegetation, i.e., 2.5 mm per day every day!

In a subsequent study at a site near Darwin, in Northern Territory, Australia, Schymanski (2007) reported an altogether different response by native vegetation. This area experiences a monsoon climate, with a wet four-month period of heavy monsoon rains, followed by 8 months of dry (non-rainy) conditions. Being tropical, potential evaporation is uniformly high during both periods. Water table is present at a depth of about 10 m all year. Schymanski reported that measured total evapotranspiration rate followed the variation of soil wetness, regardless of the energy available, i.e., potential evaporation (Schymanski, 2007). However, the adaptation strategy by the prevailing vegetation was different. In Darwin, the more permanent, deep-rooted trees tap into the groundwater table, just as in Western Australia, and were found to transpire at a rate of 1 mm/day all year, regardless of surface soil moisture. However, in addition, during the wet season, a dense under-story of grasses developed which, like crops, transpire at rates proportional to the surface soil moisture: a peak of 2.5-3.0 mm/day during the wet season, decreasing as the soil dries during the subsequent dry season, and dropping to negligible values as the grasses completely senesce and dry out. Once again, a slightly more complex, yet almost predictable transpiration pattern that arises via complex adaptation strategies adopted by the vegetation to the climate and hydrology.

Two different places, two different adaptation strategies by vegetation that developed in each setting, permitting a simplified transpiration pattern. In both cases, the strategies used by the vegetation are different from what is normally assumed for agricultural crops. This raises two issues: if one wants to develop a predictive model of evapotranspiration for a specific place, then the adaptation strategy adopted by vegetation locally must be known *a priori*. Newtonian theory by itself cannot predict the adaptation strategy one is likely to encounter in a given place, which may be governed by (as yet unknown) biological/ecological laws. The adaptation strategy adopted by vegetation would be relatively easy to determine, given the kind of observational evidence used by Silberstein et al. (2001) or Schymanski (2007). Few places would have that kind of field evidence, however. In a catchment context, many more places will have rainfall-runoff data only, from which the adaptation strategy adopted by vegetation may have to be inferred (with a lot more ambiguity, given the kind of data, especially the absence of evapotranspiration data). The fact that prevailing vegetation in different places may use different adaptation strategies also opens the way for much freedom or pluralism in the development of predictive models, as opposed to a universal model that would be expected out of Newtonian mechanics.

Ecosystem function and data based inference

A key observation from the last section is that the dynamics of evapotranspiration is intimately connected to that of vegetation adaptation. We can broaden this argument to include other catchment responses as well, such as runoff. We are used to treating runoff generation as a physical process, governed by Newtonian mechanics (Larsen et al., 1994). This presumes that we know *a priori* what mechanism of runoff generation dominates in a given place. However, Newtonian mechanics alone may not be able to determine the dominant runoff generation mechanism in any given place. Based on field evidence Dunne (1978) provided a perspective on climate, soil, topography and vegetation controls on the dominant runoff generation mechanism, popularly known as the Dunne diagram. To this day, the Dunne diagram has continued to defy explanations based on Newtonian mechanics (Larsen et al., 1994; Li et al., 2014). Vegetation adaptation may again be the underlying cause of this phenomenon, e.g., vegetation perhaps adapting itself and adapting the environment around it (i.e., soils, topography) in such a way that it can retain soil moisture longer in arid environments and drain water sooner in wet environments. Also, forest soils are known to have higher surface infiltration capacities, which impact the stormflow response. Thus, "forest" vegetation type becomes a parameter linked to infiltration and runoff generation, as well as to evapotranspiration.

Given this field evidence on evapotranspiration and runoff generation, and given the limitations of the more reductionist approach based on Newtonian mechanics, one is tempted to look for a complementary but holistic approach that can accommodate the adaptation of catchment properties (i.e., vegetation, soils etc.) to environmental conditions. What if, instead of treating catchments as physical or mechanical systems, we consider them more broadly as ecosystems. Then the same processes, i.e., evapotranspiration and runoff generation, could be deemed a catchment's ecological responses, as part of its overall ecosystem "function". This was the wisdom behind the "functional" approach proposed by Black (1997), who framed a catchment's hydrological responses to precipitation more broadly as partition, storage, transmission and release (see also Wagener et al., 2007), as opposed to point-scale processes (e.g., infiltration), and aligning them to the catchment's ecosystem function.

Another observation from the last section is that in spite of the known complexity of hydrologic processes at small time and space scales, which Newtonian mechanics may well be able to capture under some circumstances, catchment organization and ecosystem adaptation impart a level of simplification to hydrological responses at the catchment scale. One example is the dynamics of evapotranspiration seen in forested catchments in Perth and Darwin. Another example is the well-known fact that the discharge of the groundwater aquifer to streams can often be represented by simple linear reservoir theory, characterized by a mean residence time, in spite of the complexity of flow processes operating at small scales, and governed by Darcy's law (Savenije, 2017). This intriguing connection between micro-scale complexity and macro-scale simplicity has been an unsolved problem in catchment hydrology (Dooge, 1986; Sivapalan, 2003). The challenge for predictions is that the mechanisms through which such transformations happen are largely unknown. If the biological or ecological laws that govern them were known we might then use them to derive simpler, holistic parameterizations of hydrologic responses. Until such laws become available and lead to the development of universal predictive models, the problem lends itself to a plurality of modeling ideas, including data-driven approaches that rely on inferences from available rainfall-runoff data.

Wittenberg and Sivapalan (1999) presented an interesting and insightful implementation of the data-driven inference idea. They performed diagnostic analysis of rainfall-runoff data in several catchments in Western Australia (WA). This first involved analysis of streamflow recessions (i.e., following the end of individual rainfall events) in different times of the year, and in WA's seasonal climate, attributing differences in the slopes of the recession curve to changing evapotranspiration (ET). This made it possible to back-calculate ET from the recession curve slopes, and thus piece together a simple groundwater balance model for the catchments. This approach to data-based inference was later extended by Kirchner (2009) to UK catchments, calling it “doing hydrology backwards”. In both cases, however, the power of the approach owed it to the apparent simplicity of the hydrologic response manifesting at the catchment scale, resulting from the spatial organization and temporal adaptation of the catchment ecosystem to the prevailing climatic variability.

Following the lead of Wittenberg, Jothityangkoon et al. (2001) and Atkinson et al. (2002) extended the data-based inference idea further by treating the catchment’s observed rainfall-runoff response as a reflection of its ecosystem functions (i.e., partition, storage, transmission and release) manifesting themselves differently at different time scales. They assumed that the ecosystem functions are reflected collectively in several runoff signatures (i.e., patterns extracted from streamflow data at different scales), through which it was assumed the catchment reveals its internal dynamics or functioning (see Figure 3). These streamflow signatures, e.g., the regime curve (monthly time scale), flow duration curve (daily), flood frequency curve etc. are thus seen as outward manifestations of internal ecosystem functioning, and are therefore deemed emergent (temporal) patterns.

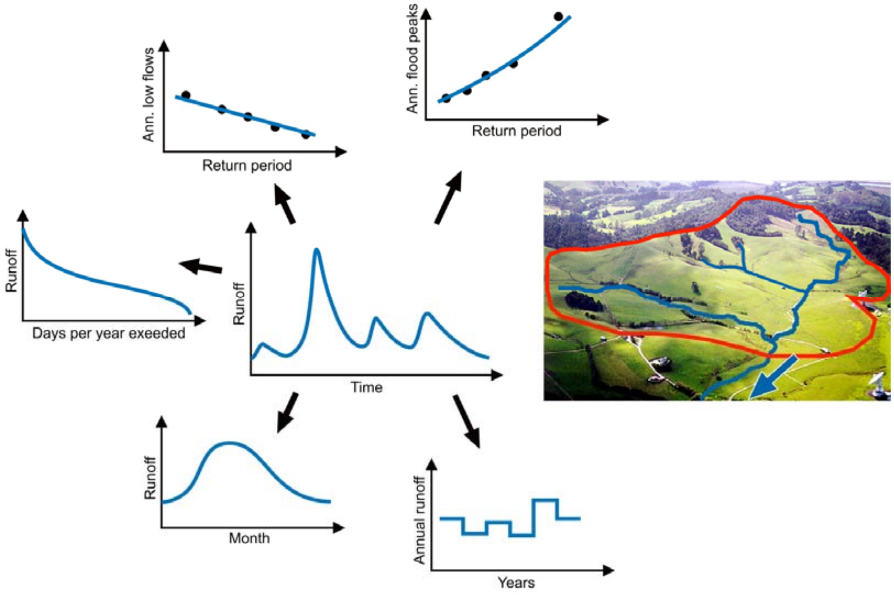

Figure 3. Runoff signatures deemed emergent patterns reflecting the functioning of the catchment ecosystem. Clockwise from bottom right: annual runoff, seasonal runoff, flow duration curves, low flows, floods and runoff hydrographs. Taken from Blöschl et al. (2012).

