AGU PUBLICATIONS

Water Resources Research

COMMENTARY

10.1002/2017WR021396

The Growth of Hydrological Understanding: Technologies, Ideas, and Societal Needs Shape the Field

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Key Points:

- This paper tracks the drivers and dynamics that have shaped the growth of hydrological understanding over the last century
- New ideas are generated by hydrologists through addressing societal needs with the technologies of their time
- Cycles of euphoria followed by disenchantment have been stimuli for progress

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Citation:
Sivapalan, M., & Blöschl, G. (2017). The growth of hydrological understanding: Technologies, ideas, and societal needs shape the field. *Water Resources Research*, *53*, 8137–8146. https://doi.org/10.1002/2017WR021396

Received 26 JUN 2017
Accepted 6 SEP 2017
Accepted article online 18 SEP 2017
Published online 14 OCT 2017

Abstract Inspired by the work of Newton, Darwin, and Wegener, this paper tracks the drivers and dynamics that have shaped the growth of hydrological understanding over the last century. On the basis of an interpretation of this history, the paper then speculates about what kind of future is in store for hydrology and how we can better prepare for it. The historical narrative underpinning this analysis indicates that progress in hydrological understanding is brought about by changing societal needs and technological opportunities: new ideas are generated by hydrologists through addressing societal needs with the technologies of their time. We suggest that progress in hydrological understanding over the last century has expressed itself through repeated cycles of euphoria and disenchantment, which have served as stimuli for the progress. The progress, for it to happen, also needed inspirational leaders as well as a supportive scientific community that provided the backdrop to major advances in the field. The paper concludes that, in a similar way to how Newton, Darwin, and Wegener conducted their research, hydrology too can benefit from synthesis activities aimed at "connecting the dots."

> The essence of research lies in the people who carry it out. Breakthroughs in research do not come from instrumentation, computers, and satellites; they grow in the minds of individual men and women.
>
> —Freeze, *1990*
>
> . . .. inspired guesses are not enough. Progress comes primarily from the introduction of new observational and theoretical tools.
>
> —Harwit, *2003*

1. What Drives the Growth of a Science?

A common question one hears in after-dinner conversations when hydrologists get together is why there are so few genuine discoveries in hydrology. We look with envy at other fields, not just physics, chemistry, and biology, but even other branches of the geosciences, and have often tended to want to emulate them. A few decades ago we even went through a period of self-criticism, concerned that we were too beholden to engineering applications to be a true science (Klemeš, 1988, p. 3), and responded to calls to rebrand our science as a geoscience (National Research Council (NRC), 1991, p. x; Rajaram et al., 2015).

This prompted us, in this paper, to do a thought experiment, to reflect on hydrology through the imagined eyes of Newton, Darwin and Wegener. We are all fully aware that Newton, Darwin, and Wegener revolutionized physics, biology, and geoscience, respectively, through their discoveries. So what if we bring them back, except this time, we would bring them back as hydrologists? How would they revolutionize hydrology? How would they go about their work in a way that would lead them to new discoveries?

Before answering these questions, let us remind ourselves about the steps that eventually led to their discoveries. In the case of Newton, the discovery of the theory of gravitation has its origins in the data on planetary motions assembled by Brahe. While Kepler saw patterns in this data, it was Newton's genius that finally explained them by universal laws. Darwin collected animal and plant species and fossils from around the world. A comparative analyis of species and their common historical roots provided him with the evidence to support his theory of evolution through natural selection. By analysing global spatial patterns, Wegener found similarities in rock type, geological structures, and fossils in far away continents, indicating to him that these continents must at one time have been together, thus laying the foundations for his theory of continental drift.

Even though their approaches were different, i.e., seeking universal laws, comparative analyses, and evaluating global spatial patterns, two things stand out: data collection by the technologies of their time, and key ideas that helped find order in the data and explain them by causal relationships. More generally, from looking at them, it is hard to tell whether ideas or technologies are more important for progress in science. Harwit the astrophysicist argues for the primacy of technology. On the other hand, hydrologist Freeze, the same Freeze who pioneered the use of powerful computers for distributed modelling while at IBM (Stephenson & Freeze, 1974), says progress comes primarily through people with ideas. So who is right? What does this mean for hydrology?

