Interactive comment on "From Engineering Hydrology to Earth System Science: Milestones in the Transformation of Hydrologic Science" by Murugesu Sivapalan

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General

I really enjoyed reading Siva's narrative about the transformation of hydrology from an engineering discipline to an earth system science. I also agree with the successive steps and failures that were mentioned: building up case by case from Newtonian Mechanics, looking down at multiple catchments using Darwinian approaches and the way they could be married to arrive at underlying principles and moving from prediction to understanding.

Author's response:

I am delighted to receive this positive and supportive review by Marc Bierkens. I am especially relieved that Marc saw it exactly as I intended the reader to see in my paper.

However, this narrative is somewhat biased towards surface and catchment hydrology. In other hydrological disciplines, concepts and modelling efforts have been tailored to understanding the underlying mechanisms of observed phenomena from the start. This should be acknowledged. This is particularly the case for groundwater hydrology and vadose zone hydrology. Examples of the former are the explanation of macrodispersion by considering flow in a heterogeneous medium (e.g. Gelhar et al. Water Resour. Res., 15, 1387–1397, 1979; Gelhar and Axness, Water Resour. Res., 19, 161–180, 1983). An example of the latter is the explanation of hysteresis of the soil water retention relationship and all its wetting and drying scanning curves by extending Darcy's law with a term that accounts for the change in time of interfacial area between air and water in the pores (Dynamic Effect in the Capillary Pressure–Saturation Relationship and its Impacts on Unsaturated Flow (Hassanizadeh et al., Vadose Zone Journal 2002 1: 1: 38-57). These approaches use Newtonian mechanics and Thermodynamics, but interactions with vegetation have been included more than a decade ago to understand e.g. root growth processes and root water uptake. In fact, the problem in stochastic subsurface hydrology seems to be the reverse: how can these theories designed to understand phenomena be used in practice, i.e. prediction (see e.g. the recent debate on this subject in Water Resources Research: Rajaram, Water Resour. Res., 52, 9215–9217, 2016; and related papers).

Author's response:

I will be the first to admit that my narrative is biased towards surface and catchment hydrology, and so Marc is right here, and I will make a brief clarification on this point in the paper. While it is tempting to respond to the remainder of Marc's comments here, I am afraid such a response

will only cause confusion to the reader of my paper. They may be reserved for a similar historical review of groundwater/vadose zone hydrology by a specialist in these fields. Suffice it to mention that my vision for the future of catchment hydrology includes aspects of vadose zone hydrology and groundwater hydrology included as part of the whole. Notions such as phenomena and understanding take on different meanings in this holistic view, different from the ones Marc mentions.

I will however mention these two examples of phenomena in groundwater transport and vadose zone hydrology in Section 5 addressing a change of focus towards phenomena.

Apart from that, I generally agree with the narrative and the conclusions drawn from it. I have just some additional specific remarks that may provide additional perspectives.

Author's response:

Thank you for these insightful comments. I have addressed them as well as I can, with the only consideration that I do not want to cause distraction to the overall narrative.

Specific remarks
Lines 180-182: Examples of meso-scale distributed models: I think that it is fair to refer to the codes that have been used more extensively at even larger scales and are most well known in the literature: PARFLOW, Cathy and Hydrogeosphere.

Author's response:

OK, I have included some of these, although I did not intend this to be a comprehensive list, only those I know that have been applied to large catchment to regional scales.

Lines 315-330 REW. Despite the examples given at the end of this paragraph, I don't think that REW really took off and is used much in practice. The problem is the estimation of the parameters of the constitutive relationships. These still need to be calibrated and observations are generally lacking to perform this calibration. I feel it is fair to mention this.

Author's response:

This is fair criticism. I thought I mentioned it clearly in the paper, but I have made it even more explicit in my revision. In fact, it is not the parameters, but the constitutive and closure relationships which need to be derived everywhere – this requires an organized effort, barring which people use parameters derived at other (smaller) scales, or continue to use constitutive relationships that are only applicable at the point scale.

Line 484 "If the biological or ecological laws were known: "But are they not known in principle? Just as one should be able to derive Darcy's law from Newtonian mechanics (Navier stokes) and the functioning of a linear reservoir from groundwater theory*, by the same reasoning

ecological laws in the end could be derived from natural selection (with the added complexity that individuals are able to influence their own environment). If this is indeed the case, then with sufficient computational resources and individual-based ecosystem models we could derive these laws for catchments in different climates and geological settings by exhaustive simulation.

*I refer to much earlier work from Kraaijenhoff and van de Leur (1957) and De Zeeuw (thesis, 1966) on solving the linear Boussinesq equation showing when a groundwater reservoir response is linear –> for later times after rainfall and always if stream entrance resistance is high).

Author's response:

Thank you for these queries, and there is a lot to unpack here. First of all, in my view the kind of simplicity that one finds when one can describe a groundwater aquifer as a linear reservoir, does not come about by some kind of mathematical manipulation of some governing equation for homogeneous systems. The simplicity is potentially a result of the heterogeneity of the aquifer and history of how the heterogeneity may have come about, which is traced back to the co-evolution of the system. My argument is that if one looks at the system in more holistic ways, then one may find a simpler theory to describe the phenomenon. I am convinced that the practical solution is through recourse top-down data based discovery at the scales of interest to us (i.e., catchments), and the old-fashioned scientific method, not the bottom-up simulation way Marc is suggesting.

Lines 645-646: It seems that the large number of modelling approaches is perceived as a problem in Hydrology. But why? Let's compare this to the field of ecology. Here, we also have a plethora of modelling approaches and partial theories used to explain a huge diversity of interacting life forms. The underlying theory in the end is evolution (diversification by mutation and crossing and selection). This insight has been around for a long time, but it has not stopped ecological model and theory development, because at ecosystem scale, emergent phenomena can be better explained with macroscopic models. The latter is also not perceived as a problem in ecology.

Author's response:

In catchment hydrology, this question is connected to the age old debate between *uniqueness of place* and *generality of place*. Juxtaposition of Newtonian mechanics/thermodynamics on the one hand and evolution on the other dictates that reality is in the middle somewhere. So in this sense, plurality of modeling approaches is entirely appropriate (as we also decided during the PUB initiative), which I reinforced in this paper. Yet, it is a problem if we decide on a unique model for every catchment – because it works against unification of the field. This is why there is so much focus on hydrologic similarity, so that it can help us to find common models and modeling approaches for hydrologically similar catchments. This is probably similar in ecology as well. I believe that this is already well articulated in the paper so I decided not make a specific change in the revised manuscript.

Lines 882-884. The Darwinian approach to discovering underlying principles or laws. But in truth: what other laws than Newtonian mechanics, thermodynamics and evolution theory will we need to explain observed phenomena?

Author's response:

At a fundamental level, yes, I can agree that Newtonian mechanics, thermodynamics and theory of evolution is all that underpins all of science. But then this is true of all science – the only question is how do we adapt or use these to benefit us in hydrology, at the scales of interest to us. There is still a lot of freedom of choice and also limitations by the scale of observations, the information and data we have available to us, and practical considerations such as the need for predictions. I could not find a way to include this point without confusing the reader, so in the end I did not make a change to the text. Hope this is OK.

Lines 1015-1017: Horton's statement. This is indeed a good foresight that can also be explained from ecological niche theory: In case of shortage, any water that cannot be used by the prevailing species is likely to be used (forms a niche for) other species that can use it.

Author's response:

This is an interesting observation, even though this is beyond the scope of the paper. I have added a note to make a connection to ecological niche and niche construction theories in ecology, for the benefit of readers who may go into this in more depth.

Lines 1030-1032. The optimality principle. I find this questionable as a general principle and it has not been embraced by ecologists for a reason. The optimal vegetation is the one that over the long run has the highest probability of survival. In functional ecology this is better explained in terms of optimal traits (leaf form, stomatal density, color, size) of which size (maximal carbon gain) is but one.

Author's response:

I completely agree. Maximization of net carbon profit is only presented here as an example. I have clarified this point now without going into more details, as it might be distracting to the overall storyline.

Lines: 1059: Humans as intrinsic part of the catchment's cycle: if humans are considered, the catchment is not the most natural unit of description anymore. It is the overlay of river basin (regional size catchments – as also confirmed hereafter) and administrative (or governance) units that are of interest. Different impacts are also in different parts of the basin: land use change and dam building in the upper reaches; water abstraction in the middle and lower reaches.

Author's response:

This is a very good and important point. I overlooked to mention it in the paper, an error I will now rectify. The more general point that with the inclusion of humans and their interferences in the water cycle, traditional definitions of catchment boundaries and movement of water must give way to include human oriented administrative units and transfers of water through human generated water conduits (including virtual water transfers).

Figure 7 and the arguments explaining the differences between natural and human influenced water ecosystems: I am not wholly convinced that this is universally true. It may well be a time-scale thing. If we look at a natural ecosystem, it is often evolving (in succession) where pioneers are eco-engineers making the bare soils suitable for other species to move in that in the end outcompete them. Sometimes, even lock in occurs. Think about birch trees in marshes that establish themselves during relatively dry periods and due to their evaporation are able to keep water tables deep enough for root aeration to occur even in wetter years. However, if some of the trees die (because of old age or two consecutive very wet years) creating a holes in the canopy, groundwater recharge may suddenly increases tremendously causing all the trees to die as a result of it (Brolsma et al., Ecological Modelling, Volume 221, Issue 10, 24 May 2010, Pages 1364-1377, 2010). So, vegetation may obey optimality principles on long time scales (or in climax state), but not on smaller time-scales. Reversing the argument, one might view the non-optimal or detrimental (lock-in) interactions of humans with their environment temporary and expect human-water systems at longer time scales to also show signs of optimality.

Author's response:

I presume that Marc is raising this point as a matter of principle, and I too agree in principle, and I have made a brief note in the revised manuscript. However, there is going to be a lot of argument and disagreement, and I reproduce a quote from an earlier paper by Sivapalan and Blöschl (2015) on the analogy to the vexed disagreement between stochasticity and determinism, and a useful quote from Kolmogoroff: ''*The possibility of using, in the treatment of a real process, schemes of well determined or of only stochastically definite processes stands in no relation to the question whether the real process is itself determined or random''* [Kolmogoroff, 1931, p. 417]. *Clearly, whether human behavior is random (irrational) or deterministic is not a scientific question. Rather it is a pragmatic modeling choice that will (usefully) depend on whether we see clear patterns with the amount of information available. Coevolutionary models may therefore account for human behavior by a stochastic treatment.*"

Lines 1126-1128: being Dutch I cannot resist to point out a more recent historical example of this lock in. I am referring to the famous Dutch polders. Many of the low lying areas in the Netherlands are the result of draining peaty soils (since the 11th century) which resulted in land subsidence and subsequent further lowering of the groundwater level to keep the soils dry leading to further subsidence etc. The result is 30% of the country lower than sea-level. An interesting by-product is the invention of Gouda cheese. The low-lying areas were only suitable for dairy farming. To save the excess milk for winter time, cheese was made out of it (see:

Erkens, G., van der Meulen, M.J. & Middelkoop, H. Double trouble: subsidence and CO2 respiration due to 1,000 years of Dutch coastal peatlands cultivation. Hydrogeol J (2016) 24: 551. https://doi.org/10.1007/s10040-016-1380-4).

Author's response:

Thank you for very much for this observation. It is an excellent example of a "lock in" phenomenon. I have included it in the text, since the concepts of lock in or path dependence are more easy to understand through this example.

Line 1301: regional hydrology. It seems you mean that the river basin would be the object of study. This is the old focus of classical Physical Geography, studying earth surface processes and their interaction with the atmosphere, the subsoil and life (including man) from sink to source, from the mountains to the sea, from headwaters to the delta.