The functional insight and the realization that catchment responses can show organization along time scales gave rise to a new approach to the modeling of catchment rainfall-runoff responses, called the top-down or downward approach (Klemeš, 1983; Sivapalan et al., 2003). We might also call it the functional approach, following Black (1997). This modeling approach is diametrically opposed to, but complementary with the bottom-up or upward approach to model development based on Newtonian mechanics (Klemeš, 1983), an example of which is the REW approach of Reggiani et al. (1998, 1999) discussed earlier. The idea behind the downward or functional approach is to develop models step by step, but starting at long time scales (e.g., the annual time scale, as in the case of Jothityangkoon et al., 2001). Once a simple (simplest possible) model is developed that reproduces the runoff signature at the annual scale, i.e., inter-annual variability, one then moves down to the monthly time scale, and adds just enough functional complexity to the model to match a new signature, now at the monthly time scale, i.e., the regime curve. If partitioning is the main function that is accommodated at the annual time scale, storage and release could be functions added at the monthly scale, and so on. This process continues until a model is developed that is able to reproduce signatures extracted from streamflow data simultaneously at all time scales (Jothityangkoon et al., 2001; Atkinson et al., 2002). The top-down modeling approach bears some similarity to the Data Based Mechanistic modeling approach proposed by Peter Young of Lancaster University, as reflected in Young and Beven (1994) and Young (2003), as also discussed in Sivapalan and Young (2005).

Interestingly the "functional" models, developed in a top-down way through inference from data (e.g., Jothityangkoon et al., 2001; Atkinson et al., 2002), are in many ways similar to what have long been known as conceptual models, which have been developed from the 1960s, beginning with the Stanford Watershed Model (Crawford and Linsley, 1966). These conceptual model types can be lumped (at the catchment scale) or distributed (at the sub-catchment scale), and are developed without recourse to Newtonian mechanics. Examples (of numerous others) include the Tank Model (Sugawara, 1967), HBV (Bergström, 1976), LASCAM (Sivapalan et al., 1996), and the FLEX generation of models proposed in recent times (Fenicia et al., 2011; Gharari et al., 2011). Both model types take the form of a combination of inter-connected storage reservoirs that mimic the functioning of different parts of a catchment, both attempt to provide some kind of mapping between landscape structure and model structure (Sivapalan, 2005), and both contain a strong subjective element. The main difference is the thought process that goes into developing these models. Development of top-down models follows a systematic procedure to decipher the model structure from observed rainfall-runoff variability at multiple time scales. In the case of traditional conceptual models, the model structure is chosen, ostensibly but often arbitrarily, to reflect the functioning of parts of the catchment, with the opportunity to further refine it through calibration with observed rainfall-runoff data. In another sense, both model types are also similar to physically-based models of intermediate complexity arising from the REW approach (e.g., Tian et al., 2006; Lee et al., 2007), in that all three model structures can be expressed in the form of coupled ordinary differential equations that reflect water balances of individual compartments (or storages).

5. Newtonian mechanics vs ecosystem function: impasse and reconciliation

In the preceding sections I outlined two complementary approaches that hydrologists have pursued over the past five decades to make catchment scale predictions. Using the terminology of Klemeš (1983), subsequently expanded by Sivapalan et al. (2003), these can be termed the upward (or bottom-up reductionist) and downward (top-down ecosystem) approaches. The upward approach fundamentally involves the application of Newtonian mechanics, either through spatially distributed models that attempt to explicitly resolve spatial heterogeneity, or through semi-distributed (e.g., REW) models that attempt to parameterize the effects of sub-grid heterogeneity, while keeping the essential physics. The downward approach to model development, on the other hand, involves making inferences from catchment scale rainfall-runoff data (and other responses, e.g., evapotranspiration).

The advantage of Newtonian mechanics-based models is that the role of spatial gradients in controlling hydrologic processes, at least in principle, can be explicitly captured and so the fidelity of process descriptions at small scales can be guaranteed (at least in principle). Yet, they have the disadvantage that they cannot (yet) account for the functioning of the catchment as an ecosystem, defined by process interactions in the time domain, the biological/ecological laws behind which are yet to be discovered in the catchment hydrologic context. The top-down approach to modeling has the advantage, being derived from rainfall-runoff data, that it can capture the holistic nature of catchment functioning. On the other hand, it cannot (yet) unambiguously account for the physical laws that govern flow processes in landscapes, especially in the spatial domain.

Indeed, it can be said that "bottom-up reductionist type models are best suited to represent "known" knowledge, and are at their weakest to reveal "unknown knowledge" (Richard Silberstein, *personal communication*); *vice versa* for top-down ecosystem type models. In this way, the biggest strength of the top-down approach is also the biggest drawback of the bottom-up approach, and *vice versa* (Sivapalan et al., 2003). These two perspectives will remain irreconcilable until major breakthroughs are made in our understanding of multi-scale spatial heterogeneity and temporal variability, no doubt governed by Newtonian mechanics at the small scales, the resulting cross-scale interactions and adaptations, and the understanding of how these contribute to whole ecosystem function and manifest themselves in more holistic, and simplified parameterizations of catchment responses at the catchment scale (Sivapalan, 2005; McDonnell et al., 2007). Presently, in this context, we are at an impasse!

One of the clearest manifestations of the impasse in modeling is in the uncertainty in the resulting hydrologic predictions. Neither approach is complete in terms of its theoretical foundation to generate the predictions we need. In the case of bottom-up models based on Newtonian mechanics, the predictive uncertainty arises from the inability to characterize the heterogeneity of landscape properties accurately, the lack of knowledge or understanding of hydrologic processes in the real world, and the inability to capture them in the models. In the case of top-down or functional models that depend on data-based inference, equally there is uncertainty due to diversity of catchment adaptations to climate and consequently in the plurality of model structures. In addition, there is further uncertainty due to the inability to unambiguously estimate parameter values through calibration, in the absence of physical guidance or universal

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laws to constrain the parameter values. In general, the uncertainty arises from, in a broad sense, both inadequate understanding of catchment behavior (epistemic uncertainty) and inability to characterize the catchment heterogeneity fully (aleatory uncertainty) (Beven, 2016). Further progress in modeling will depend on our ability to break the impasse between the different modeling approaches by changing the science questions that have been behind hydrologic research over the past decades (Sivapalan, 2009).

Breaking the impasse by changing the question

True reconciliation is unlikely to come about if we stay within the existing paradigms, i.e., through mere refinements to existing approaches to estimation and prediction. Reconciliation between Newtonian mechanics and ecosystem function based approaches will require a new era of research aimed at explanation and discovery rather than estimation or prediction (see also Burt and McDonnell, 2015). Reconciliation will require, on the one hand, that we understand the functional role of landscape heterogeneity, and on the other hand, the physics (i.e., mechanics or thermodynamics) underpinning ecosystem function. This might require going beyond Newtonian mechanics and searching for other universal laws or organizing principles that explain ecosystem functioning of catchments in particular places. Instead of parameterizing the effects of heterogeneity, the focus should be on recognizing it as an emergent pattern and coming up with explanations to describe how it came about and discover its ecosystem function (Figure 4, Sivapalan, 2005). The modeling question should no longer be whether we can explicitly account for the effects of heterogeneity mechanistically but whether its ecosystem function can be reproduced (McDonnell et al., 2007; Schaefli et al., 2011). In other words, to move forward towards improved predictions, the research goals and associated scientific questions must broaden from just estimation to explanation!

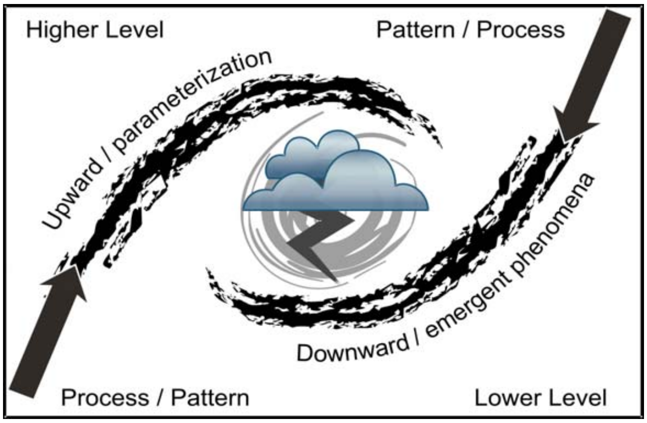

Figure 4. Reconciliation of downward and upward approaches – break from a reliance on parameterization of lower-level features to discovery and explanation of emergent phenomena at the higher level. Taken from Sivapalan (2005).

Moving from estimation to explanation: focus on phenomena

As we have seen, the focus on estimation goes back to the beginnings in Engineering Hydrology. In spite of the enormous progress we have made in our ability to make predictions, these advances have not progressed to generalized theories that operate universally across catchments and places. General theories are very much needed to bring about the reconciliation of the diversity of modeling approaches we now have and to achieve a unification of the field. Hydrologic research will thus have turn to new types of questions (Sivapalan, 2009), which are focused on explanation and discovery, perhaps as a necessary prelude to prediction. Organization of catchment responses and patterns of ecosystem function that one observes in the real world are no longer objects to be mimicked by our models ("grist to the calibration mill", *a la* hydrograph fitting), but need to be seen as emergent phenomena. The enormous computational power and data availability that we now have should be utilized to discover and/or explain previously unobserved or explained phenomena at all scales and places (Li et al., 2014; Dunne, 1978).