In this paper, driven by these questions, and inspired by the approaches of Newton, Darwin, and Wegener, we explore, from our own personal (admittedly narrow) perspectives, the drivers and dynamics that have shaped the growth of hydrological understanding over the last century. On the basis of these interpretations, we then speculate about what kind of future is in store for hydrology, and how we can better prepare for it.

2. Tracking the Progress of Hydrological Understanding

Understanding is a highly misused word, so to be absolutely clear about what we mean, we use Merriam-Webster's definition of understanding as "the capacity to apprehend general relations of particulars." More specifically, in the context of hydrology, it is useful to highlight two particular facets of understanding:

1. Cause-effect relationships about how the hydrological system works. We might derive these through discoveries of interesting phenomena. Consider, for illustration, the phenomenon of the infiltration capacity during a storm continually decreasing with time. The cause-effect relationship of this is the reduction of infiltration capacity due to a reduced hydraulic gradient as the soil wets up.
2. Predictive models based on these observed relationships. They allow us to test whether the understanding gained is sound, i.e., whether the models are able to predict these phenomena under other circumstances. For example, the above infiltration phenomenon can be expressed more generally as Time Condensation Approximation from which the Green-Ampt infiltration model derives.

The second question we must address before we proceed is, what do we mean by progress? In hydrology, this could be dealing with richer, more complex phenomena, and developing models for a wider class of phenomena that are right for the right reasons. For example, instead of the understanding of phenomena related to infiltration alone, we may focus on understanding runoff generation more broadly, which involves many different interacting processes.

2.1. Eras in the Growth of Hydrological Understanding and Contributing Factors

Using these yardsticks, one can conclude that the 20th century has seen enormous progress in hydrological understanding. One can interpret the progress over the last hundred years in many different ways. What we present here is our personal view, as we surveyed and interpreted trends in the progression of hydrology wearing two hats, as both observers and participants. From our vantage point, the progress of hydrological understanding seemed to naturally fall into six eras of two decades (i.e., one generation of researchers) each, based on dominant thought paradigms that we recognized as having shaped the field (Table 1). These eras build on those suggested 50 years ago by Chow (1964, p. 1–9), which we adapted and extended to the present time.

We go back to the beginning of the 20th century, toward the end of the Victorian era in England and the decline of some of the big Monarchies on the European continent. Motivated by the need to mitigate flood damage in increasingly populated floodplains in Europe, national scale hydrological networks were established taking advantage of new technologies then becoming available, such as stream gauges and

Table 1
Eras in the Growth of Hydrological Understanding since 1910 and the Factors Contributing to That Growth

Era	Societal needs	Technological opportunities	Euphoria	Typical discoveries of phenomena	Typical progress in prediction methods	Disenchantment
1910–1930 Empirical Era[a]	Flood design	National instrumented networks	Predictability, clear benefit for technical progress	Correlations between water levels exist	Regressions, envelope curves	Lack of transferablity to other places
1930–1950 Rationalization Era[a]	Land and forest management	First experimental basins	Causality (to overcome lack of transferability)	Hortonian runoff generation mechanism	SCS curve number method for runoff estimation	Subjectivity
1950–1970 Systems Era	Economic efficiency	Operations Research, first digital applications	Objectivization by Systems Approach (to overcome subjectivity)	Linearity of hydrological response	Unit hydrograph estimation, time series models	Inability to extrapolate to other conditions
1970–1990 Process Era	Water quality (chemical)	Fast computers, new data collection methods	Solve hydrology as a physical problem (to overcome inability to extrapolate)	Variable source area runoff generation; Event water stems from pre-event rainfall	Physically-based spatially distributed models, stochastic hydrogeology	Scale problems, it is not just a physical but also a biological problem (transpiration, roots)
1990–2010 Geosciences Era	Climate change, ecosystem health	Remote sensing, internet	Interdisciplinarity allows more accurate representation of complex processes	Controls on spatial patterns of soil moisture	Coupled process models, model chains, climate scenarios, data assimilation	Quasi-stationary coupling misses long term dynamics
2010–2030 Coevolution Era	Sustainable development given dominant human footprint	Big data, faster computers, finer resolution remote sensing	Including feedbacks explicitly promises predictability over decades/centuries	Root adaptation to climate, levee effect of people moving into floodplains	Models representing catchments as complex systems (linking time scales)	Parameters of complex systems cannot be measured, spatial feedbacks missed