Author's response:

I agree with this point, but want to highlight three subtle differences. Firstly, the title I used was regional process hydrology (not just regional hydrology). Secondly, the scale here is larger than the river basin, a region that represents the land area between the mountains (water towers) and the oceans at the downstream end. Thirdly, I argued for recognition of phenomena at this scale and their interpretation/explanation in terms of regional scale processes and process interactions and feedbacks. My argument is that the scale of interest of catchment hydrology must expand to include regional scale processes. I have added test to bring this out better.

Lines 1365-1366 future earth system hydrology: The crystal ball of Bierkens (2015) came to a similar conclusion.

Author's response:

Thank you for reminding me of this paper. I will now cite this reference to add strength to my argument.

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

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Based on the 2017 Alfred Wegener Medal Lecture, presented on April 26, 2017, Vienna, Austria

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 find 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 admittedly narrow prism of my own observations and experience as a catchment hydrologist, 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

86 frequency curve approach to flood estimation (Linsley et al., 1958). The focus of the training was
87 on estimation, especially flood estimation (event scale, recipe style) and the approach was
88 lumped and empirical. Compared to now, these were relatively much simpler problems, framed
89 directly at the catchment scale, and formed the *bread and butter* of engineering hydrology, not
90 just in Sri Lanka, but all over the world. The three building blocks of engineering hydrology were
91 indeed legacies of three different previous eras in the growth of the field up until the 1970s
92 (Sivapalan and Blöschl, 2017): empirical era (flood frequency analysis), rationalization era (SCS
93 curve number method) and systems era (unit hydrograph method). These methods remain
94 relevant to this day, very much the core of engineering hydrology, judging by the popularity of
95 advanced textbooks such as Chow et al. (1988), which is still widely used for the training of
96 hydrologists in engineering schools.
97
98 For some of us who have received training in mechanics – solid mechanics, fluid mechanics, soil
99 mechanics etc. – the hydrology being taught and practiced using the traditional estimation
100 methods might have appeared strange and even mysterious. In the early days, I remember being
101 frustrated that I could not make much physical sense of the cookbook treatment of the hydrologic
102 estimation process, unable to connect it to fundamental fluid mechanics principles. Yet, there
103 was also wide appreciation for these otherwise simpler methods that efficiently solved practical
104 problems of that day and age. In fact, even today's standard engineering practice would still be
105 impossible without these simpler approaches.
106
107 There was also a profound fascination. How is it possible that something so inherently complex,
108 as hydrology is, still comes out as so simple (apparently) in practice? Over the years, there was a
109 grudging realization that perhaps hydrology is more than about fluid mechanics (Yevjevich, 1968).
110 Indeed, the search for simplicity in amongst the enormous mechanistic complexity has been a
111 constant theme in hydrologic research over the last 50 years (Rodriguez-Iturbe and Valdes, 1979;
112 Sivapalan, 2003; Savenije, 2017). The answer to this question, we now know in hindsight, is tied
113 up with the issue of scale (both space and time) and the objects of our study, catchments, being
114 not simple physical (or mechanical) objects but complex ecosystems (Gaál et al., 2012), consisting
115 of component parts that have co-evolved together over time, and are thus co-dependent (Dooge,
116 1986; Davies, 1992). I return to this theme throughout this paper.
117
3. Spatial heterogeneity and scale: promise of Newtonian mechanics
119
120 While the simple black box methods of engineering hydrology did solve practical problems
121 efficiently, they had limitations when extrapolating to circumstances beyond those from which
122 they were developed. For example, what is the effect of antecedent wetness on runoff
123 generation (Mein and Larson, 1973)? How does one account for the nonlinearity of catchment
124 response to the size of rainfall events (Minshall, 1960)? How does one deal with the climatic and
125 geologic controls when extrapolating flood frequencies to ungauged catchments (IACWD, 1982)?
126 Also, new and more complex problems were emerging, such as the effects of land use changes
127 on streamflows and flooding, and increased concerns about river water quality, which demanded
128 application of more process physics (Woolhiser, 1973). There was increasing realization that only

129 a recourse to fluid mechanics and process physics will help address such questions, bring about
130 needed improvements to the methods and make them applicable more generally.

131

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

146

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

153

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

165

166 ***Heterogeneity: To resolve or to parameterize?***

167

168 The Freeze and Harlan modeling paradigm has remained in force to this day, and several formal
169 models have been developed based on the paradigm, such as the SHE model and variants of the
170 same (Abbott et al., 1986). Due to data limitations and limits on computing power, early modeling
171 efforts were restricted to small catchments, and their goal was limited to generating process
172 understanding, and not so much to make predictions in real catchments (Stephenson and Freeze,

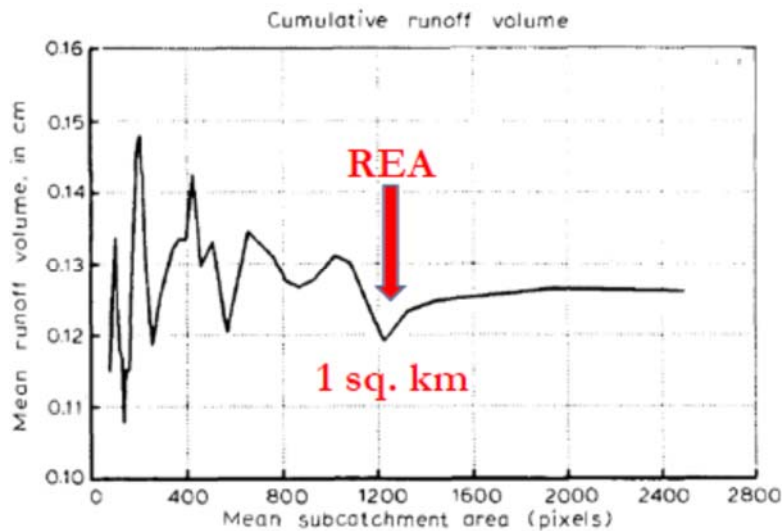
173 1974; Freeze, 1974). Their adoption and use in real world applications did not take off for a long
174 time because of their enormous data needs and insufficient computing power and also concerns
175 about the appropriateness of the process physics that could be included in the models at the
176 model element scale (Beven, 1989; Beven and Germann, 1982; Grayson et al., 1992).

178 As computing power increased many-fold and the landscapes began to be mapped at increased
179 resolution for soil, vegetation and topographic characteristics in many parts of the world, there
180 has been a revival of sorts in recent times, with several models being developed and beginning
181 to be applied to *larger* (e.g., meso-scale) catchments using more realistic data. Some (of the
182 many) examples include ParFlow (Kollet and Maxwell, 2008), FIHM (Kumar et al., 2009), PAWS
183 (Shen and Phanikumar, 2010), and HydroGeoSphere (Brunner and Simmons, 2012). These
184 modeling efforts are expanding and I will not be surprised if, before long, such models are used
185 not just to reproduce field observations but also, as in the case of Freeze (1980), to discover and
186 explain previously unobserved phenomena.

188 In recent times, as part of climate change studies, modeling has been extended to continental
189 and global scales to serve as the land-surface hydrology components of regional or global climate
190 models. Because of the large scales, spatial resolution of these models in the past tended to be
191 very coarse, of the order of hundreds of kilometers (e.g., bucket model, Manabe, 1969).
192 However, progress is continually being made to improve the resolution from hundreds of
193 kilometers to hundreds of meters, helped along by increased computational power and
194 availability of terrain information at finer resolutions (e.g., Community Land Model, Oleson et al.,
195 2013). There is now a new thrust to improve the resolution of these models to 30 m for the whole
196 globe (note: 30 m is the resolution of terrain information globally available), under the theme of
197 "hyper-resolution modeling" (Wood et al., 2011; Bierkens, 2015; Wing et al., 2017). Concerns and
198 debates about the appropriateness of the physics used in these models, including the
199 appropriateness of constitutive relations being used (Loritz et al., 2017), and the resulting
200 uncertainty in predictions, have not gone away, however (Clement, 2011; Beven and Cloke, 2011;
201 Wood et al., 2012).

203 An ostensible reason for going for finer resolution, is of course, since now we can do it, i.e., with
204 data availability and computing power, why not, and also since the benefits of hyper-resolution
205 modeling for both science and practice are increasingly becoming evident. For example, hyper-
206 resolution models over regional or continental scale domains can track large-scale storm
207 movements and the resulting impacts at scales relevant to human wellbeing, as well as generate
208 insights about the large-scale teleconnections between or within regions (Senatore et al., 2015;
209 Fang and Shen, 2017). A more immediate reason, however, is that as one improves the
210 resolution, the (fervent) hope is that all heterogeneity will disappear and the governing equations
211 used will match the spatial scales of the processes one is trying to model (e.g., Clark et al., 2015,
212 2017; Peters-Lidard et al., 2017). In reality, of course, field evidence has strongly indicated that
213 the heterogeneity does not disappear even if one goes to finer scales, and there is a limit to how
214 far we can split the landscape to achieve any desired level of homogeneity and still maintain a
215 continuum (Beven, 1989; Blöschl and Sivapalan, 1995). Besides, the presence of macro-pores and
216 other preferred pathways (Beven and Germann, 1982), and explicit treatment of runoff

217 phenomena involving concepts such as the "old water, new water" concept (McDonnell, 1990),
218 present major challenges to traditional continuum representations of water movement on and
219 particularly below the land surface based on Newtonian mechanics alone (Beven, 2006). One
220 therefore reaches the alternative conclusion that, whatever grid scale one chooses, there is no
221 alternative but to parameterize the effects of any remaining heterogeneity at the sub-grid scale.
222
223 The end result for spatially-distributed, physically-based models of catchment hydrology is that
224 model development has been caught between two temptations (Hrachowitz and Clark, 2017): 1.
225 split the landscape more and more down to the continuum (hydrodynamic) scale so that
226 heterogeneity disappears as an issue (i.e., heterogeneity is completely resolved); 2. aggregate to
227 some scale at which the effects of heterogeneity are taken care of through simplified treatments
228 with process parameterizations that can account for the effects of all sub-grid heterogeneity.
229 Advancing technological capability and increased process knowledge at small scales are the
230 drivers towards the former option (Wood et al., 2011). Appreciation of scale effects, including
231 expectation of simplicity through averaging (Sivapalan, 2003), concerns about predictive
232 uncertainty (Beven and Cloke, 2011), and about the domination of techniques and other quick
233 fixes (e.g., model-data assimilation) over the important search for hydrological understanding
234 (Klemeš, 1986), are the key drivers towards the latter option. The issue of heterogeneity is not
235 unique to hydrology, and applies to all environmental sciences, and approaches to mediate these
236 alternative perspectives may draw inspiration from a quote from ecologist Simon Levin (1992):
237
238 *"To scale from the leaf to the ecosystem to the landscape and beyond . . . we must*
239 *understand how information is transferred from fine scales, and vice versa. We*
240 *must learn how to aggregate and simplify, retaining essential information without*
241 *getting bogged down in unnecessary detail. The essence of modeling is, in fact, to*
242 *facilitate the acquisition of this understanding, by abstracting and incorporating*
243 *just enough detail to produce observed patterns. . . the objective of a model should*
244 *be to ask how much detail can be ignored without producing results that contradict*
245 *specific sets of observations, on particular scales of interest".* ….. Levin (1992).
246
247 Levin's (1992) is an argument for "coarse graining", i.e., to formulate models with only the
248 necessary degree of complexity, and an argument against attempting to resolve the enormous
249 heterogeneity and complexity of hydrologic processes at progressively smaller time and space
250 scales, which is echoed by hydrologist Thomas Dunne as well (Dunne, 1998).
251
252 ***Organized heterogeneity and preferred space scales: REA***
253
254 Inspired by the organization that nature exhibits around a hierarchy of spatial scales, i.e.,
255 hillslope, catchment, region etc. (Blöschl and Sivapalan, 1995), there have been concerted efforts
256 to identify whether a characteristic space scale, which reflects the spatial organization and can
257 thus serve as the building block of distributed models, exists in catchment hydrology. This idea is
258 similar to the continuum or REV concept used in groundwater hydrology with some degree of
259 success (Bear, 1972; Hassanizadeh and Gray, 1979). The argument has been that aggregating the
260 governing equations or process descriptions to this building block scale might lead to simplified