Phenomena abound in hydrology, differing in complexity and richness, and arising in different contexts, which warrants a separate review article by itself, given their increasing importance in hydrology research. Examples of phenomena include the old water-new water concept (McDonnell, 1990), the pan evaporation paradox (Roderick and Farquhar, 2004), the Budyko hypothesis (Budyko, 1974), the proportionality hypothesis that lies behind the success of the SCS-curve number method (Wang et al., 2014), and the linear reservoir approximation to groundwater contributions to streamflow (Savenije, 2017). The goal of research will increasingly revolve around coming up with plausible hypotheses about their causes and testing them out through further observations or targeted modeling. If the explanations hold in several places, then it contributes to accumulation of knowledge and understanding, and eventually to general theories. Until recently, under the weight of the dominant estimation/prediction (i.e., hydrograph fitting) paradigm, inadequate attention has been given to the study of phenomena. Here I will illustrate, through two simple examples, how the physical causes of phenomena can be explored, and how this might contribute to generalized understanding.

The two examples I present here involve an apparent power law relationship with catchment size (area). The first one involves the annual maximum flood peak (scaled by catchment area), in this case, taken from several nested catchments in the Appalachian region of the United States (Figure 5a; Smith, 1992; Robinson and Sivapalan, 1997; Sivapalan, 2005). The second one involves the sediment delivery ratio (the fraction of eroded sediment at event scale that actually reaches the catchment outlet (Figure 5b, Lu et al., 2005). Even though these examples are obtained from specific places, the phenomena themselves are universally observed. The question is: Why is it a power law? Is there a causal explanation? Answers to such questions test our understanding of the underlying processes and the interpretation of observations of all kinds.

Robinson and Sivapalan (1997) showed that the power law can be explained by a simple argument, supported by a simple linear "bucket" model with two different time scales (event duration, and a mean response time that is a function of catchment area, due to the geometric relationship between length of travel and area), and an understanding of rainfall variability. If rainfall intensity is a constant during a single storm event, the magnitude of the flood peak can be analytically derived based on storm duration and mean response time: it does not follow the power law (see dotted line …. in Figure 5a). Firstly, the introduction of within-storm rainfall variability raises the flood peak for small catchments (due to their fast response) but has no impact in large catchments (denoted by the symbol "* * *" in the figure). Secondly, the introduction of between-event interactions and seasonality increases the flood peak for large catchments (due to their effect on antecedent conditions), but has no influence for small catchments (denoted by o o o). Their combination leads to a combination of the two effects (denoted by --- and —): flood peak is raised for small catchments (because of within-storm variability) and for large catchments (because of interaction between events and/or seasonality). So what looks like a power law is really an emergent pattern that falls out as a result of a complex interplay across different time scales, and the geometry of the catchment's organization.

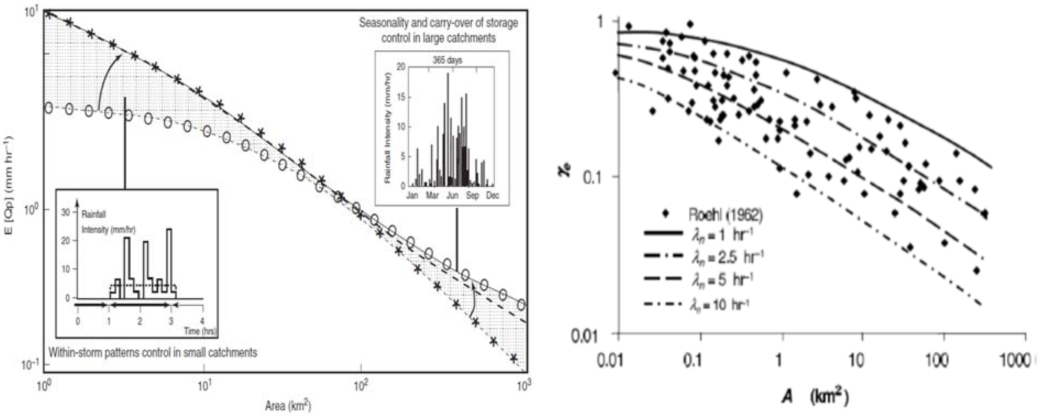

Figure 5. Explaining power law relationships as emergent phenomena arising from time scale interactions: (a) mean annual flood as a function catchment area in the Appalachian region (taken from Sivapalan, 2005); (b) sediment delivery ratio (SDR) γ_e as a function of catchment area with changing channel depositional parameter λ_n (taken from Lu et al., 2005)

The scaling of sediment delivery ratio is an even more complex phenomenon to explain (with considerable scatter, see Figure 5b), because it involves not only runoff processes as discussed above, but also sediment transport processes. Even in this case, however, Lu et al. (2005) proposed an explanation that was similar, indeed followed that of Robinson and Sivapalan (1997). They too used a simple conceptual model that consisted of two linear stores arranged in series: a hillslope store that addresses transport of sediment to the nearest streams and a channel store that addresses sediment routing in the channel network. They showed analytically that, as with Robinson and Sivapalan (1997), the spatial scaling of sediment delivery ratio (as an emergent pattern) can be explained, to first order, in terms of the interactions between several time scales (i.e., storm duration, hillslope/channel travel times, and two depositional timescales), and also catchment geometry as before.

I used these simple examples to also highlight the effects of the interactions between multi-scale temporal variability of both climate inputs and catchment response, and how they tend to generate emergent patterns due to the resonance that is generated through these interactions, even in the absence of adaptations of vegetation or catchment properties. In other words, the way that the catchment responds to a sequence of events is different from the way it responds to a single event, indicating that the response of the catchment must be considered holistically across multiple time scales. The importance of time scale interactions has also been highlighted in other contexts to explain several environmental phenomena: power-law type streamflow recessions resulting from landscape heterogeneity (Harman and Sivapalan, 2009); effect of rainfall event variability on pesticide leaching risk of groundwater (McGrath et al., 2010); and, climate controls on vadose zone contaminant transport (Harman et al., 2011). This issue will be explored in more detail in later sections using an expanded, co-evolutionary framework.

Towards explanation and extrapolation: new kinds of models, new kinds of phenomena

As the focus turns from estimation to explanation, the types of models one uses may also need to change. It is not an accident that in the two examples discussed above, I have demonstrated how simple models are able to provide first order explanations of otherwise complex phenomena. In this age of big data, data mining and hyper-resolution modeling (Wood et al., 2011; Peters-Lidard et al., 2017), one might be surprised that I advocate the use of simple models. I do this deliberately because the focus here is not on prediction of the complete system response in one place with all its gory complexity, but as per the Einstein quote below (see also the earlier quote from Simon Levin), on the ability to explain complex, possibly universal phenomena more simply, and thus contribute to accumulation of knowledge and understanding. Furthermore, in the spirit of top-down reasoning, we will therefore be better off starting with simple models targeted on the phenomenon of interest, not models of everything, and increasing the complexity only when needed.

> *"If you can't explain it simply, you don't understand it well enough"* – Albert Einstein

Phenomena of interest to us can be dynamics (temporal patterns) at a single place, at a range of time scales (Burt and McDonnell, 2015). Similarly, in the space domain, phenomena can be spatial patterns at a single place (within a catchment, Blöschl et al., 2016), or spatial patterns between places (catchments) or scales (as in the two examples above), extending all the way to regional or global patterns. Increasingly, as discussed before, the focus turns towards developing generalized understanding of whole catchment responses and ecosystem functioning, and the discovery of universal laws. Therefore, it is no longer sufficient to study phenomena relating to a single place or a few places. Increasingly, the phenomena of interest to us will come from simultaneous observations in many different places with different histories of the kinds of time scale interactions shown to be critical in the two examples presented above (Hipsey et al., 2015), and the synthesis of data collected from across places, scales and processes (Blöschl et al., 2013).

6. Time scale interactions and catchment co-evolution: the Darwinian approach

Understanding the reasons for differences in required model structure between catchments, including the controls of climate and landscape properties, may be a good starting point in the search for more generalized understanding, drawing from many different places with different histories. Atkinson et al. (2002) and Farmer et al. (2003), who implemented the top-down modeling approach, in a comparative way, to two dozen catchments around Australia and New Zealand. They found systematic variations in model structure, with the differences reflecting differences in climate and in how vegetation and soils may have adapted to the climate. The modeling studies indicated evidence of a hierarchy of required model structures, with changing time scales (i.e., annual, monthly, daily etc.), and with changing aridity. For example, the required model complexity increased with decreasing time scales, and increased with increasing aridity. The argument could thus be made that the required model structure, reflecting the functioning of a catchment, is itself an emergent property in terms of how the catchment has adapted itself to the prevailing climate and geology.

Catchments "marching to a different drummer": comparative hydrology

In order to shed more light on the required level of model complexity, Jothityangkoon and Sivapalan (2009) compared a dozen catchments from all around Australia and New Zealand, using the same top-down modeling approach described above (i.e., matching streamflow signatures at a range of time scales). They carried out a diagnostic analysis in each catchment that focused on elucidating the climate controls on one particular signature, i.e., inter-annual variability of runoff. In particular, they were interested in discovering the aspect of the within-year rainfall variability (i.e., storminess, seasonality) that may have a dominant control on the observed inter-annual runoff variability. The diagnostic analysis involved running calibrated top-down hydrological models in each catchment, but now with artificial rainfall inputs that included storminess and seasonality separately, before being combined. The outputs from the model in each catchment, for each of the artificial climate inputs, were compared to the observed inter-annual variability. The question pursued was: what combination of within-year climate variability (seasonality, storminess) is needed to reproduce the observed inter-annual variability of runoff?