[a] After Chow (1964).

raingauges (Schaffernak, 1935). These data were used in descriptive *empirical* ways, such as regressions and nomograms, but the benefits to society were clear—more reliable flood protection measures and reduced damages. We note in passing that apart from ideas and technologies, societal needs have always been an important driver of scientific progress in hydrology. Indeed, societal drivers of hydrological progress go back all the way to the very beginnings of civilization. The Nilometer, one of the earliest stream gauges, was motivated by the need for taxation in the Egypt of the Pharoahs (Dooge, 1988).

One now moves to the then New World of the United States, to the time just after the great "dust bowl." The pressing need was for erosion control and forest management in a vast new continent with little history of stream gauging. The kinds of *descriptive* empirical methods used in Europe were not suitable because long-term data supporting the empirical methods were not available, and what was needed were new prediction methods that could be applied in places with minimum data (Rallison & Miller, 1982, p. 353). Necessity being the mother of invention, the pioneers of American hydrology carried out field experiments to understand and derive cause-effect relationships. Examples include the infiltration experiments that led to Horton's infiltration equation (Horton, 1939), paired catchment studies, and groundwater pumping tests, and the resulting *rationalization* of hydrological processes in the form of models such as the SCS Curve Number method (Mockus, 1949) and Theis's nonequilibrium theory of well hydraulics (Theis, 1935).

Following World War II, countries recovering from the war went through a period of economic expansion through investment in thousands of dams, highways, and irrigation systems. The massive expansion of infrastructure had to be done in the most economical way. The methods pioneered by Horton and others of the previous era were now considered inadequate for water allocation problems, e.g., as experienced by the Tennessee Valley Authority, as they were subjective without any concept of economic optimality (Werick & Whipple, 1994, A2). A breakthrough came with the availability of the *systems* approach pioneered by the Harvard Water Programme that sought to optimize the efficiency of the entire system (Maass et al., 1962). The first digital computers, and the 20 or so years of data available from the previous era of stream gauging, made the optimization possible. One outcome of this period is the theory pioneered by Dooge (Dooge, 1959, 1973), that considered catchments as linear systems.

The economic boom of the post World War II years also contributed to water quality degradation in much of the Western world due to sewer effluents from cities and nonpoint source contaminants from agricultural areas discharging into streams. Legislation was introduced to deal with the resulting water quality issues, such as the Clean Water Act in the US and the Water Framework Directive in Europe. It was soon realized that the (black-box) input-output relationships of the systems approach (e.g., Chow, 1970) were not adequate for extrapolating to situations not covered by gauged data, as would be needed for water quality predictions (Woolhiser, 1973). Physically based models began to be introduced aimed at capturing detailed hydrological *processes*, with the Richards equation becoming the archetype, and Freeze being the standard-bearer (Freeze & Harlan, 1969). These modeling breakthroughs were made possible by faster computers then becoming available that allowed numerical solutions of the associated partial differental equations, and more sophisticated data collection methods. Hydrology also benefited from new technologies such as Digital Elevation Models (DEMs) and from rapid advances in other cognate fields (e.g., soil physics, pedology, micrometeorology).

Growing concerns about not only water quality but also general ecosystem health, as well as climate change, put the spotlight on coupled hydrological and biogeochemical cycles, especially carbon and nutrient cycles modulated by water. There was increasing demand for coupled models representing these cycles, which prompted Eagleson's Opportunities book (NRC, 1991, xi–xii) to push the case for hydrology to be a branch of the *Geosciences*. In the context of climate change Eagleson also pioneered a global view of hydrology (Eagleson, 1986), which was supported by new remote sensing products becoming available. As we move into the present time, with the growing anthropogenic footprint on Planet Earth, longer term predictions are needed more than ever for sustainable management, with humans playing a key interactive role (Wagener et al., 2010), which is not explicitly included within the geoscience framework.