261 (effective) lumped or continuum treatments, thus avoiding the need to split the catchment into
262 smaller elements to capture the effects of heterogeneity. This way of thinking reflects the long-
263 standing conviction, supported by observations, that in spite of the enormous complexity of
264 hydrologic processes in landscapes, catchment scale hydrologic responses can often be described
265 by simpler models with only a few parameters (Jakeman and Hornberger, 1993; Sivapalan, 2003).
266 Dooge (1986) has argued that catchments are complex systems with some level of organization,
267 and "simplicity out of complexity" is a useful property of such complex systems (Davies, 1992).
268 When one opts for the parameterization approach inspired by this reasoning, one still needs to
269 know the key features of the underlying heterogeneity, e.g., their statistical distributions or
270 organizational structure (not necessarily the actual observed patterns). Furthermore, we also
271 need to have information about cross-scale process interactions that might lead to the simplicity
272 we desire (Hassanizadeh and Gray, 1979), and utilize efficient approaches to incorporate them in
273 models through appropriate model structures and parameterizations (Zehe et al., 2014).
274

275
276
277 **Figure 1.** Mean event runoff volume as a function of mean subcatchment area (for the case of
278 variable topography but uniform soils and precipitation). Taken from Wood et al. (1988).
279
280 Motivated by this reasoning, Wood et al. (1988) pursued this question in the context of runoff
281 generation responses at the catchment scale. On the basis of spatial averaging of numerical
282 simulation outcomes from a distributed rainfall-runoff model of hypothetical catchments, Wood
283 et al. (1988) postulated that such a spatial scale could exist, which they called the representative
284 elementary area (REA), and estimated its size to be about 1 km^2 (Figure 1). Subsequent field
285 observations and simulations in New Zealand and Germany supported the idea with some
286 reservations and further refinements (Woods et al., 1995; Didszun and Uhlenbrook, 2008). The
287 claims about both the existence and size of the REA have been questioned by others, based on
288 perceived limitations of the averaging approach used to resolve these questions (Fan and Bras,
289 1995; Blöschl et al., 1995). A further limitation of the REA of Wood et al. (1988) is that it focused
290 on surface runoff volume, and not its timing. Robinson et al. (1995) explored the change of
291 dominant controls on runoff timing (e.g., hydrograph dispersion) with increased catchment area,

292 and showed that the scale at which the dispersion is maximally reproduced can be affected by
293 whether (fast) surface or (slower) subsurface runoff pathways dominate. The significance of the
294 existence of the REA, whatever its size, is that it is small enough to still account for relevant spatial
295 hydrological variations, and yet large enough to avoid the overwhelming data and parameter
296 needs of small scale (distributed) models. As a result, despite the reservations, the notion of using
297 a representative watershed scale as the building block towards the development of distributed
298 models (now at a sub-catchment scale) has remained as a working hypothesis for organizing our
299 thought processes in respect of modeling.
300
301 Inspired by the possibility that adoption of such a representative scale might lead to simplified
302 yet physically based hydrologic prediction models, Reggiani (1999) developed a new theory of
303 hydrology around this building block, now named the representative elementary watershed or
304 REW, which accounts for some of the limitations of the earlier REA concept. Reggiani's theory
305 was expressed in the form of balance equations for mass, momentum, energy and entropy
306 written down directly at the scale of the REW (Reggiani et al., 1998), and an accompanying
307 constitutive theory (Reggiani et al., 1999) to ensure the theory gives rise to a determinate set of
308 governing equations. Subsequently, Zehe et al. (2006) derived soil moisture characteristic (i.e.,
309 constitutive) relationships at the REW scale through the upscaling of corresponding point scale
310 observations. Likewise, Lee et al. (2007) developed a set of closure relations for the many
311 boundary fluxes for the catchment system – between different REWs and between different sub-
312 regions within each REW – again, to account for the effects of sub-grid heterogeneity and process
313 complexity, thus helping to complete the specification of the governing equations representing
314 the catchment response.
315
316 The net advantage of the REW approach is that it ends up with the solution of a system of coupled
317 ordinary differential equations (as opposed to a system of partial differential equations, which
318 one obtains if they were to split a catchment into rectangular or triangular elements). Both Tian
319 et al. (2006) and Lee et al. (2007) developed numerical schemes to solve these governing
320 equations, thus forming a new generation of models based on the REW approach that parallel
321 distributed models based on rectangular or triangular finite elements following the Freeze and
322 Harlan paradigm. In this way Tian et al. (2006) and Lee et al. (2007) have contributed to a new
323 class of models of intermediate complexity, resolving processes occurring at scales larger than
324 the REW scale, and parameterizing those happening at smaller scales (Beven, 2012). Their
325 potential as a new modeling framework has also been highlighted through several applications.
326 For example, models based on the REW approach have been applied to real catchments,
327 generating space-time predictions of the rainfall-runoff response for catchments in Australia
328 (near Darwin, Lee et al., 2007) and in Oklahoma in the United States (Li et al., 2012; Tian et al.,
329 2012). In recent years, these models have been extended to make distributed predictions of
330 sediment and nutrient transport and export at the catchment scale and across the corresponding
331 stream networks (Patil et al., 2013; Ye et al., 2012). In spite of this, it should be noted that the
332 REW approach has still not taken off as would be expected, due to the lack of progress in the
333 development of constitutive and closure relations to account for the effects of sub-REW
334 heterogeneity and process complexity; this is discussed next.
335

4. Catchments as ecosystems: Limits of Newtonian mechanics

In spite of its promise and the 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.

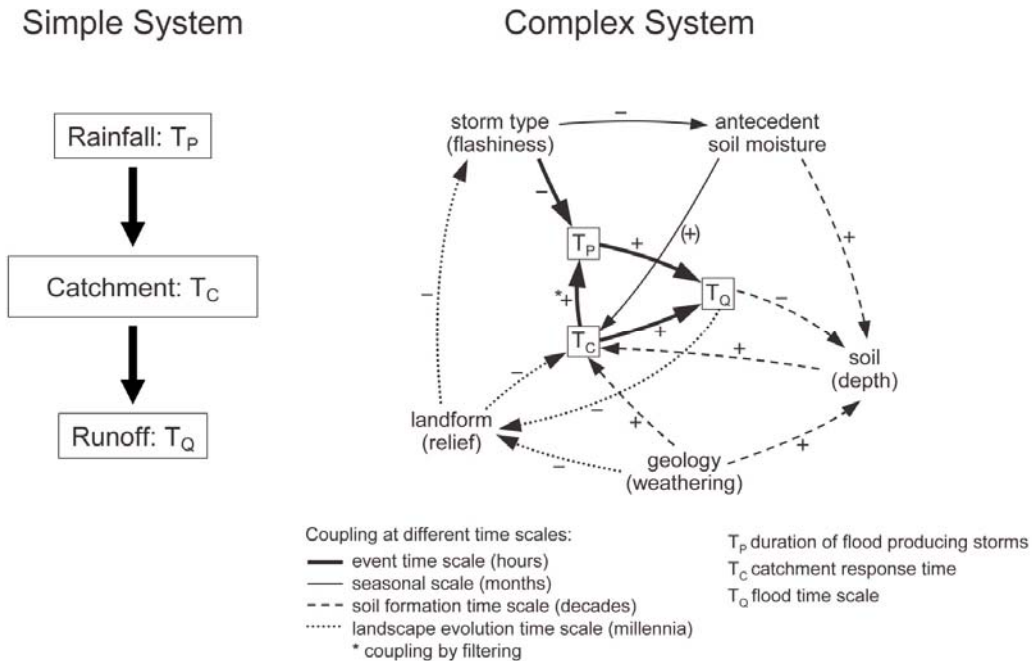



Figure 2. Simple and complex system representations of time scales contributing to floods. Interactions of multiple time scales makes the response an emergent outcome of a complex system. Taken from Gaál et al. (2012).

364 The most obvious example of a catchment subsystem that evolves dynamically is vegetation,
365 which is directly involved in the crucial process of evapotranspiration. Vegetation adapts itself
366 dynamically over multiple time scales in response to changing climate and hydrology, even as it
367 has an impact on the hydrology. Also, over much longer time scales it can modify the
368 environment around it (e.g., soil structure, macro-pores and topography, to name a few). In this
369 way the temporal dynamics of vegetation can also indirectly impact runoff generation processes.
370 As well as evolving with the dynamic hydrology, such biologic activity renders the system even
371 more internally dynamic. The adaptations of vegetation and their modifications of landscapes
372 may be governed by biological or ecological processes, and cannot be captured by universal
373 descriptions based on Newtonian mechanics that focus on flow processes alone; presently their
374 effects on flow can only be described by empirical, place-based relationships. As in the case of
375 spatial upscaling problems discussed before, it is always tempting to ask the question whether
376 the *temporal* organization of a catchment's hydrologic response, arising from vegetation
377 adaptations to the multi-scale temporal variability of climate and hydrology, and the resulting
378 landscape modifications, could also be averaged to produce a simplified description of catchment
379 response. This question is explored next by highlighting different examples of vegetation (and
380 even landscape) adaptations to natural climate variability and hydrology.
381
382 ***Adaptation Strategies by Vegetation***
383
384 Understanding vegetation adaptation processes is a rich and multifaceted problem, but here I
385 will use examples from my own modeling experience to illustrate the point about simplicity in
386 spite of complexity, and how this might arise as a result of vegetation adaptations. Many existing
387 catchment models, including the ones mentioned before, approximate evapotranspiration rates
388 by vegetation (e.g., forests, grasses etc.) as if they function like agricultural crops, i.e., they
389 transpire at a potential rate (e.g. potential evaporation) when the soil is wet, and reduce their
390 evapotranspiration rate when soil moisture falls below the saturation value. In reality, this is not
391 normally the case under native vegetation, and such approximations can lead to serious
392 discrepancies since evapotranspiration is a large fraction of annual water balance in most places
393 around the world (Sivapalan et al., 1996; Thompson et al., 2011a). This was highlighted in the
394 Darling Range region of south-west Western Australia during field experiments carried out by
395 Silberstein et al. (2001).
396
397 South-west Western Australia experiences a strong Mediterranean climate, with warm dry
398 summers and cold wet winters. Field measurements made by Silberstein et al. (2001) in a
399 forested catchment in this region showed that daily evapotranspiration rate (bare soil
400 evaporation plus transpiration) was roughly 2.5 mm per day during a 2-week period in the wet
401 winter part of the experiment. Remarkably, when the experiment was repeated 6 months later
402 during a 2-week period following a very dry summer, the evapotranspiration rate turned out to
403 be very much the same, about 2.5 mm/day every day. The assumption that trees, like agricultural
404 crops, might reduce their transpiration rates during dry periods (due to their experiencing water
405 stress) was found not to be the case. It turned out that native Eucalyptus trees in this part of
406 Western Australia have adapted to the strong seasonality effects (hot dry summers and cold wet
407 winters) by growing dynamic deep roots that tap into a groundwater aquifer that is over 30 m