The study found that in catchments in Queensland in north-eastern Australia, inter-annual variability of runoff was most sensitive to storminess (not seasonality), whereas in catchments in Western Australia and South Australia, seasonality was the feature that contributed most to the observed inter-annual variability. This finding is remarkable, in that the climate of Queensland is indeed dominated by storminess (i.e., small number of large storms), and the climates of South and Western Australia were indeed dominated by strong seasonality. The outcomes from these diagnostic analyses indicated that the water balance dynamics of catchments (i.e., model structure and parameters inferred from the data in a top-down way) somehow resonate with the dominant within-year variability, i.e., storminess in Queensland and seasonality in Western Australia. In other words, and paraphrasing American naturalist Henry David Thoreau, these results indicated that each catchment is "marching to a different drummer", the drummer being the variability of climate drivers present in a given place.

> *"If a (wo)man does not keep pace with (her)his companions, perhaps it is because (s)he hears a different drummer. Let (her)him step to the music which (s)he hears, however measured or far away."* adapted from *Henry David Thoreau: Walden, 1854*

The modeling results also reaffirm the ecosystem view of catchments presented earlier, including the argument that there is much to be gained by making inferences from observed rainfall-runoff time series. They also raise the hope that a more universal understanding of both ecosystem function and catchment response and their relationship to climate and geology may be gained through repeating these modeling and diagnostic studies simultaneously in many more catchments around the world, in a comparative way, across gradients of climate and geology. This leads to the notion of *comparative hydrology*, introduced by Falkenmark and Chapman (1989), and defined more broadly in the next section by linking it to catchment co-evolution.

Catchment co-evolution and Earth System Science: A Darwinian view

Berghuijs et al. (2014) extended the above comparative hydrology approach to the modeling of seasonal water balances of over 400 catchments across the continental United States. On the basis of these modeling results they came up with a classification of observed seasonal water balances (i.e., regime curve, a key signature of runoff variability), expressed in terms of three driving factors: climate aridity, seasonality (i.e., relative timing of the precipitation within year) and the fraction of snow as precipitation. On the basis of this similarity analysis, they identified 10 dominant catchment classes among the 400-odd catchments. Not surprisingly, they found a geographic aspect to the locations of the 10 classes, in that they were clustered geographically, influenced by the slow climatic and geologic variations across the continent. In addition they found that similarity of seasonal water balances carried over to have an imprint on between-class differences in several other signatures of runoff variability, such as the flow duration curve, flood frequency curve etc., and yet there was also considerable within-class variability due to other climatic and landscape factors.

An even more interesting finding from Berghuijs et al.'s (2014) results, however, was that the regional mapping of catchments on the basis of similarity of seasonal water balances was closely aligned with the regional mapping of not only vegetation classes and ecoregions (i.e., the different ways ecologists map vegetation and ecosystems), but also soil orders. This clearly indicated that the seasonal water balance response is not just about the partitioning of incoming precipitation into spatially resolved hydrologic processes, i.e., runoff, evaporation and storage change. In fact, it is both a contributor to, and an outcome of, the co-evolution of physical, biological and pedologic processes governing vegetation establishment and adaptation, and soil formation, as well as water balance, which together reflect an underlying ecosystem function. Indeed, it is well known in the ecological literature that it is the seasonal water balance that determines vegetation types that become established in a given place, their functioning and productivity (Stephenson, 1990; Robinson et al., 2012).

One can speculate therefore that the phenomenon of each catchment "marching to a different drummer" is a reflection of vegetation adapting to (and in turn changing) the environment around it (e.g., hydrology, soils), in response to the fluctuating water and energy supply at any place of interest (Sivapalan and Blöschl, 2015). This is tantamount to the soils, vegetation and topography belonging to a catchment co-evolving together in response to the climate above and geology below through both land-forming and life sustaining processes operating and interacting across multiple time scales (Figure 6). The focus can no longer be on just hydrological processes, but all land surface processes that operate together and feed back on each other, which thus takes hydrology into the realm of Earth System Science. With this broader view, the focus of analysis is therefore no longer on streamflow signatures alone, but also on signatures arising from the co-evolution of Earth System processes, such as vegetation and erosional patterns that one sees on landscapes (Sivapalan, 2005). Examples include patterns in measured evapotranspiration at individual (e.g., FLUXNET) sites (Thompson et al., 2011a), regional patterns of evapotranspiration measured by remote sensing (Cheng et al., 2011), and vegetation, soil and micro-topography patterns in landscapes at a range of scales (Thompson et al., 2011b; Saco et al., 2013; Harman et al., 2014). These are the kinds of ecohydrologic and hydrogeomorphic phenomena that will need to be further explored in the future and synthesized to generate the new understanding and new theories required to close the gap between bottom-up (reductionist) and top-down (ecosystem) approaches to modeling.

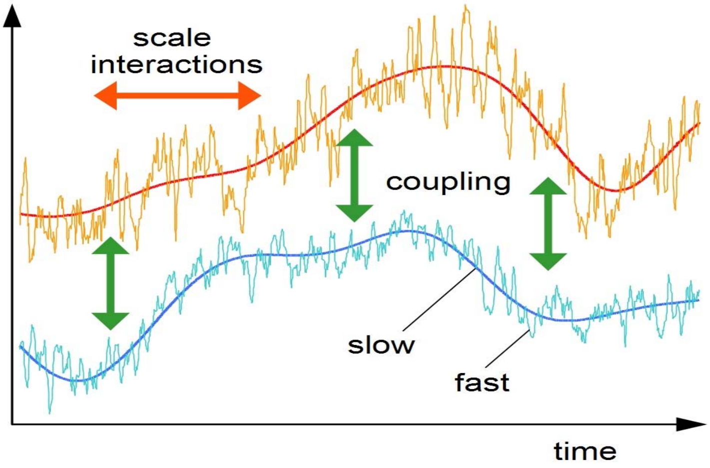

Figure 6. Coevolution resulting from the interaction of a number (at least two: one represents hydrological processes and the other landscape physical or ecological or social processes) each of which consists of fast and slow components, producing emergent dynamics. Redrawn from Sivapalan and Blöschl [2015].

These outcomes of co-evolution, framed as emergent phenomena, may be different in different places, because of differences in the history of co-evolution and initial and boundary conditions

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of climate and geology. Comparative hydrology, i.e., comparing many catchments in different places along gradients of climate and geology, helps us to shed light on their co-evolution, just as Charles Darwin interpreted differences between animals, birds and plants he found in his travels through the lens of their natural history (Harman and Troch, 2014). The Darwinian approach to comparative hydrology embraces the history of each place, including features that are relics of historical events, as central to understanding both its present and its future. The essence of the Darwinian approach is to develop generalizations beyond individual catchments through learning from differences between catchments, and interpreting them as legacies of past co-evolution.

Hydrologic similarity and catchment classification: steps towards generalization

Given the co-evolved nature of catchments, their structure and function, and the resulting hydrologic responses, explanation of the similarity and differences between catchments must take a more Darwinian approach that emphasizes time scale interactions specific to a place, and how the catchment ecosystem may have adapted to these. While there can be considerable diversity and randomness allowed in Darwinian co-evolution of catchments due to contingency effects (Beven, 2015), patterns and connections may yet be discernible which may lead to relationships of more general applicability. One approach to creating order in an otherwise heterogeneous world, widely adopted in chemistry and ecology, is through the means of classification. As in the case of the periodic table in chemistry, classification of catchments based on hydrologic similarity may be used to group catchments, helping to simplify relationships and generalize findings. Hydrologic similarity is the foundation for the transfer of information from one catchment to another, including from gauged to ungauged catchments, and was the basis of the successful outcomes of the "predictions in ungauged basins" (PUB) initiative (Sivapalan et al., 2003; Blöschl et al., 2013; Hrachowitz et al., 2013). The PUB synthesis study by Blöschl et al. (2013) framed hydrologic similarity in terms of several signatures of runoff variability, such as the flow duration curve and the flood frequency curve. The diversity of catchment responses is such that no two catchments are so similar that all signatures are the same between them, and so for prediction purposes one concentrates only on the signature of interest. Yet, as in the case of the comparative hydrology study by Berghuijs et al. (2014), the synthesis project by Blöschl et al. (2013) also found that similarity of seasonal water balance had a significant influence on the similarity of other signatures, and may be the strongest indicator used to delineate hydrologically similar regions (Weingartner and Aschwanden, 1992).

The organization of catchments into distinct classes based on hydrologic similarity can open the way to understanding the differences between the classes themselves in terms of the underlying climatic, geologic and landscape controls. The most celebrated example of progress in this area is the empirically derived Budyko curve, famously named after Russian hydrologist Mikhail Budyko. The Budyko curve graphically expresses the long term (or mean annual) water balance, defined by the ratio of long-term average evapotranspiration to precipitation, E/P, as a universal function of climatic aridity, the ratio of long-term average potential evaporation to precipitation, E_p/P (Budyko, 1974). The existence of the Budyko curve is usually explained as resulting from a competition between water available (precipitation) and energy available (potential evaporation). In the case of the MOPEX catchments across the United States, Berghuijs et al.

(2014) found that the different catchment seasonal water balance (and also vegetation/soil) classes clustered along different segments of the Budyko curve, with little overlap. On the basis of this and other evidence, one can argue that the competition between water and energy available is mediated by the vegetation that forms through natural selection, highlighting the key role of ecohydrology in hydrologic theory development (Eagleson, 2002; Rodriguez-Iturbe, 2000).