2.2. Punctuated Growth and the Euphoria-Disenchantment Cycles

The historical narrative that we have presented above illustrates how, in each era, interaction of new technologies, new ideas and changing societal needs played out and gave rise to what to us appear as step changes in the progress of hydrological understanding, followed by periods of stagnation. The step changes reflect changes in the dominant paradigm as brought about by discoveries of phenomena such as the Variable Source Area concept of runoff generation by Dunne and Black (1970), or the introduction of new predictive methods such as physically based distributed models (Abbott et al., 1986; Freeze & Harlan, 1969;). These changing paradigms are also reflected in the citation analysis presented by Rajaram et al. (2015).

From a broader scientific perspective this pattern seems quite normal. Kuhn's (1962) "Structure of Scientific Revolutions," and Wheeler's (1980) "Staircase of Progress in Physics" describe more generally the discontinous nature of the progress of science. This pattern is also reminiscent of the evolutionary process of "punctuated equilibria" proposed by Eldredge and Gould (1972), according to which most social processes—the growth of science being one of them—fall into an extended period of stasis, to be later punctuated by sudden shifts.

The punctuated growth pattern presented in Figure 1 expresses our view that progress in hydrologic understanding is sandwiched between two main external drivers:

1. Changing societal needs, such as flood design, land management, and improving water quality—hydrological understanding cannot be less than what society really needs;
2. Changing technological opportunities, such as instrumentation technology and computing power that come from advances made in other fields—hydrological understanding cannot be more than what technology allows.

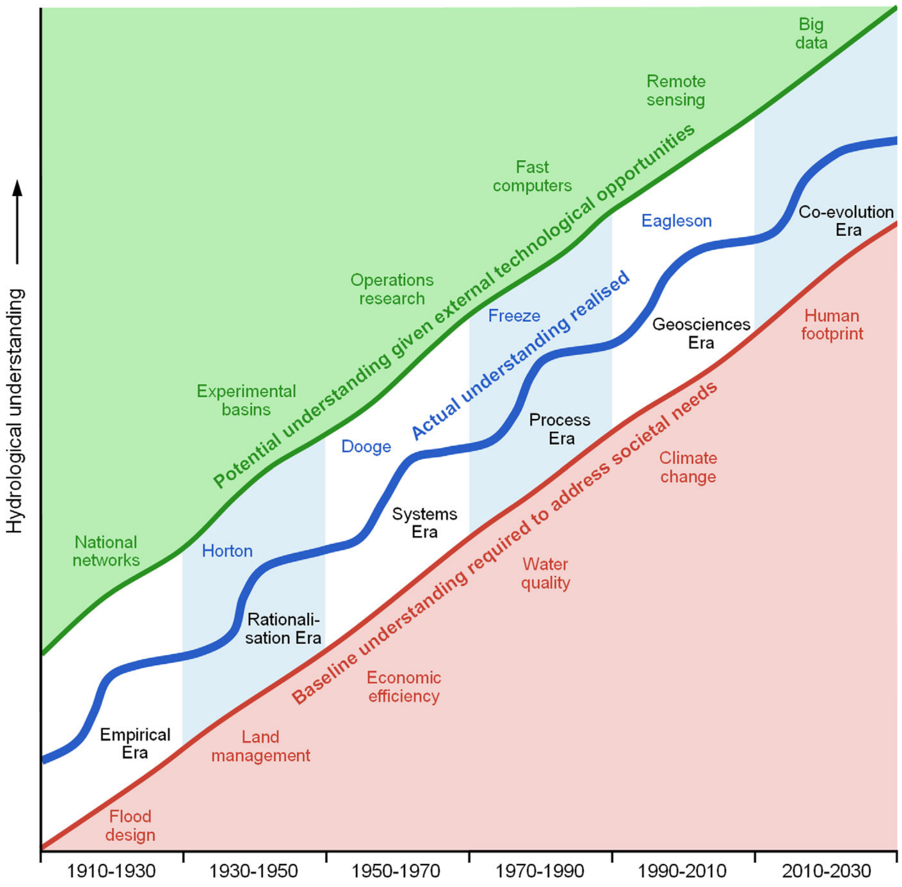

Figure 1. "History does not repeat itself, but it does rhyme" (Mark Twain). Staircase growth of hydrological understanding sandwiched between baseline understanding required to address societal needs and potential understanding given external technological opportunities. Names in blue epitomise dominant paradigms of the eras.