408 deep. Indeed, it was found that tree roots remained always in contact with the deep water table
409 even when the latter fluctuated between summer and winter and between years. The net result
410 is an apparently constant transpiration response by the vegetation, i.e., 2.5 mm per day every
411 day!
412
413 In a subsequent study at a site near Darwin, in Northern Territory, Australia, Schymanski (2007)
414 reported an altogether different response by native vegetation. This area experiences a monsoon
415 climate, with a wet four-month period of heavy monsoon rains, followed by 8 months of dry
416 (non-rainy) conditions. Being tropical, potential evaporation is uniformly high during both
417 periods. Water table is present at a depth of about 10 m all year. Schymanski reported that
418 measured total evapotranspiration rate followed the variation of soil wetness, regardless of the
419 energy available, i.e., potential evaporation (Schymanski, 2007). However, the adaptation
420 strategy by the prevailing vegetation was different. In Darwin, the more permanent, deep-rooted
421 trees tap into the groundwater table, just as in Western Australia, and were found to transpire
422 at a rate of 1 mm/day all year, regardless of surface soil moisture. However, in addition, during
423 the wet season, a dense under-story of grasses developed which, like crops, transpire at rates
424 proportional to the surface soil moisture: a peak of 2.5-3.0 mm/day during the wet season,
425 decreasing as the soil dries during the subsequent dry season, and dropping to negligible values
426 as the grasses completely senesce and dry out. Once again, a slightly more complex, yet almost
427 predictable transpiration pattern that arises via complex adaptation strategies adopted by the
428 vegetation to the climate and hydrology.
429
430 Two different places, two different adaptation strategies by vegetation that developed in each
431 setting, permitting a simplified transpiration pattern. In both cases, the strategies used by the
432 vegetation are different from what is normally assumed for agricultural crops. This raises two
433 issues: if one wants to develop a predictive model of evapotranspiration for a specific place, then
434 the adaptation strategy adopted by vegetation locally must be known *a priori*. Newtonian theory
435 by itself cannot predict the adaptation strategy one is likely to encounter in a given place, which
436 may be governed by (as yet unknown) biological/ecological laws. The adaptation strategy
437 adopted by vegetation would be relatively easy to determine, given the kind of observational
438 evidence used by Silberstein et al. (2001) or Schymanski (2007). Few places would have that kind
439 of field evidence, however. In a catchment context, many more places will have rainfall-runoff
440 data only, from which the adaptation strategy adopted by vegetation may have to be inferred
441 (with a lot more ambiguity, given the kind of data, especially the absence of evapotranspiration
442 data). The fact that prevailing vegetation in different places may use different adaptation
443 strategies also opens the way for much freedom or pluralism in the development of predictive
444 models, as opposed to a universal model that would be expected out of Newtonian mechanics.
445

446 ***Ecosystem function and data based inference***

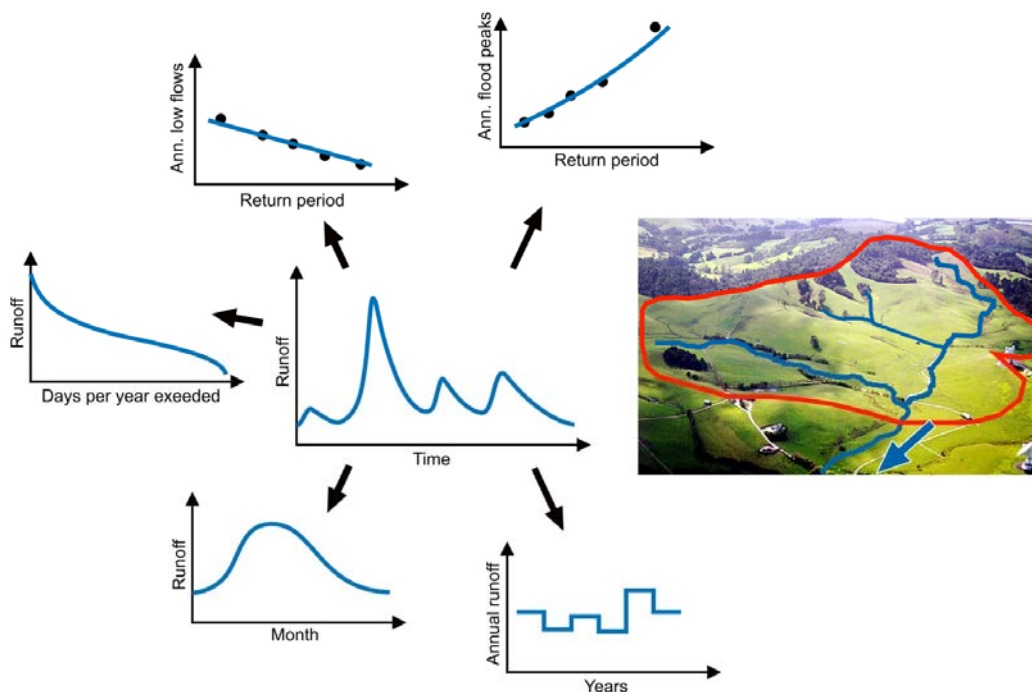
447
448 A key observation from the last section is that the dynamics of evapotranspiration is intimately
449 connected to that of vegetation adaptation. We can broaden this argument to include other
450 catchment responses as well, such as runoff. We are used to treating runoff generation as a
451 physical process, governed by Newtonian mechanics (Larsen et al., 1994). This presumes that we

452 know *a priori* what mechanism of runoff generation dominates in a given place. However,
453 Newtonian mechanics alone may not be able to determine the dominant runoff generation
454 mechanism in any given place. Based on field evidence Dunne (1978) provided a perspective on
455 climate, soil, topography and vegetation controls on the dominant runoff generation mechanism,
456 popularly known as the Dunne diagram. To this day, the Dunne diagram has continued to defy
457 explanations based on Newtonian mechanics (Larsen et al., 1994; Li et al., 2014). Vegetation
458 adaptation may again be the underlying cause of this phenomenon, e.g., vegetation perhaps
459 adapting itself and adapting the environment around it (i.e., soils, topography) in such a way that
460 it can retain soil moisture longer in arid environments and drain water sooner in wet
461 environments. Also, forest soils are known to have higher surface infiltration capacities, which
462 impact the stormflow response. Thus, "forest" vegetation type becomes a parameter linked to
463 infiltration and runoff generation, as well as to evapotranspiration.

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

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

494 Wittenberg and Sivapalan (1999) presented an interesting and insightful implementation of the
495 data-driven inference idea. They performed diagnostic analysis of rainfall-runoff data in several

496   catchments in Western Australia (WA). This first involved analysis of streamflow recessions (i.e.,
497   following the end of individual rainfall events) in different times of the year, and in WA's seasonal
498   climate, attributing differences in the slopes of the recession curve to changing
499   evapotranspiration (ET). This made it possible to back-calculate ET from the recession curve
500   slopes, and thus piece together a simple groundwater balance model for the catchments. This
501   approach to data-based inference was later extended by Kirchner (2009) to UK catchments,
502   calling it "doing hydrology backwards". In both cases, however, the power of the approach owed
503   it to the apparent simplicity of the hydrologic response manifesting at the catchment scale,
504   resulting from the spatial organization and temporal adaptation of the catchment ecosystem to
505   the prevailing climatic variability.
506
507   Following the lead of Wittenberg and Sivapalan, Jothityangkoon et al. (2001) and Atkinson et al.
508   (2002) extended the data-based inference idea further by treating the catchment's observed
509   rainfall-runoff response as a reflection of its ecosystem functions (i.e., partition, storage,
510   transmission and release) manifesting themselves differently at different time scales. They
511   assumed that the ecosystem functions are reflected collectively in several runoff signatures (i.e.,
512   patterns extracted from streamflow data at different scales), through which it was assumed the
513   catchment reveals its internal dynamics or functioning (see Figure 3). These streamflow
514   signatures, e.g., the regime curve (monthly time scale), flow duration curve (daily), flood
515   frequency curve etc. are thus seen as outward manifestations of internal ecosystem functioning,
516   and are therefore deemed emergent (temporal) patterns.
517

518
519
520   **Figure 3.** Runoff signatures deemed emergent patterns reflecting the functioning of the
521   catchment ecosystem. Clockwise from bottom right: annual runoff, seasonal runoff, flow
522   duration curves, low flows, floods and runoff hydrographs. Taken from Blöschl et al. (2012).

523

524 The functional insight and the realization that catchment responses can show organization along
525 time scales gave rise to a new approach to the modeling of catchment rainfall-runoff responses,
526 called the top-down or downward approach (Klemeš, 1983; Sivapalan et al., 2003). We might also
527 call it the functional approach, following Black (1997). This modeling approach is diametrically
528 opposed to, but complementary with the bottom-up or upward approach to model development
529 based on Newtonian mechanics (Klemeš, 1983), an example of which is the REW approach of
530 Reggiani et al. (1998, 1999) discussed earlier. The idea behind the downward or functional
531 approach is to develop models step by step, but starting at long time scales (e.g., the annual time
532 scale, as in the case of Jothityangkoon et al., 2001). Once a simple (simplest possible) model is
533 developed that reproduces the runoff signature at the annual scale, i.e., inter-annual variability,
534 one then moves down to the monthly time scale, and adds just enough functional complexity to
535 the model to match a new signature, now at the monthly time scale, i.e., the regime curve. If
536 partitioning is the main function that is accommodated at the annual time scale, storage and
537 release could be functions added at the monthly scale, and so on. This process continues until a
538 model is developed that is able to reproduce signatures extracted from streamflow data
539 simultaneously at all time scales (Jothityangkoon et al., 2001; Atkinson et al., 2002). The top-
540 down modeling approach bears some similarity to the Data Based Mechanistic modeling
541 approach proposed by Peter Young of Lancaster University, as reflected in Young and Beven
542 (1994) and Young (2003), as also discussed in Sivapalan and Young (2005).

543

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

565

566

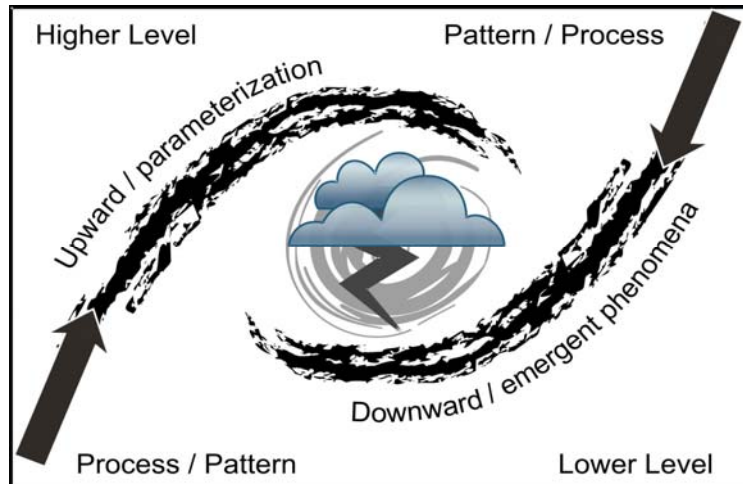
5. Newtonian mechanics vs ecosystem function: impasse and reconciliation

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 (Beven and Binley, 1992). 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

611 consequently in the plurality of model structures. In addition, there is further uncertainty due to
612 the inability to unambiguously estimate parameter values through calibration, in the absence of
613 physical guidance or universal laws to constrain the parameter values. In general, the uncertainty
614 arises from, in a broad sense, both inadequate understanding of catchment behavior (epistemic
615 uncertainty) and inability to characterize the catchment heterogeneity fully (aleatory
616 uncertainty) (Beven, 2016). Further progress in modeling will depend on our ability to break the
617 impasse between the different modeling approaches by changing the science questions that have
618 been behind hydrologic research over the past decades (Sivapalan, 2009).
619

620
621
622 **Figure 4.** Reconciliation of downward and upward approaches – break from a reliance on
623 parameterization of lower-level features to discovery and explanation of emergent phenomena
624 at the higher level. Taken from Sivapalan (2005).
625

Breaking the impasse: change the question

627
628 True reconciliation is unlikely to come about if we stay within the existing paradigms, i.e., through
629 mere refinements to existing approaches to estimation and prediction. Reconciliation between
630 Newtonian mechanics and ecosystem function based approaches will require a new era of
631 research aimed at explanation and discovery rather than estimation or prediction (see also Burt
632 and McDonnell, 2015). Reconciliation will require, on the one hand, that we understand the
633 functional role of landscape heterogeneity, and on the other hand, the physics (i.e., mechanics
634 or thermodynamics) underpinning ecosystem function. This might require going beyond
635 Newtonian mechanics and searching for other universal laws or organizing principles that explain
636 ecosystem functioning of catchments in particular places. Instead of parameterizing the effects
637 of heterogeneity, the focus should be on recognizing it as an emergent pattern and coming up
638 with explanations to describe how it came about and discover its ecosystem function (Figure 4,
639 Sivapalan, 2005). The modeling question should no longer be whether we can explicitly account
640 for the effects of heterogeneity mechanistically but whether its ecosystem function can be
641 reproduced (McDonnell et al., 2007; Schaefli et al., 2011). In other words, to move forward