The fact that most of the MOPEX catchments (and other catchments of the world) fall on or about the Budyko curve (leaving a large part of the Budyko space unoccupied) can be seen as an empirical organizing principle, i.e., only some combinations of climate, soil and vegetation characteristics may exist in reality (i.e., are behavioral, Schaefli et al., 2011), indicating a mutual co-dependence through Darwinian co-evolution and selection (Eagleson, 2002). Inspired by these observations, in recent times several hydrologists have embarked on a search for physical explanations for the existence the Budyko curve (Wang and Tang, 2014; Wang et al., 2015; Westhoff et al., 2016). Wang and Tang (2014) and Wang et al. (2015) studied the conceptual bases for empirical models developed by engineers (and geographers) from the 1930s to the 1950s to describe water balances across three different time scales: event, seasonal and annual. These were the SCS Curve Number method for runoff estimation at the event scale (Mockus, 1949), the *abcd* model for seasonal (monthly) water balance developed during the Harvard Water Program during the 1960s (Thomas, 1981), and the L'vovich method developed in the former Soviet Union for partitioning of annual precipitation into runoff and evaporation (L'vovich, 1979). In the first phase of their work, Wang and Tang (2014) and Wang et al. (2015) showed that all three of them can be described in terms of the so-called *proportionality hypothesis*, which is long understood as providing the conceptual basis for the SCS curve number method. In the second phase of their work, they showed that the proportionality hypothesis, in turn, can be explained thermodynamically, in terms of the principle of maximum entropy production (MEP). One can thus see that the empirical proportionality hypothesis and the thermodynamic MEP principle appear to provide a vehicle to extend the hydrologic similarity arising from co-evolution across to multiple time scales. These are only the first tentative steps in the quest for new theories of hydrology, and still more creative approaches are needed to extend the notions of similarity and optimality to cover not just the Budyko curve but all other signatures, in order that we fully exploit the order that may arise out of Darwinian co-evolution.

The MEP principle, or the equivalent maximum power principle proposed by Kleidon and Renner (2013) and used by Westhoff et al. (2016) to derive the Budyko curve, can be viewed as providing a constraint to the diversity of Darwinian co-evolution and natural selection, possibly as a mechanism to increase system resilience (Lotka et al., 1922). Furthermore, existence of such physically based organizing principles, valid at a range of time scales as indicated in the work of Wang et al. (2015), can pave the way for a new generation of behavioral models (Schaefli et al., 2011). This is a promising development for two reasons. On the one hand, it can help constrain model structures inferred from rainfall-runoff data, and on the other hand, it can constrain the parameter combinations allowed for otherwise physically based models based on Newtonian mechanics (Li et al., 2014). A unique advantage of the approach adopted by Wang et al. is that it involved connecting the dots between empirical methods that have been widely used in engineering hydrology for over 50 years, exploiting the simplicity in these estimation methods arising from the very co-evolution we are trying to capture in our models (e.g., flood frequency, Guo et al., 2014). Potentially, if continued further, it will have the salutary effect of making fundamental advances while maintaining coherence, through avoiding fragmentation (Graham and Dayton, 2002; Blöschl et al., 2013).

7. Time scale interactions in the Anthropocene: from ecohydrology to socio-hydrology

The focus of the discussion in the last section was on time scale interactions and the co-evolution of hydrologic and other physical and biologic processes occurring in landscapes. In the otherwise natural catchments considered so far, the dynamic nature of catchment co-evolution was centered on vegetation, its adaptation of itself and its environment through feedbacks between hydrologic and ecologic processes across multiple time scales. This perspective was introduced to assist with developing transferable understanding between places in the course of data-based inference and top-down modeling under otherwise stationary conditions.

As one begins to look to the future, one recognizes the expanding human footprint, including land use and land cover (e.g., vegetation) changes and human interferences in the hydrologic cycle (e.g., water extraction from rivers or groundwater aquifers) and the inevitable acceleration of the time scale interactions. One can no longer count on stationarity in making predictions of catchment responses under these circumstances (Milly et al., 2002; Wagener et al., 2010). Furthermore, over longer periods of time the time scale interactions must include two-way feedbacks between hydrological (and other earth system processes) and human-social processes, and the emergent dynamics that result from these. Thus, as we transition from our focus on ecohydrology so far (Eagleson, 2002; Rodriguez-Iturbe, 2000) to the new field of socio-hydrology (Sivapalan et al., 2012), we can recognize both similarities as well as differences between the behaviors of vegetation and humans and, where possible, benefit from lessons learned from the practice of ecohydrology in the past two decades.

The co-evolution of water and vegetation does not stop with vegetation adapting to the water and energy balances and *vice versa*. We noticed that over time vegetation not only adapts itself to the prevailing climate variability and water balance dynamics (even as it modifies it at the same time), but it does so through adapting (or engineering) the landscape or environment around it as well, such as through modifying the soils or topography. Work by Gao et al. (2014) drew an analogy between humans and vegetation and highlighted parallels in water consumption behavior between them. We know humans build storages to cater to periods of drought – in engineering hydrology we estimate the required storage using (for example) the so-called Rippl method (Rippl, 1883). Analogously, Gao et al. (2014) proposed a root storage design method for vegetation, similar to Rippl, where the required storage capacity (with an analogy to root depth) was the between-year maximum of the within-year (seasonal) fluctuation (peak to trough) of soil moisture storage. They extracted this information from the outcomes of their modeling work done on a large number of MOPEX catchments across the United States, from which they estimated the pattern of root depth variation between the catchments. They discovered strong correlations between the root depth distributions obtained from such water balance analyses and those independently obtained for the actual vegetation classes found in these catchments.

This observation lends strong support to the argument that vegetation adapts itself optimally to the prevailing water balance (seasonal and annual) through adapting itself and adapting its environment so as to, in this case, make maximum use of the water available (see also Yang et al., 2017). This confirms the prescient insight of Robert E. Horton, an early pioneer of hydrology who wrote:

> *"Natural vegetation of a region tends to develop to such an extent that it can utilize the largest possible proportion of the available soil moisture supplied by infiltration." Robert E. Horton (1933)*

Admittedly, this is very much a top-down treatment of vegetation adaptation, which I invoked only to make the connection to comparative hydrology, and to highlight how model structures and parameterizations may vary between places through such adaptations. In reality, these broad-scale patterns indicative of co-evolution will require further refinement in the context of new ecohydrologic theories regarding vegetation adaptation to its environment. One example of this (one of many) is the vegetation optimality model (VOM) proposed by Schymanski et al. (2009) based on the hypothesis that natural vegetation co-evolves with its environment and over time natural selection leads to a species composition most suited for the given environmental conditions. In VOM this is represented by a trade-off between water loss and carbon gain formulated in terms of the costs associated with the maintenance of roots, water transport tissues and foliage, and the benefits related to the exchange of water for CO_2 with the atmosphere, driven by photosynthesis. The optimal vegetation is one that maximizes "net carbon profit", i.e., difference between carbon acquired by photosynthesis and carbon spent on maintenance of organs involved in its uptake. There is increasing availability of data on evaporative fluxes from a large number of flux towers located in different biomes of the world (Thompson et al., 2011a, 2011b) and new remotely sensed datasets on both vegetation cover and evapotranspiration rates over regional scales (Cheng et al., 2011) to complement existing rainfall-runoff data at catchment scales. There is enormous scope for these new datasets to be used to test alternative theories of vegetation adaptation, to provide guidance for the choice of model structures in top-down models, and thus help bridge the current impasse between top-down and bottom-up models.

Human engineered landscapes and catchment water balances

We now know, at a minimum, how vegetation adapts itself to the water balance and adapts the water balance through its control. Increasingly, humans too interact with catchment water balances, in some ways similar to how vegetation interacts with the natural water balance. Humans extract water directly from rivers or groundwater aquifers to meet their needs, or might build dams across rivers to store water when nature's supply is low, such as during low flow or drought periods. Just as vegetation engineers the landscape to gain and maintain access to water, humans too engineer the landscape (e.g., catchments) to gain and maintain access to water, and to serve other human functions.

Previously hydrologists may only have been interested in the short-term (and local) effects of land-use changes and human interferences in the hydrologic cycle to satisfy human needs or functions. With the expansion of the human footprint, they are increasingly concerned with longer-term hydrological changes brought about by human actions and how the changed hydrology then feeds back to generate secondary human reactions. Consequently, it is no longer sufficient, as in the past, to model the hydrology of pristine catchments and add human effects at the end (Wagener et al., 2010). For long-term planning and strategic decision-making purposes, humans must be treated as an intrinsic part of the catchment's water cycle. One can imagine then that over time how this might give rise to a co-evolution of water and people. For example, many ancient civilizations established themselves around sources of water, and their success and eventual collapse or dispersal was an emergent outcome of co-evolutionary feedbacks between humans and water (e.g., Tarim basin in Western China, Liu et al., 2014). Under these changed circumstances, one thus moves from ecohydrology, the study of two-way feedbacks between vegetation response and catchment water balance, to socio-hydrology, the new science dealing with two-way feedbacks between human behavior (e.g., water management) and catchment responses (e.g., water balance, flooding dynamics) (Sivapalan et al., 2012, 2014). This extends our earlier Earth System Science perspective now to include human-social processes as well.