In other words, in contrast to the self-criticism in some hydrological circles that addressing societal needs is an impediment to progress (Klemeš, 1988), history indicates to us that it was actually a positive driving force. Two recent examples come to mind. The practical motivation for predictions in ungauged basins has, in our view, significantly advanced the understanding of catchments as complex systems (Gupta et al., 2013). The practical motivation for regional flood estimation has in turn led to advances in the understanding of climate change effects on regional flood processes (Blöschl et al., 2017).

Figure 1 illustrates that new ideas were generated by hydrologists addressing societal needs with the technologies of their time. This suggests to us that the question of primacy between ideas and technology does not arise in hydrology. Rather, it is the interplay between advancing technology and addressing societal needs that produced the creativity and innovation that led to major breakthroughs. Discovery of the Hortonian runoff generation mechanism (Horton, 1939) is a case in point. Alternatively, ideas may come from other fields too: Dooge's linear systems theory came from electrical engineering; Freeze's numerical approaches came from applied mathematics; and Eagleson's geoscience ideas came from his strong background in Newtonian mechanics (Eagleson, 1970). Note that Darwin himself was influenced by ideas from economist Malthus. Following this tradition, the growth of many cross-disciplinary areas of inquiry in the last few decades has continued to enrich the field of hydrology (McCurley & Jawitz, 2017).

Our account of 20th century progress in hydrology also suggests that history tends to repeat itself. We reason that each era commenced with euphoria brought about by new opportunities that permitted hydrologists to address changing societal needs and promised to overcome the challenges of the previous era. Each era ended with disenchantment in that, although substantial progress was made, new questions arose that could not be resolved. For example, at the start of the process era much hope was placed in the ability of physically based distributed models to make predictions in the absence of observations. An illustration of this hope is this quote from Abbott et al. (1986, p. 45) who developed the SHE model: "The SHE developed from the perception that conventional rainfall/runoff models are inappropriate to many pressing hydrological problems, especially those related to the impact of man's activities on land use change and water quality. Only through the use of models which have a physical basis and allow for spatial variations within a catchment can these problems be tackled." This hope did not materialize and major problems with the overall concept were identified. An example of this realization is this quote from Grayson et al. (1992, p. 2664): "The seductive attraction of the more complex models is their ability to provide information about points within the catchment, but it is concluded that the representations used in current process-based models are often too crude to enable accurate, a priori application to predictive problems."

How does the disenchantment lead to new ideas? There are two possible responses. One is to abandon the concept altogether and look for alternative ways to make progress. The other response is to find ways to overcome the difficulties faced (e.g., by new measurements). An example of the latter, in our view, are the observed soil moisture patterns in the Tarrawarra catchment in Australia collected by Western and Grayson (1998) with the express intention to improve the development and testing of physically based distributed models. This may be seen as the first foray into the geoscience era that followed.

Symptoms of euphoria are concerted efforts at exploiting new opportunities through new research programs, new hydrologic tools, and waves of publications. Symptoms of disenchantment are fragmention of knowledge, proliferation of models, and preoccupation with predictability and predictive uncertainty, ending up with an upsurge of inconclusive philosophical debates (Graham & Dayton, 2002). However, it is precisely such disenchantment that has paved the way for new ideas that triggered the start of a new era, followed by a similar cycle of initial euphoria and eventual disenchantment.