642   towards improved predictions, the research goals and associated scientific questions must
643   broaden from just estimation to explanation!
644
645   ***Moving from estimation to explanation: focus on phenomena***
646
647   As we have seen, the focus on estimation goes back to the beginnings in Engineering Hydrology.
648   In spite of the enormous progress we have made in our ability to make predictions, these
649   advances have not progressed to generalized theories that operate universally across catchments
650   and places. General theories are very much needed to bring about the reconciliation of the
651   diversity of modeling approaches we now have and to achieve a unification of the field.
652   Hydrologic research will thus have turn to new types of questions (Sivapalan, 2009), which are
653   focused on explanation and discovery, perhaps as a necessary prelude to prediction. Organization
654   of catchment responses and patterns of ecosystem function that one observes in the real world
655   are no longer objects to be mimicked by our models ("grist to the calibration mill", *a la*
656   hydrograph fitting), but need to be seen as emergent phenomena. The enormous computational
657   power and data availability that we now have should be utilized to discover and/or explain
658   previously unobserved or explained phenomena at all scales and places (Li et al., 2014; Dunne,
659   1978).
660
661   Phenomena abound in hydrology, differing in complexity and richness, and arising in different
662   contexts, which warrants a separate review article by itself, given their increasing importance in
663   hydrology research. Examples of phenomena in catchment hydrology include the old water-new
664   water concept (McDonnell, 1990), the pan evaporation paradox (Roderick and Farquhar, 2004),
665   the Budyko hypothesis (Budyko, 1974), the proportionality hypothesis that lies behind the
666   success of the SCS-curve number method (Wang et al., 2014), and the linear reservoir
667   approximation to groundwater contributions to streamflow (Savenije, 2017). The goal of
668   research will increasingly revolve around coming up with plausible hypotheses about their causes
669   and testing them out through further observations or targeted modeling. If the explanations hold
670   in several places, then it contributes to accumulation of knowledge and understanding, and
671   eventually to general theories. There is a long history in other branches of hydrology where a
672   focus on phenomena has led to major advances in hydrologic understanding. One can point as
673   examples the phenomenon of *macrodispersion* in groundwater transport in heterogeneous
674   porous media (Gelhar and Axness, 1983) and that of *hysteresis* in vadose zone hydrology
675   (Hassanizadeh et al., 2002), where sound explanations were found while remaining within the
676   Newtonian and/or thermodynamic frameworks.
677
678   Until recently, under the weight of the dominant estimation/prediction (i.e., hydrograph fitting)
679   paradigm, inadequate attention has been given to the study of phenomena in catchment
680   hydrology. Here I will illustrate, through two simple examples, how the physical causes of
681   phenomena can be explored, and how this might contribute to generalized understanding. The
682   two examples I present here involve an apparent power law relationship with catchment size
683   (area). The first one involves the annual maximum flood peak (scaled by catchment area), in this
684   case, taken from several nested catchments in the Appalachian region of the United States
685   (Figure 5a; Smith, 1992; Robinson and Sivapalan, 1997; Sivapalan, 2005). The second one involves

686   the sediment delivery ratio (the fraction of eroded sediment at event scale that actually reaches
687   the catchment outlet (Figure 5b, Lu et al., 2005). Even though these examples are obtained from
688   specific places, the phenomena themselves are universally observed. The question is: Why is it a
689   power law? Is there a causal explanation? Answers to such questions test our understanding of
690   the underlying processes and the interpretation of observations of all kinds.

691

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

708

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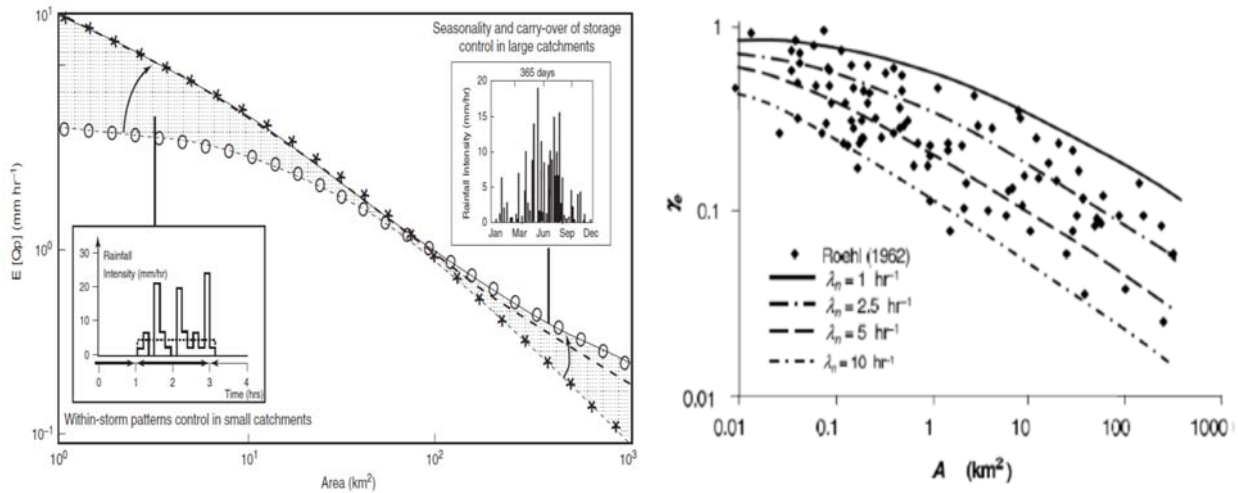

710

711

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

716

717   The scaling of sediment delivery ratio is an even more complex phenomenon to explain (with
718   considerable scatter, see Figure 5b), because it involves not only runoff processes as discussed
719   above, but also sediment transport processes. Even in this case, however, Lu et al. (2005)
720   proposed an explanation that was similar, indeed followed that of Robinson and Sivapalan
721   (1997). They too used a simple conceptual model that consisted of two linear stores arranged in
722   series: a hillslope store that addresses transport of sediment to the nearest streams and a
723   channel store that addresses sediment routing in the channel network. They showed analytically
724   that, as with Robinson and Sivapalan (1997), the spatial scaling of sediment delivery ratio (as an
725   emergent pattern) can be explained, to first order, in terms of the interactions between several
726   time scales (i.e., storm duration, hillslope/channel travel times, and two depositional timescales),
727   and also catchment geometry as before.
728
729   I used these simple examples to also highlight the effects of the interactions between multi-scale
730   temporal variability of both climate inputs and catchment response, and how they tend to
731   generate emergent patterns due to the resonance that is generated through these interactions,
732   even in the absence of adaptations of vegetation or catchment properties. In other words, the
733   way that the catchment responds to a sequence of events is different from the way it responds
734   to a single event, indicating that the response of the catchment must be considered holistically
735   across multiple time scales. The importance of time scale interactions has also been highlighted
736   in other contexts to explain several environmental phenomena: power-law type streamflow
737   recessions resulting from landscape heterogeneity (Harman and Sivapalan, 2009); effect of
738   rainfall event variability on pesticide leaching risk of groundwater (McGrath et al., 2010); and,
739   climate controls on vadose zone contaminant transport (Harman et al., 2011). This issue will be
740   explored in more detail in later sections using an expanded, co-evolutionary framework.
741
742   ***Towards explanation and extrapolation: new kinds of models, new kinds of phenomena***
743
744   As the focus turns from estimation to explanation, the types of models one uses may also need
745   to change. It is not an accident that in the two examples discussed above, I have demonstrated
746   how simple models are able to provide first order explanations of otherwise complex
747   phenomena. In this age of big data, data mining and hyper-resolution modeling (Wood et al.,
748   2011; Peters-Lidard et al., 2017), one might be surprised that I advocate the use of simple models.
749   I do this deliberately because the focus here is not on prediction of the complete system response
750   in one place with all its gory complexity, but as per the Einstein quote below (see earlier quote
751   from Simon Levin), on the ability to explain complex, possibly universal phenomena more simply,
752   and thus contribute to accumulation of knowledge and understanding.
753
754   *"If you can't explain it simply, you don't understand it well enough"* – Albert Einstein
755
756   Note that the simplicity I advocate here is, in the words of James Dooge, a "search for … *a rational*
757   *simplicity*, not the simplicity of crude assumptions, ….i.e., assuming the difficulty out of the way"
758   (Dooge, 1995). In the spirit of the top-down reasoning, as also argued by Dooge (1995), we will
759   be better off starting with simple models targeted on the phenomenon of interest, not models

760 of everything, and increasing the complexity only as needed. Dooge suggested linearization and
761 similarity analysis as effective ways to simplify models and gain understanding of phenomena.
762
763 Phenomena of interest to us can be dynamics (temporal patterns) at a single place, at a range of
764 time scales (Burt and McDonnell, 2015). Similarly, in the space domain, phenomena can be
765 spatial patterns at a single place (within a catchment, Blöschl et al., 2016), or spatial patterns
766 between places (catchments) or scales (as in the two examples above), extending all the way to
767 regional or global patterns. Increasingly, as discussed before, the focus turns towards developing
768 generalized understanding of whole catchment responses and ecosystem functioning, and the
769 discovery of universal laws. Therefore, it is no longer sufficient to study phenomena relating to a
770 single place or a few places. Increasingly, the phenomena of interest to us will come from
771 simultaneous observations in many different places with different histories of the kinds of time
772 scale interactions shown to be critical in the two examples presented above (Hipsey et al., 2015),
773 and the synthesis of data collected from across places, scales and processes (Blöschl et al., 2013).
774
775 **6. Time scale interactions and catchment co-evolution: the Darwinian approach**
776
777 Understanding the reasons for differences in required model structure between catchments,
778 including the controls of climate and landscape properties, may be a good starting point in the
779 search for more generalized understanding, drawing from many different places with different
780 histories. Atkinson et al. (2002) and Farmer et al. (2003), who implemented the top-down
781 modeling approach, in a comparative way, to two dozen catchments around Australia and New
782 Zealand. They found systematic variations in model structure, with the differences reflecting
783 differences in climate and in how vegetation and soils may have adapted to the climate. The
784 modeling studies indicated evidence of a hierarchy of required model structures, with changing
785 time scales (i.e., annual, monthly, daily etc.), and with changing aridity. For example, the required
786 model complexity increased with decreasing time scales, and increased with increasing aridity.
787 The argument could thus be made that the required model structure, reflecting the functioning
788 of a catchment, is itself an emergent property in terms of how the catchment has adapted itself
789 to the prevailing climate and geology.
790
791 *Catchments "marching to a different drummer": comparative hydrology*
792
793 In order to shed more light on the required level of model complexity, Jothityangkoon and
794 Sivapalan (2009) compared a dozen catchments from all around Australia and New Zealand, using
795 the same top-down modeling approach described above (i.e., matching streamflow signatures at
796 a range of time scales). They carried out a diagnostic analysis in each catchment that focused on
797 elucidating the climate controls on one particular signature, i.e., inter-annual variability of runoff.
798 In particular, they were interested in discovering the aspect of the within-year rainfall variability
799 (i.e., storminess, seasonality) that may have a dominant control on the observed inter-annual
800 runoff variability. The diagnostic analysis involved running calibrated top-down hydrological
801 models in each catchment, but now with artificial rainfall inputs that included storminess and
802 seasonality separately, before being combined. The outputs from the model in each catchment,
803 for each of the artificial climate inputs, were compared to the observed inter-annual variability.