How far can we push the analogy between vegetation and humans? Unlike vegetation, humans need water not just for their physiological needs (i.e., for drinking), but also for sanitation, and even more so for use in industries, and for food and energy production. This introduces an economic purpose to the use of water, and excessive water extraction for economic uses impacts the environment in adverse ways, and impacts the ability of the environment to produce the ecosystem services (including the delivery of water) that humans also depend on. This introduces the notion of the water-food-energy-environment nexus, and the requirement to make tradeoffs between these human needs. Two additional factors that enter the management of the water-food-energy-environment nexus are advances in technology (e.g., infrastructure that enables extraction and transfers of real water between places) and trade (e.g., trade of food and other commodities that depend on water for their production). Another compounding factor is the role of institutional system of administration, legislation and regulation of water (Sivapalan and Blöschl, 2015). Human involvement in hydrologic systems has been studied extensively in the context of water resource management, where the focus has been on optimal management (Loucks et al., 2005). Much of this work has worked on the belief that humans are optimizers, assumed to make rational decisions about allocation of resources between various needs, and opting to maximize economic livelihood. However, with the advent of socio-hydrology, hydrologic science has broadened to include the practices and outcomes of water resource management, in the presence of the aforementioned complexities, as themselves subjects for explanation and deeper understanding (Thompson et al., 2013).

A major complexity in understanding and eventually predicting human behavior in the context of water management is human agency (Sanderson et al., 2017). Unlike natural systems, e.g., vegetation, humans can choose among different modes of thinking and courses of action that impact the natural systems within which they are embedded. A major challenge is that human decision-making shapes, and is shaped by, the cultural contexts within which human societies are embedded. Humans draw upon commonly held values, beliefs and norms to guide their actions, and in turn can collectively change their cultures in the long-term (Caldas et al., 2015). Human-water interactions are heavily influenced by differences and/or dynamic changes in human values and norms in respect of their economic livelihood and the environment. Unlike natural systems whose long-term co-evolutionary behavior can be expressed in terms of organizing principles (e.g., vegetation optimality, maximum entropy production), humans can make decisions away from any optimality principles and may violate their own laws (Figure 7, Sivapalan and Blöschl, 2015). For example, they may extract water from a well, even if it is illegal to do so; or they may choose to live with pollution, away from optimality reasons, giving the impression that humans are irrational. These may manifest as puzzles, paradoxes, and other unintended consequences, exhibiting similarities and differences that reflect distinct hydro-climatic, eco-environmental, and socio-economic features (Sivapalan, 2015; Pande and Sivapalan, 2017). These factors make human-water interactions much more complex and thus add to the already difficult prediction challenges in hydrology (Westerberg et al., 2017).

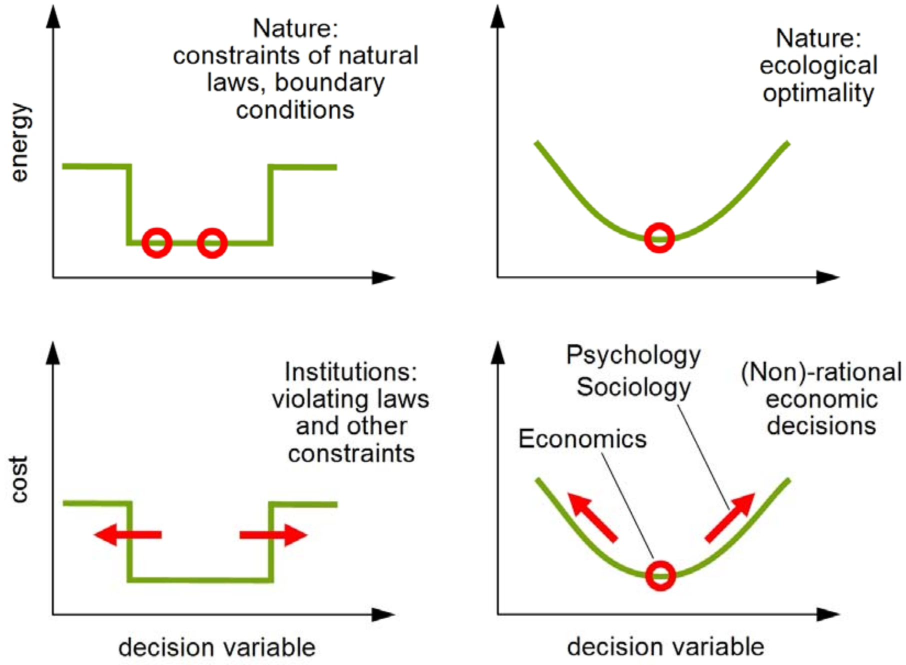

Figure 7. (top) Natural systems follow constraints and optimality laws; (bottom) Human systems may violate constraints and make irrational decisions away from optimality (taken from Sivapalan and Blöschl, 2015).

Indeed, it has been suggested that changes in culture and associated values and preferences may be more predictive of human behavior in the context of sustainability than rationality, or utility maximization (Caldas et al., 2015). Examples of human behavior different from utility maximization include (Sivapalan et al., 2014): the peaking in water resource availability as basins develop (peak water paradox, Kandasamy et al., 2014); increasing levee heights in urban environments at the expense of increased flood risk (levee effect, Di Baldassarre et al., 2013); increasing agriculture water consumption in spite of irrigation efficiency improvements (irrigation efficiency paradox) (Scott, 2011); and over-exploitation of coastal aquifers at the risk of causing saltwater intrusion (Chang and Clement, 2012). Another example of non-optimal behavior in the context of coupled human-water system dynamics is lock-in or path dependence, which is one explanation offered for the collapse of the Maya civilization (Kuil et al., 2016). The science of socio-hydrology aims to explain these kinds of phenomena that arise from two-way feedbacks associated with coupled human-water system dynamics, and to develop generalized understanding that can connect diverse phenomena across many places and times (Sivapalan and Blöschl, 2015). There is still room for predictions in this new era of socio-hydrology: but given the difficulties of dealing with human agency and complex human behavior, the focus is not on predicting what will happen at a future prescribed time, as it is in traditional hydrology, but on mapping out the possibility space of future trajectories of system co-evolution (see Figure 8, Srinivasan et al., 2017).

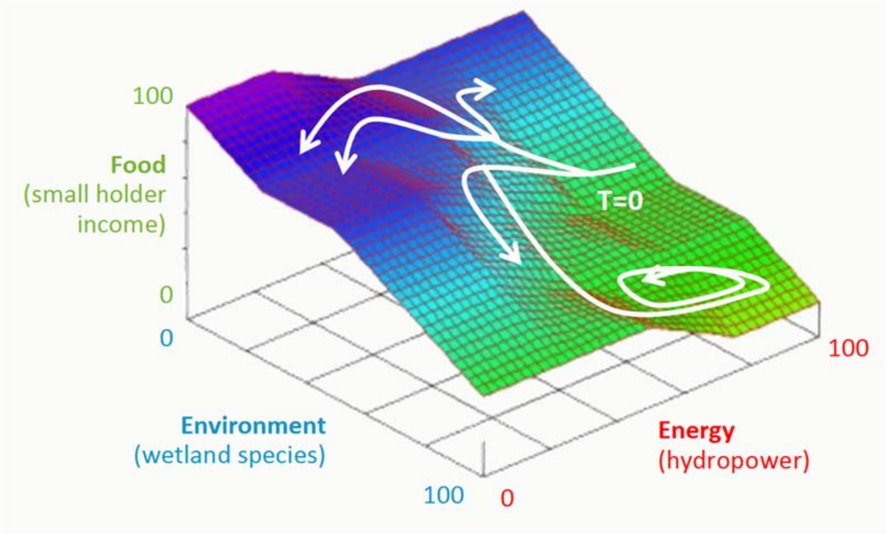

Figure 8. Trajectories illustrating the future possibility space that may be predicted by a socio-hydrological model addressed to management of the water-food-energy-environment nexus (taken from Srinivasan et al., 2017).

8. Engineering Hydrology to Earth System Science: from Newton to Darwin to Wegener

There is no question that there has been a fundamental transformation of hydrology in the past 50 years. My goal in this narrative has been to connect the dots and draw up a continuous thread through what I thought were major milestones in the evolution of the science. Hydrology (for me) started as Engineering Hydrology, addressing rather simple, well-defined problems (e.g., what is the 100-year flood?). Over time, problems became increasingly complex, such as the need to predict the effects of land use changes or climate change (e.g., on 100-year floods), which required more process-based approaches invoking Newtonian mechanics. Even as the ability to make predictions using such physically based models advanced, they encountered limitations due to unknown (and unknowable) heterogeneity of landscapes, and the lack of understanding of process interactions in the time domain, including how catchments functioned as whole ecosystems. Conceptual or functional models based on data-based inference partially helped to overcome these limitations, but they in turn suffered from heavy dependence on data, and the absence of holistic theories of catchment responses and ecosystem functioning.

The seeming impasse between the two approaches to predictions, mechanistic and functional, has motivated hydrologists to broaden the research from the traditional focus on estimation and prediction towards understanding, explanation and discovery. The shift towards understanding and explanation does not signify a lack of commitment to applications of hydrology, however. The goal of hydrology as use-inspired basic science (Stokes, 1997; Thompson et al., 2013) remains, which is to generate the basic understanding necessary to address the complex water sustainability or management problems that appear on the horizon. The nature and role of predictions have also evolved as problems become more complex and highly inter-disciplinary. The change in focus towards understanding and explanation is contributing to two major shifts in hydrology research. The first is increased attention to phenomena, emergent patterns that arise through process interactions across time and space scales. Numerical models are increasingly now used to test hypotheses about how these phenomena may have arisen and thus contribute towards accumulation of knowledge and understanding. The second major shift is towards comparative hydrology, i.e., comparative studies across gradients of climate, geology and human impacts. This is a Darwinian approach, which seeks to develop new insights and theories about catchments, as consisting of components that have coevolved together, and to learn from the common history of their co-evolution.