804   The question pursued was: what combination of within-year climate variability (seasonality,
805   storminess) is needed to reproduce the observed inter-annual variability of runoff?
806

807   The study found that in catchments in Queensland in north-eastern Australia, inter-annual
808   variability of runoff was most sensitive to storminess (not seasonality), whereas in catchments in
809   Western Australia and South Australia, seasonality was the feature that contributed most to the
810   observed inter-annual variability. This finding is remarkable, in that the climate of Queensland is
811   indeed dominated by storminess (i.e., small number of large storms), and the climates of South
812   and Western Australia were indeed dominated by strong seasonality. The outcomes from these
813   diagnostic analyses indicated that the water balance dynamics of catchments (i.e., model
814   structure and parameters inferred from the data in a top-down way) somehow resonate with the
815   dominant within-year variability, i.e., storminess in Queensland and seasonality in Western
816   Australia. In other words, and paraphrasing American naturalist Henry David Thoreau, these
817   results indicated that each catchment is "marching to a different drummer", the drummer being
818   the variability of climate drivers present in a given place.
819

820   *"If a (wo)man does not keep pace with (her)his companions, perhaps it is*
821   *because (s)he hears a different drummer. Let (her)him step to the music*
822   *which (s)he hears, however measured or far away."* adapted from *Henry*
823   *David Thoreau: Walden, 1854*
824

825   The modeling results also reaffirm the ecosystem view of catchments presented earlier, including
826   the argument that there is much to be gained by making inferences from observed rainfall-runoff
827   time series. They also raise the hope that a more universal understanding of both ecosystem
828   function and catchment response and their relationship to climate and geology may be gained
829   through repeating these modeling and diagnostic studies simultaneously in many more
830   catchments around the world, in a comparative way, across gradients of climate and geology.
831   This leads to the notion of *comparative hydrology*, introduced by Falkenmark and Chapman
832   (1989), and defined more broadly in the next section by linking it to catchment co-evolution.
833

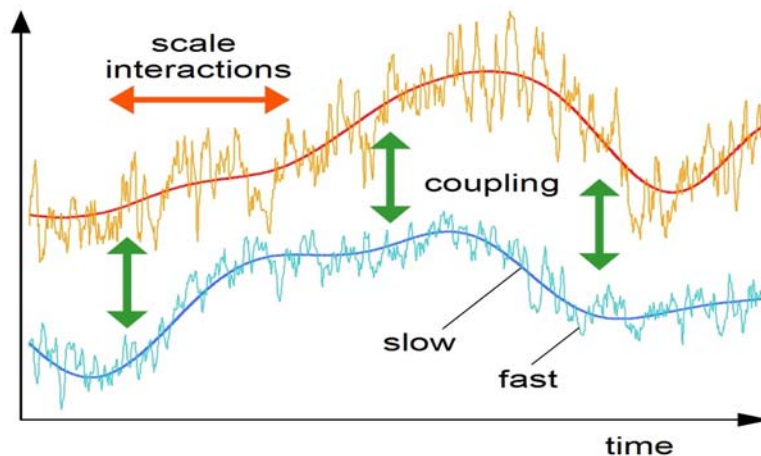
834   ***Catchment co-evolution and Earth System Science: A Darwinian view***
835

836   Berghuijs et al. (2014) extended the above comparative hydrology approach to the modeling of
837   seasonal water balances of over 400 catchments across the continental United States. On the
838   basis of these modeling results they came up with a classification of observed seasonal water
839   balances (i.e., regime curve, a key signature of runoff variability), expressed in terms of three
840   driving factors: climate aridity, seasonality (i.e., relative timing of the precipitation within year)
841   and the fraction of snow as precipitation. On the basis of this similarity analysis, they identified
842   10 dominant catchment classes among the 400-odd catchments. Not surprisingly, they found a
843   geographic aspect to the locations of the 10 classes, in that they were clustered geographically,
844   influenced by the slow climatic and geologic variations across the continent. In addition they
845   found that similarity of seasonal water balances carried over to have an imprint on between-class
846   differences in several other signatures of runoff variability, such as the flow duration curve, flood

847 frequency curve etc., and yet there was also considerable within-class variability due to other
848 climatic and landscape factors.

849

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

862

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864

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

869

870 One can speculate therefore that the phenomenon of each catchment "marching to a different
871 drummer" is a reflection of vegetation adapting to (and in turn changing) the environment
872 around it (e.g., hydrology, soils), in response to the fluctuating water and energy supply at any
873 place of interest (Sivapalan and Blöschl, 2015). This is tantamount to the soils, vegetation and
874 topography belonging to a catchment co-evolving together in response to the climate above and
875 geology below through both land-forming and life sustaining processes operating and interacting
876 across multiple time scales (Figure 6). The focus can no longer be on just hydrological processes,
877 but all land surface processes that operate together and feed back on each other, which thus
878 takes hydrology into the realm of Earth System Science. With this broader view, the focus of
879 analysis is therefore no longer on streamflow signatures alone, but also on signatures arising

880   from the co-evolution of Earth System processes, such as vegetation and erosional patterns that
881   one sees on landscapes (Sivapalan, 2005; Brantley et al., 2017). Examples include patterns in
882   measured evapotranspiration at individual (e.g., FLUXNET) sites (Thompson et al., 2011a),
883   regional patterns of evapotranspiration measured by remote sensing (Cheng et al., 2011), and
884   vegetation, soil and micro-topography patterns in landscapes at a range of scales (Thompson et
885   al., 2011b; Saco et al., 2013; Harman et al., 2014). These are the kinds of ecohydrologic and
886   hydrogeomorphic phenomena that will need to be further explored in the future and synthesized
887   to generate the new understanding and new theories required to close the gap between bottom-
888   up (reductionist) and top-down (ecosystem) approaches to modeling.
889
890   These outcomes of co-evolution, framed as emergent phenomena, may be different in different
891   places, because of differences in the history of co-evolution and initial and boundary conditions
892   of climate and geology. Comparative hydrology, i.e., comparing many catchments in different
893   places along gradients of climate and geology, helps us to shed light on their co-evolution, just as
894   Charles Darwin interpreted differences between animals, birds and plants he found in his travels
895   through the lens of their natural history (Harman and Troch, 2014). The Darwinian approach to
896   comparative hydrology embraces the history of each place, including features that are relics of
897   historical events, as central to understanding both its present and its future. The essence of the
898   Darwinian approach is to develop generalizations beyond individual catchments through learning
899   from differences between catchments, and interpreting them as legacies of past co-evolution.
900
901   ***Hydrologic similarity and catchment classification: steps towards generalization***
902
903   Given the co-evolved nature of catchments, their structure and function, and the resulting
904   hydrologic responses, explanation of the similarity and differences between catchments must
905   take a more Darwinian approach that emphasizes time scale interactions specific to a place, and
906   how the catchment ecosystem may have adapted to these. While there can be considerable
907   diversity and randomness allowed in Darwinian co-evolution of catchments due to contingency
908   effects (Beven, 2015), patterns and connections may yet be discernible which may lead to
909   relationships of more general applicability. One approach to creating order in an otherwise
910   heterogeneous world, widely adopted in chemistry and ecology, is through the means of
911   classification. As in the case of the periodic table in chemistry, classification of catchments based
912   on hydrologic similarity may be used to group catchments, helping to simplify relationships and
913   generalize findings. Hydrologic similarity is the foundation for the transfer of information from
914   one catchment to another, including from gauged to ungauged catchments, and was the basis of
915   the successful outcomes of the "predictions in ungauged basins" (PUB) initiative (Sivapalan et al.,
916   2003; Blöschl et al., 2013; Hrachowitz et al., 2013). The PUB synthesis study by Blöschl et al.
917   (2013) framed hydrologic similarity in terms of several signatures of runoff variability, such as the
918   flow duration curve and the flood frequency curve. The diversity of catchment responses is such
919   that no two catchments are so similar that all signatures are the same between them, and so for
920   prediction purposes one concentrates only on the signature of interest. Yet, as in the case of the
921   comparative hydrology study by Berghuijs et al. (2014), the synthesis project by Blöschl et al.
922   (2013) also found that similarity of seasonal water balance had a significant influence on the

923   similarity of other signatures, and may be the strongest indicator used to delineate hydrologically
924   similar regions (Weingartner and Aschwanden, 1992).
925

926   The organization of catchments into distinct classes based on hydrologic similarity can open the
927   way to understanding the differences between the classes themselves in terms of the underlying
928   climatic, geologic and landscape controls. The most celebrated example of progress in this area
929   is the empirically derived Budyko curve, famously named after Russian hydrologist Mikhail
930   Budyko. The Budyko curve graphically expresses the long term (or mean annual) water balance,
931   defined by the ratio of long-term average evapotranspiration to precipitation, E/P, as a universal
932   function of climatic aridity, the ratio of long-term average potential evaporation to precipitation,
933   E_p/P (Budyko, 1974). The existence of the Budyko curve is usually explained as resulting from a
934   competition between water available (precipitation) and energy available (potential
935   evaporation). In the case of the MOPEX catchments across the United States, Berghuijs et al.
936   (2014) found that the different catchment seasonal water balance (and also vegetation/soil)
937   classes clustered along different segments of the Budyko curve, with little overlap. On the basis
938   of this and other evidence, one can argue that the competition between water and energy
939   available is mediated by the vegetation that forms through natural selection, highlighting the key
940   role of ecohydrology in hydrologic theory development (Eagleson, 2002; Rodriguez-Iturbe, 2000).
941

942   The fact that most of the MOPEX catchments (and other catchments of the world) fall on or about
943   the Budyko curve (leaving a large part of the Budyko space unoccupied) can be seen as an
944   empirical organizing principle, i.e., only some combinations of climate, soil and vegetation
945   characteristics may exist in reality (i.e., are behavioral, Schaefli et al., 2011), indicating a mutual
946   co-dependence through Darwinian co-evolution and selection (Eagleson, 2002). Inspired by these
947   observations, in recent times several hydrologists have embarked on a search for physical
948   explanations for the existence the Budyko curve (Wang and Tang, 2014; Wang et al., 2015;
949   Westhoff et al., 2016). Wang and Tang (2014) and Wang et al. (2015) studied the conceptual
950   bases for empirical models developed by engineers (and geographers) from the 1930s to the
951   1950s to describe water balances across three different time scales: event, seasonal and annual.
952   These were the SCS Curve Number method for runoff estimation at the event scale (Mockus,
953   1949), the *abcd* model for seasonal (monthly) water balance developed during the Harvard Water
954   Program during the 1960s (Thomas, 1981), and the L'vovich method developed in the former
955   Soviet Union for partitioning of annual precipitation into runoff and evaporation (L'vovich, 1979).
956   In the first phase of their work, Wang and Tang (2014) and Wang et al. (2015) showed that all
957   three of them can be described in terms of the so-called *proportionality hypothesis*, which is long
958   understood as providing the conceptual basis for the SCS curve number method. In the second
959   phase of their work, they showed that the proportionality hypothesis, in turn, can be explained
960   thermodynamically, in terms of the principle of maximum entropy production (MEP). One can
961   thus see that the empirical proportionality hypothesis and the thermodynamic MEP principle
962   appear to provide a vehicle to extend the hydrologic similarity arising from co-evolution across
963   to multiple time scales. These are only the first tentative steps in the quest for new theories of
964   hydrology, and still more creative approaches are needed to extend the notions of similarity and
965   optimality to cover not just the Budyko curve but all other signatures, in order that we fully
966   exploit the order that may arise out of Darwinian co-evolution.

967

968 The MEP principle, or the equivalent maximum power principle proposed by Kleidon and Renner
969 (2013) and used by Westhoff et al. (2016) to derive the Budyko curve, can be viewed as providing
970 a constraint to the diversity of Darwinian co-evolution and natural selection, possibly as a
971 mechanism to increase system resilience (Lotka et al., 1922). Furthermore, existence of such
972 physically based organizing principles, valid at a range of time scales as indicated in the work of
973 Wang et al. (2015), can pave the way for a new generation of behavioral models (Schaefli et al.,
974 2011). This is a promising development for two reasons. On the one hand, it can help constrain
975 model structures inferred from rainfall-runoff data, and on the other hand, it can constrain the
976 parameter combinations allowed for otherwise physically based models based on Newtonian
977 mechanics (Li et al., 2014). A unique advantage of the approach adopted by Wang et al. is that it
978 involved connecting the dots between empirical methods that have been widely used in
979 engineering hydrology for over 50 years, exploiting the simplicity in these estimation methods
980 arising from the very co-evolution we are trying to capture in our models (e.g., flood frequency,
981 Guo et al., 2014). Potentially, if continued further, it will have the salutary effect of making
982 fundamental advances while maintaining coherence, through avoiding fragmentation (Graham
983 and Dayton, 2002; Blöschl et al., 2013).

984

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

986

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

994

995 As one begins to look to the future, one recognizes the expanding human footprint, including
996 land use and land cover (e.g., vegetation) changes and human interferences in the hydrologic
997 cycle (e.g., water extraction from rivers or groundwater aquifers) and the inevitable acceleration
998 of the time scale interactions. One can no longer count on stationarity in making predictions of
999 catchment responses under these circumstances (Milly et al., 2002; Wagener et al., 2010).
1000 Furthermore, over longer periods of time the time scale interactions must include two-way
1001 feedbacks between hydrological (and other earth system processes) and human-social processes,
1002 and the emergent dynamics that result from these. Thus, as we transition from our focus on
1003 ecohydrology so far (Eagleson, 2002; Rodriguez-Iturbe, 2000) to the new field of socio-hydrology
1004 (Sivapalan et al., 2012), we can recognize both similarities as well as differences between the
1005 behaviors of vegetation and humans and, where possible, benefit from lessons learned from the
1006 practice of ecohydrology in the past two decades.

1007

1008 The co-evolution of water and vegetation does not stop with vegetation adapting to the water
1009 and energy balances and *vice versa*. We noticed that over time vegetation not only adapts itself
1010 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 Troch et al., 2009; Yang et al., 2017). These studies confirm and build on 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. Note also in passing the similarities between Horton's foresight with ideas expressed in terms of *ecological niche theory* (Chase, 2011) and *niche construction theory* (Odling-Smee et al., 2003) that relate to, respectively, how organisms modify themselves and modify their environment. 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 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. In VOM the optimal vegetation is taken as the 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. Note that this just one of many optimality theories that have been proposed, and is only presented as an example here. 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 (Brantley et al., 2017), 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. This also means that traditional definitions catchments as topographically defined must be replaced or refined to also account for administrative (or governance) units. 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-

1099   food-energy-environment nexus are advances in technology (e.g., infrastructure that enables
1100   extraction and transfers of real water between places) and trade (e.g., trade of food and other
1101   commodities that depend on water for their production). Another compounding factor is the role
1102   of institutional system of administration, legislation and regulation of water (Sivapalan and
1103   Blöschl, 2015). Human involvement in hydrologic systems has been studied extensively in the
1104   context of water resource management, where the focus has been on optimal management
1105   (Loucks et al., 2005). Much of this work has worked on the belief that humans are optimizers,
1106   assumed to make rational decisions about allocation of resources between various needs, and
1107   opting to maximize economic livelihood. However, with the advent of socio-hydrology,
1108   hydrologic science has broadened to include the practices and outcomes of water resource
1109   management, in the presence of the aforementioned complexities, as themselves subjects for
1110   explanation and deeper understanding (Thompson et al., 2013).
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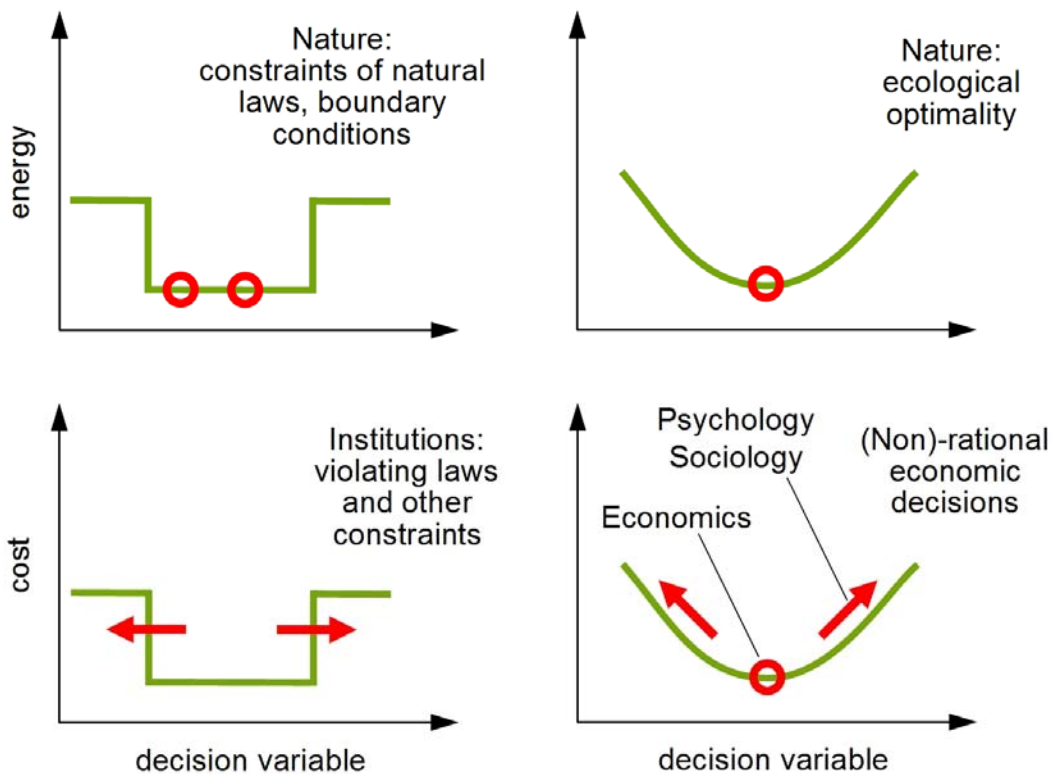
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1114   **Figure 7**. (top) Natural systems follow constraints and optimality laws; (bottom) Human
1115   systems may violate constraints and make irrational decisions away from optimality
1116   (taken from Sivapalan and Blöschl, 2015).
1117

1118   A major complexity in understanding and eventually predicting human behavior in the context of
1119   water management is human agency (Sanderson et al., 2017). Unlike natural systems, e.g.,
1120   vegetation, humans can choose among different modes of thinking and courses of action that
1121   impact the natural systems within which they are embedded. A major challenge is that human
1122   decision-making shapes, and is shaped by, the cultural contexts within which human societies are
1123   embedded. Humans draw upon commonly held values, beliefs and norms to guide their actions,

1124 and in turn can collectively change their cultures in the long-term (Caldas et al., 2015). Human-
1125 water interactions are heavily influenced by differences and/or dynamic changes in human values
1126 and norms in respect of their economic livelihood and the environment. Unlike natural systems
1127 whose long-term co-evolutionary behavior can be expressed in terms of organizing principles
1128 (e.g., vegetation optimality, maximum entropy production), humans can make decisions away
1129 from any optimality principles and may violate their own laws (Figure 7, Sivapalan and Blöschl,
1130 2015). For example, they may extract water from a well, even if it is illegal to do so; or they may
1131 choose to live with pollution, away from optimality reasons, giving the impression that humans
1132 are irrational. These may manifest as puzzles, paradoxes, and other unintended consequences,
1133 exhibiting similarities and differences that reflect distinct hydro-climatic, eco-environmental, and
1134 socio-economic features (Sivapalan, 2015; Pande and Sivapalan, 2017). These factors make
1135 human-water interactions much more complex and thus add to the already difficult prediction
1136 challenges in hydrology (Westerberg et al., 2017). Note that the differences highlighted above
1137 between natural and human-impacted systems are impacted by the relative time scales of
1138 processes and length of data records: it is tempting to think that given long enough records co-
1139 evolutionary behavior in respect of coupled human-water system dynamics may indeed be
1140 governed by some as yet unknown organizing principles. In the end it is a pragmatic choice
1141 whether one sees or assumes well organized patterns within the available data records (Sivapalan
1142 and Blöschl, 2005).
1143
1144 Indeed, it has been suggested that changes in culture and associated values and preferences may
1145 be more predictive of human behavior in the context of sustainability than rationality, or utility
1146 maximization (Caldas et al., 2015). Examples of human behavior different from utility
1147 maximization include (Sivapalan et al., 2014): the peaking in water resource availability as basins
1148 develop (peak water paradox, Kandasamy et al., 2014); increasing levee heights in urban
1149 environments at the expense of increased flood risk (levee effect, Di Baldassarre et al., 2013);
1150 increasing agriculture water consumption in spite of irrigation efficiency improvements
1151 (irrigation efficiency paradox) (Scott, 2011); and over-exploitation of coastal aquifers at the risk
1152 of causing saltwater intrusion (Chang and Clement, 2012). An example of non-optimal behavior
1153 in the context of coupled human-water system dynamics is lock-in or path dependence, which is
1154 one explanation offered for the collapse of the Maya civilization (Kuil et al., 2016). A more recent
1155 example of lock-in is the self-reinforcing action of the people of the Netherlands since the 11th
1156 century to drain their naturally peaty soils, leading to land subsidence, which ultimately led to
1157 the invention of the famous Gouda cheese, since the resulting low-lying areas that these actions
1158 produced were only suitable for dairy farming (Erkens et al., 2016). To save the excess milk for
1159 winter time, cheese was made out of it The science of socio-hydrology aims to explain these kinds
1160 of phenomena that arise from two-way feedbacks associated with coupled human-water system
1161 dynamics, and to develop generalized understanding that can connect diverse phenomena across
1162 many places and times (Sivapalan and Blöschl, 2015). There is still room for predictions in this
1163 new era of socio-hydrology: but given the difficulties of dealing with human agency and complex
1164 human behavior, the focus is not on predicting what will happen at a future prescribed time, as
1165 it is in traditional hydrology, but on mapping out the possibility space of future trajectories of
1166 system co-evolution (see Figure 8, Srinivasan et al., 2017).
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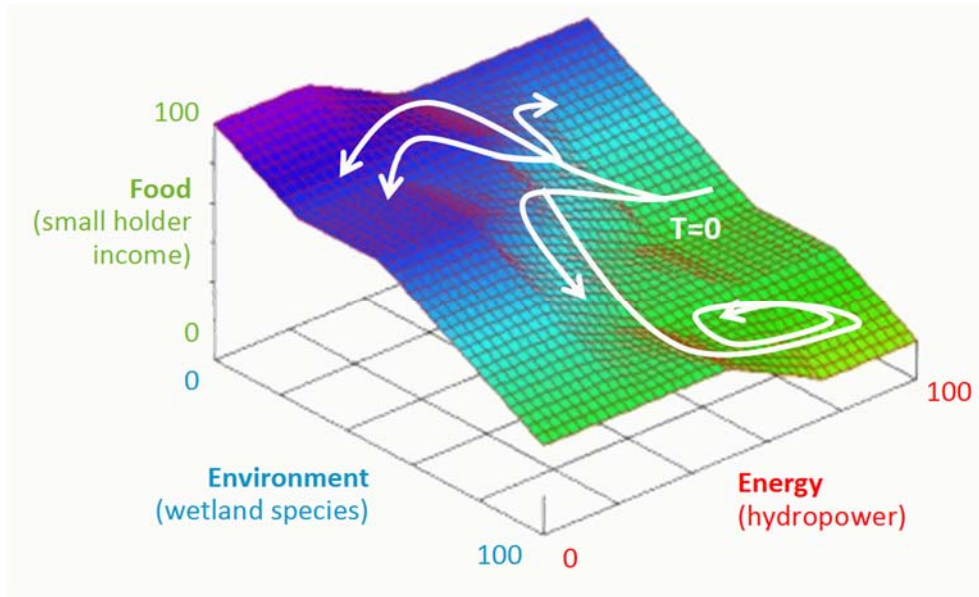
Figure 8. Trajectories illustrating the future possibility space that may be predicted by a socio-hydrological model addressed to management of the water-food-energy-environment nexus (taken from Srinivasan et al., 2017).