Given this co-evolutionary perspective, hydrological problems needed to be framed broadly as inter-disciplinary problems that extend beyond the study of water flows in landscapes. In natural landscapes we are increasingly concerned with water flow processes interacting with and feeding back on land-forming (e.g., pedogenesis, soil erosion and deposition etc.), and life sustaining (e.g., biogeochemical, ecological) processes. With the expanding human footprint, hydrology also has to deal with vastly complex social processes. An example (one of many) of a new problem that hydrologists have to deal with in this context is the nature of interactions between people and droughts that might lead to exacerbation of water shortages (Apurv et al., 2017), conflicts, human migration, and even collapse (Kuil et al., 2016). This places hydrology squarely within the realm of Earth System Science, with an alternate set of problems, questions and study tools. With the broadening of the science there is increasing attention to a diversity of emergent phenomena that arise in the context of co-evolution of climate, soils, vegetation, and now humans.

Exploring phenomena of all kinds – defined as interesting catchment responses or ecosystem functioning with no obvious or immediate explanation – and asking how they came about, which is the scientific method practiced and perfected over centuries, is increasingly the main focus of most hydrological investigations. Bronowski (1956) describes the majesty of the scientific method in these terms:

> *"All science is the search for unity in hidden likenesses . . . The progress of science is the discovery at each step of a new order which gives unity to what had long seemed unlike . . . For order does not display itself of itself; if it can be said to be there at all, it is not there for the mere looking . . . order must be discovered and, in a deep sense, it must be created. What we see, as we see it, is mere disorder."* -- Bronowski (1956)

Increasingly, in a co-evolutionary context, one can adopt three different kinds of approaches to generate and study phenomena of interest to us. These may be framed as historical hydrology, comparative hydrology and process hydrology. Historical hydrology generates phenomena in the form of emergent dynamics in the time domain arising from time scale interactions. Comparative hydrology generates patterns of catchment responses between different catchments or places. Process hydrology generates patterns at a single place, resulting from process interactions in space (or space-time).

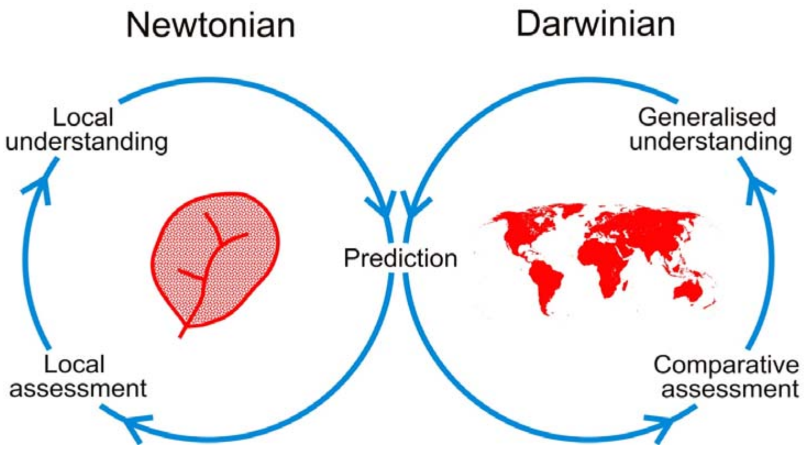

Figure 9. Newtonian-Darwinian synthesis: Relative contributions of Newtonian (learning from individual catchments through detailed studies) and Darwinian (learning from a population of catchments through comparative studies) approaches (taken from Blöschl et al., 2013).

The evolution of the science and the growth of hydrological understanding over the past 50 years have benefited from the use of a combination of Newtonian and Darwinian approaches to address and explore increasingly complex prediction problems and emergent phenomena. The Newtonian approach benefits from the fact that it is based on universal laws of mass, momentum and energy balances, with clear causality. It gains predictive power through advances in observing and understanding processes, and approaches to account for landscape heterogeneity and the resulting complexity of flow pathways and residence times. Yet it loses effectiveness in making general predictions by not being able to fully account for process interactions and feedbacks and parameter co-dependency that manifest in catchments through co-evolutionary processes. The legacy of past co-evolutionary processes in landscapes and their interconnections over long time periods lead to complex emergent spatial patterns and temporal dynamics. So an alternative approach to studying patterns and dynamics arising from such co-evolution is to study many catchments comparatively, treating them as legacies of past co-evolution, which is the Darwinian way. In short, the Newtonian approach generalizes by discovering universal laws governing particular processes through experimentation, inductive reasoning and through mathematical derivations, whereas the Darwinian approach generalizes by recognizing emergent phenomena through comparative analyses across places and then seeking explanations for how they came about (Guo et al., 2014). Of course, Newtonian and Darwinian methods are complementary to each other, and progress in terms of new theories of hydrology and improvements in our ability make future predictions everywhere will require a synthesis of these two approaches (Figure 9) (Harte, 2002; Bloschl et al., 2013).

Crystal balling the future: from comparative hydrology to regional process hydrology

One of the benefits of developing a historical narrative, as I have done here, is that it provides a perspective view (rightly or wrongly) of where we have come from and where we may be (or should be) headed. I will therefore be amiss if I do not use the “crystal ball” that I have created in my mind based on this review to say something about what is in store for hydrology in the coming decade(s). In doing so I stand to benefit from a perspective that has helped me most to organize my narrative: this is the scale perspective. The issue of scale has been at the heart of most of the difficulties hydrologists have had in terms of developing new theories and advancing predictions. If at all we have made any progress in hydrology this may be attributed to advances we have made in addressing scale issues (Blöschl and Sivapalan, 1995; Blöschl et al., 2013). So now, going over the progress we have made in hydrology over the last 50 years (Sivapalan and Blöschl, 2017), one cannot but recognize the change in focus from *time* during the empirical era (Engineering Hydrology), to *space* (Newtonian mechanics) during the process era, and back to *time* (Darwinian comparative hydrology) in the current co-evolutionary era. By induction, this symmetry tells me that even while remaining within the co-evolutionary framework, the next major change in focus is likely to be (or even should be) to go back to *space*, and to *space-time*.

It occurs to me that for far too long we hydrologists (or far too many of us) have focused on catchments as isolated objects, with an exclusive focus on their rainfall-runoff (input-output) transformations. Even in the context of comparative hydrology, we have continued to treat them as spatially distinct and independent objects, even while acknowledging or exploiting their common or similar co-evolutionary history. Clearly this is limiting, in terms of the phenomena that we can explore, and the kinds of predictions we increasingly have to make at larger spatial scales. If we extend the size of the study domain from isolated catchments to a whole region, then in many cases the catchments present within the region have spatial connectivity, as well as a common history. Catchments within a region can be connected to each other in three ways: downwind movement of water in the atmosphere, downstream water movement through surface pathways (e.g., rivers), and subsurface water movement (e.g., regional aquifers) from recharge areas in the mountains towards the ocean, leading to groundwater outcropping in streams, lakes and wetlands, and to estuaries and deltas in coastal regions. In this way there is a continual transformation across the region in the nature of interactions between atmospheric, surface and subsurface pathways of water, producing unique waterscapes. This inexorably takes us into a new field that we might as well call *regional process hydrology*. Just as a single catchment is viewed as a co-evolved ecosystem, owing to the co-evolution of different components (i.e., mountain range, headwater catchments, river network and flood plains, wetlands and estuaries), the *region* too needs to be looked at and managed as a whole ecosystem. An example of such a region satisfying these features is the arid Kaidu-Kongqi river basin in Western China, which is supplied by snow and glacier melt in its headwaters, feeding an extensive oasis and the terminal Bosten Lake, both of which support a thriving agricultural community in the midst of a vast desert (Figure 10). The Kaidu-Konqi river basin, and many others like it around the world (e.g., Indus river basin in present day Pakistan, Cauvery river basin in southern India), have been cradles of human civilization that have waxed and waned as a result of long-term, large scale climatic changes, as well as human alterations of their waterscapes and over-exploitation of land and water resources (Liu et al., 2014). The complexity of water balances and long-term water management problems across such regions cannot be tackled by studying a few isolated catchments.

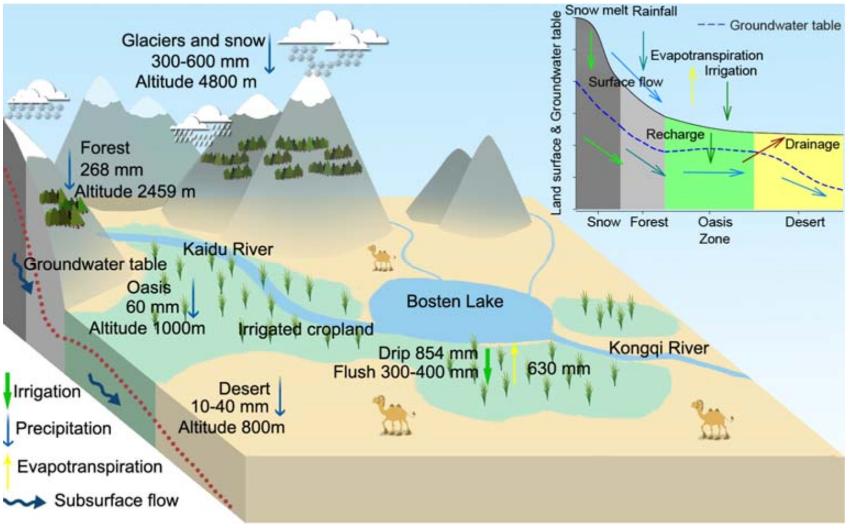

Figure 10: Regional process hydrology: Schematic of the regional hydrologic cycle and waterscape in Kaidu–Kongqi River Basin, part of the much larger Tarim River Basin, Xingjiang Province in Western China (taken from Zhang et al., 2014).