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).

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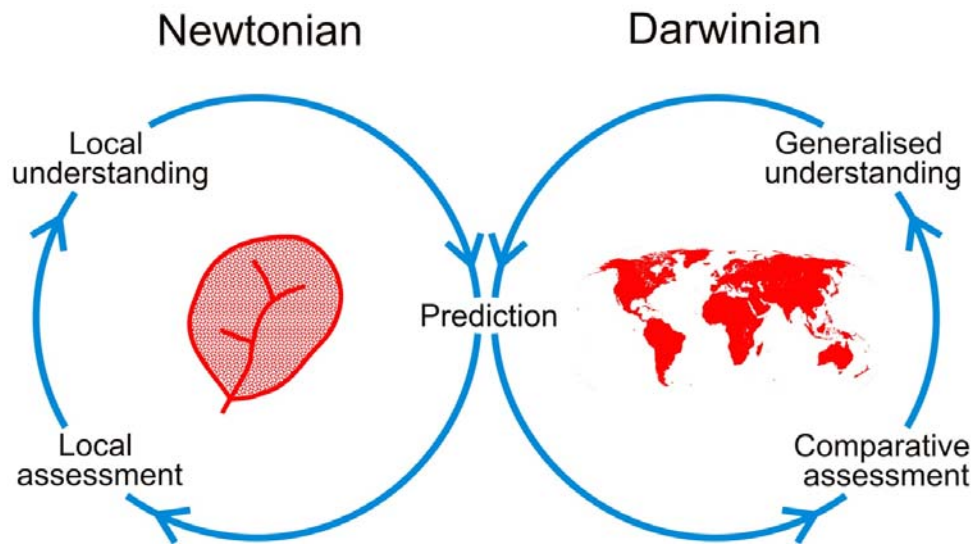
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1244   **Figure 9**. Newtonian-Darwinian synthesis: Relative contributions of Newtonian (learning from
1245   individual catchments through detailed studies) and Darwinian (learning from a population of
1246   catchments through comparative studies) approaches (taken from Blöschl et al., 2013).
1247

1248   The evolution of the science and the growth of hydrological understanding over the past 50 years
1249   have benefited from the use of a combination of Newtonian and Darwinian approaches to
1250   address and explore increasingly complex prediction problems and emergent phenomena. The
1251   Newtonian approach benefits from the fact that it is based on universal laws of mass, momentum
1252   and energy balances, with clear causality. It gains predictive power through advances in
1253   observing and understanding processes, and approaches to account for landscape heterogeneity
1254   and the resulting complexity of flow pathways and residence times. Yet it loses effectiveness in
1255   making general predictions by not being able to fully account for process interactions and
1256   feedbacks and parameter co-dependency that manifest in catchments through co-evolutionary
1257   processes. The legacy of past co-evolutionary processes in landscapes and their interconnections
1258   over long time periods lead to complex emergent spatial patterns and temporal dynamics. So an
1259   alternative approach to studying patterns and dynamics arising from such co-evolution is to study
1260   many catchments comparatively, treating them as legacies of past co-evolution, which is the
1261   Darwinian way. In short, the Newtonian approach generalizes by discovering universal laws
1262   governing particular processes through experimentation, inductive reasoning and through
1263   mathematical derivations, whereas the Darwinian approach generalizes by recognizing emergent
1264   phenomena through comparative analyses across places and then seeking explanations for how
1265   they came about (Guo et al., 2014). Of course, Newtonian and Darwinian methods are
1266   complementary to each other, and progress in terms of new theories of hydrology and
1267   improvements in our ability make future predictions everywhere will require a synthesis of these
1268   two approaches (Figure 9) (Harte, 2002; Bloschl et al., 2013).
1269
1270
1271

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

1316 over-exploitation of land and water resources (Liu et al., 2014). The complexity of water balances
1317 and long-term water management problems across such regions cannot be tackled by studying a
1318 few isolated catchments.
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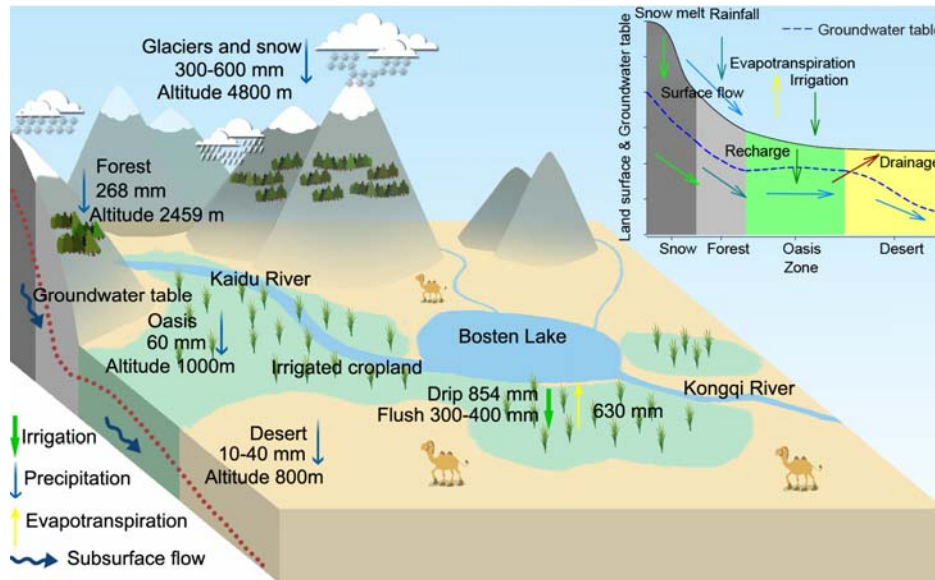
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1322 **Figure 10:** Regional process hydrology: Schematic of the regional hydrologic cycle and
1323 waterscape in Kaidu–Kongqi River Basin, part of the much larger Tarim River Basin, Xingjiang
1324 Province in Western China (taken from Zhang et al., 2014).
1325

1326 As we begin to look at a region as a whole, this regional outlook opens up new possibilities to
1327 advance hydrology, with altogether new emergent phenomena that arise through interactions
1328 of the atmosphere, the land surface and the regional groundwater aquifers, including the
1329 waterscapes that form as a result. This regional hydrology focus can also bring about the overdue
1330 unification of surface (catchment) hydrology with groundwater hydrology, and extensions of
1331 ecohydrology and socio-hydrology, to explore interesting, regional scale phenomena. I am not
1332 the first one to make the case for regional hydrology, however. Tom Dunne, in his famous Abel
1333 Wolman Lecture (Dunne, 1998), called for a renewed focus on research targets at large spatial
1334 scales (i.e., regional) that are "of broad significance and might attract sustained interest from
1335 scientists in other fields and society at large." There is already much activity in regional process
1336 hydrology, that is beginning to bring surface and/or groundwater hydrologists together with
1337 atmospheric scientists, with a focus on modeling, large-scale synergistic observations and data-
1338 model syntheses (Fan, 2015; Hipsey et al., 2015; Maxwell et al., 2015; Blöschl et al., 2017).
1339 Echoing Dunne (1998) himself, my main argument is to go beyond mere descriptions or narratives
1340 as we may have done in the past, and to reinforce the focus on phenomena, now regional-scale
1341 phenomena, and on process explanation and discovery, as a prelude to eventual predictions at
1342 these scales. The relevant processes of interest occur at all space and time scales, and not limited
1343 to just small scales, and emergent phenomena arise out of these multi-scale (space, space-time)
1344 process interactions. Both Newtonian (bottom-up reductionist) and Darwinian (top-down
1345 functional) approaches and their synthesis retain currency, including the use of coarse-grained

1346 models to explore observed phenomena. So this is regional process hydrology that requires a
1347 whole system synergistic perspective.
1348
1349 Within the spirit of use-inspired basic science (Stokes, 1997; Thompson et al., 2013) the move
1350 towards regional hydrology also coincides with the evolution of the nature of water management
1351 problems that will be faced in the emergent Anthropocene. Thompson et al. (2013) presented
1352 several examples of anticipated century-scale trends in the main hydrologic drivers that will
1353 impact humanity in the future. These emerging future challenges include changing demography
1354 (Wagener et al., 2010), warming climate (Vörösmarty et al., 2000), rapid urbanization (Di
1355 Baldassarre et al., 2010), changing rainfall variability (Blöschl et al., 2017), loss of freshwater
1356 resources due to rising sea levels and saltwater intrusion (Chang et al., 2011), and globalization
1357 of water systems through real and virtual water trade (Konar et al., 2016). One can anticipate a
1358 range of water-related problems and secondary effects that will emerge in response to these
1359 drivers. Increasingly these problems will manifest at regional (and global) scales and can no
1360 longer be addressed through the study of individual, isolated catchments. Instead, we need a
1361 regional, increasingly global, approach to the study of these problems. Each of these problems is
1362 likely draw attention to an array of emergent phenomena that manifest at the regional scale, and
1363 associated science questions, which could be the basis for the next major exciting phase of
1364 research in scientific hydrology.
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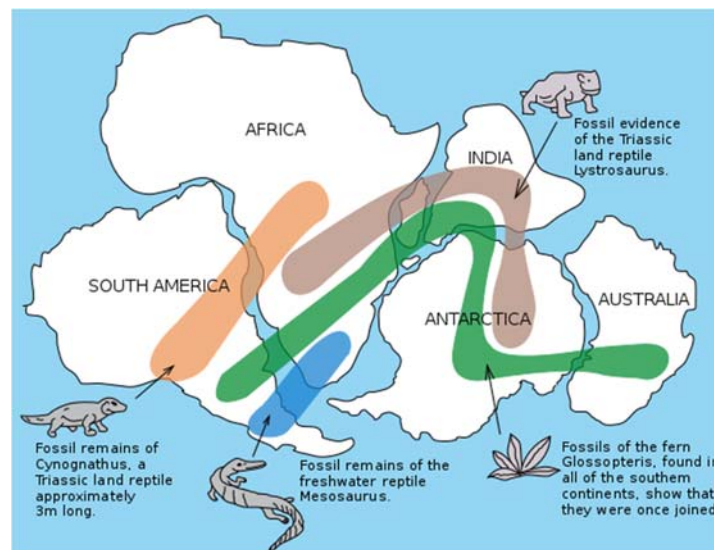
1366
1367
1368 **Figure 11:** Connecting the dots: schematic describing the fossil patterns across continents that
1369 were the basis upon which Alfred Wegener proposed his continental drift theory:
1370 https://en.wikipedia.org/wiki/Alfred_Wegener (accessed on October 28, 2017)
1371
1372 The extension of the co-evolutionary perspective in space towards the regional scale takes us
1373 further from even Darwinian comparative hydrology (of isolated catchments) to the kind of
1374 approach adopted by Alfred Wegener, which eventually led to the discovery of plate tectonics.
1375 During his extensive journeys around the world, Wegener evaluated multiple variables (e.g., fossil
1376 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.

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, as also concluded in an earlier review by Bierkens (2015). 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)

9. Acknowledgements

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. They 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.

The paper has benefited from suggestions and comments I received from Keith Beven, Marc Bierkens, Günter Blöschl, Prabhakar Clement, John Ding, Markus Hrachowitz, Hong-yi Li, Saket Pande, Jose Salinas, Majid Shafiee-Jood, Stan Schymanski, Richard Silberstein, Kevin Wallington, Dingbao Wang and Erwin Zehe. I am extremely grateful for their inputs, but in the final analysis, this is a personal account, and I am ultimately responsible for any errors of omission and commission that remain.

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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