As we begin to look at a region as a whole, this regional outlook opens up new possibilities to advance hydrology, with altogether new emergent phenomena that arise through interactions of the atmosphere, the land surface and the regional groundwater aquifers, including the waterscapes that form as a result. This regional hydrology focus can also bring about the overdue unification of surface (catchment) hydrology with groundwater hydrology, and extensions of ecohydrology and socio-hydrology, to explore interesting, regional scale phenomena. I am not the first one to make the case for regional hydrology, however. Tom Dunne, in his famous Abel Wolman Lecture (Dunne, 1998), called for a renewed focus on research targets at large spatial scales (i.e., regional) that are "of broad significance and might attract sustained interest from scientists in other fields and society at large." There is already much activity in regional process hydrology, that is beginning to bring surface and/or groundwater hydrologists together with atmospheric scientists, with a focus on modeling, large-scale synergistic observations and data-model syntheses (Fan, 2015; Hipsey et al., 2015; Maxwell et al., 2015; Blöschl et al., 2017). Echoing Dunne (1998) himself, my main argument is that we reinforce the focus on phenomena, now large-scale phenomena, and on explanation and discovery, as a prelude to eventual predictions at these scales. The relevant processes of interest occur at all space and time scales, and not limited to just small scales, and emergent phenomena arise out of these multi-scale (space, space-time) process interactions. Both Newtonian (bottom-up reductionist) and Darwinian (top-down functional) approaches and their synthesis retain currency, including the use of coarse-grained models to explore observed phenomena. So this is regional process hydrology that requires a whole system synergistic perspective.

Within the spirit of use-inspired basic science (Stokes, 1997; Thompson et al., 2013) the move towards regional hydrology also coincides with the evolution of the nature of water management problems that will be faced in the emergent Anthropocene. Thompson et al. (2013) presented several examples of anticipated century-scale trends in the main hydrologic drivers that will impact humanity in the future. These emerging future challenges include changing demography (Wagener et al., 2010), warming climate (Vörösmarty et al., 2000), rapid urbanization (Di Baldassarre et al., 2010), changing rainfall variability (Blöschl et al., 2017), loss of freshwater resources due to rising sea levels and saltwater intrusion (Chang et al., 2011), and globalization of water systems through real and virtual water trade (Konar et al., 2016). One can anticipate a range of water-related problems and secondary effects that will emerge in response to these drivers. Increasingly these problems will manifest at regional (and global) scales and can no longer be addressed through the study of individual, isolated catchments. Instead, we need a regional, increasingly global, approach to the study of these problems. Each of these problems is likely draw attention to an array of emergent phenomena that manifest at the regional scale, and associated science questions, which could be the basis for the next major exciting phase of research in scientific hydrology.

The extension of the co-evolutionary perspective in space towards the regional scale takes us further from even Darwinian comparative hydrology (of isolated catchments) to the kind of approach adopted by Alfred Wegener, which eventually led to the discovery of plate tectonics. During his extensive journeys around the world, Wegener evaluated multiple variables (e.g., fossil records, rock types) across several continental regions with which he drew coherent spatial connections across places to support his reasoning on the continental drift (Figure 11). Such an approach becomes feasible in hydrology too with the extraction of spatial patterns of multiple variables (e.g., climate, hydrology, vegetation, animals, people) across large regions, which could then serve as the basis for breakthroughs in understanding of regional water balance, and the co-evolutionary dynamics of climate, soils, vegetation, and human settlements that contribute to the formation of regional waterscapes. Much can be learned from studying spatial teleconnections (especially upstream-downstream) through remote sensing techniques and regional models (Guan et al., 2014), and how they impact and in turn are impacted by human alterations to landscapes and watercourses. Even though much of this is necessarily place-based, unique to particular regions, there is also much that can be transferred to other regions.

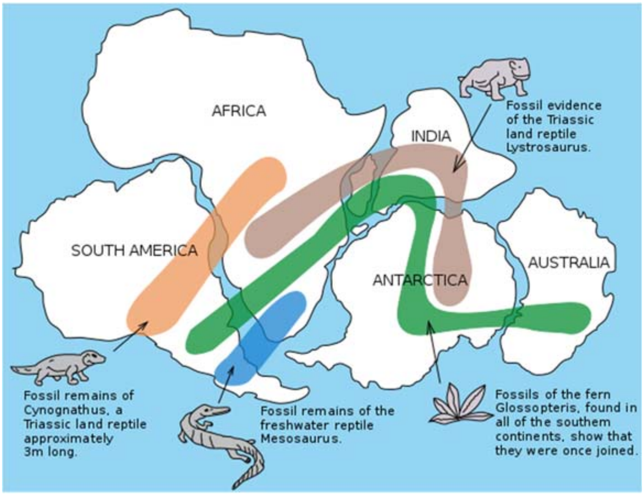

Figure 11: Connecting the dots: schematic describing the fossil patterns across continents that were the basis upon which Alfred Wegener proposed his continental drift theory: https://en.wikipedia.org/wiki/Alfred_Wegener (accessed on October 28, 2017)

Increasingly as the world becomes inter-connected through improvements in communications technology, trade and the movement of people and ideas, along with global teleconnections in the climate system, it is increasingly necessary to go even further and treat the world as a *single* inter-connected system (Eagleson, 1986; Lall, 2014). With the one-world system, anticipated global changes are likely to give rise to yet more complex phenomena manifesting as new and challenging water-related problems at both regional and global scales. This will require a truly global and long-term vision and passion, the type of passion that led Alfred Wegener to discover continental drift and open up the debate that ultimately led to the development of the theory of plate tectonics. Achieving this grand vision will probably take us into what we have called the Globalization Era (Sivapalan and Blöschl, 2017), with a grand synthesis of global hydrology integrated with economics and climate science. These are exciting times to be a hydrologist.

Lessons from Newton, Darwin and Wegener: connecting the dots

This paper being an outgrowth of my Wegener Medal Lecture, I feel duty bound to reflect on the lessons we as hydrologists can learn from the methods adopted by not only Wegener, but also Newton and Darwin, and their contributions to science and the scientific pursuit. The ultimate goal in science is to "connect the dots", i.e., "to find order in disorder" (Bronowski, 1956), which should be the ultimate goal in hydrologic science too. It is in this spirit that Dooge (1986) exhorted us "to look for hydrological laws" and Klemeš (1986) warned against the "dilettantism" that results from failure to distinguish between science and applications of the science and between hydrograph fitting and hydrological understanding. In his paper on "a hydrologic perspective", Klemeš (1988) emphasized the primacy of process understanding over techniques, i.e., the unravelling of the puzzles of the water cycle over technologies adopted to solve societal problems, and warned against defining catchments merely by the different techniques that we might use to analyze them as engineering hydrologists. Regardless of the different methods they may have used, Newton, Darwin and Wegener, were ultimately giants in the art of *connecting the dots*, and we stand to benefit from the legacy they have left behind. Methods come and go, but success depends on us not becoming slaves to the methods but treating them as necessary tools for a higher purpose, i.e., *advancing science through connecting the dots*.

> *"The method-oriented (wo)man is shackled; the problem-oriented (wo)man is at least reaching freely toward what is most important …… willing repeatedly to put aside his(her) last methods and teach him(her)self new ones."* Adapted from: Platt (1964)

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This paper is an outgrowth from the Alfred Wegener Medal Lecture I gave at the General Assembly of the European Geosciences Union in April 2017. I thank EGU for bestowing this honor on me and for giving me the opportunity to publish this paper in HESS. My thoughts on the evolution of hydrology came about through interactions with many students and colleagues over the years. It gained potency through my involvement in three community activities: the Predictions in Ungauged Basins (PUB) initiative, the University of Illinois Hydrologic Synthesis activity, and the Predictions under Change activity, which morphed into the Socio-hydrology movement, and both contributed to the launch of the IAHS Panta Rhei initiative. I am proud of the global hydrology community I served and learned from.

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In closing, I bring up a line from *Kondraiventhan,* an anthology of poems written by legendary Tamil Poetess Avvaiyar, who lived in southern India c. 1000 years ago: it reads:

எண்ணும் எழுத்தும் கண் எனத் தகும்
Numbers (mathematics) and letters (language) are like our twin eyes
(i.e., our windows to the world)

These immortal words of Avvaiyar help me to celebrate the memory of two teachers I had at Hartley College, Point Pedro, Sri Lanka, the high school from which I entered university. Mr S. Ratnasabapathy taught me Mathematics and Mr S. S. Manuelpillai taught English. They both also shaped my intellectual outlook and the way to approach personal and professional challenges. It is not an exaggeration to say that the discipline, persistence and pursuit of excellence they instilled in me continue to guide me more than 50 years after they had taught me.

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