This cycle is not unique to hydrology. It is a widespread cultural phenomenon where disenchantment stimulates progress. It is part of Oberg's (1960) u-curve hypothesis of cultural shock, and it resembles views on the growth of financial markets (Pixley, 2012). One might think that it is even part of Murphy's life cycle (i.e., euphoria, disillusion, a search for the guilty, the punishment of the innocent, the reward of the uninvolved), sometimes adopted in project management circles (Allinson, 1997). The progress comes about by a social process within the scientific community stimulated by the cycles of euphoria and disenchantement. Even though this is a communal process within the context of broad scale dynamics such as technological advances and change of societal needs, the most important progress in hydrology, as Freeze says, was dominated by a few individuals such as Horton, Dooge, and Eagleson (and Freeze himself).

And yet, as in the case of Newton, Darwin, and Wegener, their achievements were built on the support cast of a large community of scientists. The community created the scientific environment, contributed to the culture of discussion and debates that happened in the background, all of which created the seeding bed of innovative new ideas that eventually led to major breakthroughs. Quoting Bertrand Russell: "the edifice of science needs its masons, bricklayers, and common labourers as well as its foremen, master-builders, and architects."

3. Navigating Through the Coevolution Era

If the past is any guide to the future, we may apply what we have learned from the past century to speculate about possible advances in hydrologic understanding that might emerge in the near future as we navigate between addressing changing societal needs and benefitting from technological opportunities. Since we are interested in what it takes to generate breakthroughs, not just incremental progress, we do this through the prism of three hypothetical hydrologists in the present-day female images of Newton, Darwin, and Wegener.

There are pressing societal needs that underpin present-day hydrology (see e.g., Montanari et al., 2015). The 21st century is heralded as the age of the Anthropocene where the human footprint is fast becoming a dominant feature in the hydrological cycle. Sustainably managing coupled human-environmental systems in a fast changing world requires a much longer term perspective than ever before. Avoiding the pitfalls of short-term thinking requires an understanding of how fast and slow processes interact, coevolve and lead to emergent dynamics. We could therefore term the current (2010–2030) era the Coevolution Era, where the Earth system is treated as an interconnected whole system.

There are certainly emerging technological opportunities in this era that Newton, Darwin, and Wegener, would take advantage of. Wegener would be surely fascinated by remote sensing products that would allow her to make spatial connections, and she would keenly contrast products of all types in a similar way as her historical counterpart evaluated multiple variables (e.g., fossil records, rock types) to support his reasoning on the continental drift. Darwin would be excited about the idea of treating catchments as complex systems where water, vegetation, landscape and humans coevolve over wide-ranging time scales and speeds, from 10^{-10} m/s of tectonic processes to 10^1 m/s of atmospheric motions, and to 10^8 m/s if internet communication was included. She would be keen to swap HMS Beagle with the Hydrological Observatories set up around the world, and to seek connections between them. And she would be certainly pleased to use modern DNA technology to track microbes and thus the sources of the water, or to use trace elements to connect the ages of landscapes.

3.1. Phenomena With and Without Humans

Newton, Darwin, and Wegener would look at phenomena of all kinds—interesting hydrological behavior with no obvious or immediate explanation—and ask how they came about. They would look at emergent phenomena arising from two-way feedbacks with slow and fast time scales. One such coevolutionary phenomenon they might examine is the finding that root depths of native plants seem to match the seasonal water balance deficits (Gao et al., 2014). Apparently, plants tend to optimize the tradeoff between limiting root growth to save carbon and growing roots to enhance water storage capabilities. Other phenomena that involve coevolutionary processes are the natural organization of soils and vegetation down hillslopes (i.e., catena) (Thompson et al., 2011), and the interplay between storm types, topographic slopes, and flood flashiness (Gaál et al., 2012).

Given the central role of humans in the water cycle, Newton, Darwin, and Wegener would surely not miss phenomena that arise from human-water interactions. One such phenonmenon could be the levee effect that refers to the observation of increasing flood risk when people move into floodplains ostensibly protected by levees (Di Baldassarre et al., 2015). Other coevolutionary phenomena involving humans include the efficiency paradox, whereby improvements in agricultural water use efficiency actually increase rather than decrease total water consumption (Scott et al., 2014); increase in human vulnerability to droughts due to the over-reliance on technology (Kuil et al., 2016); and the pendulum swing of agricultural water consumption through a change in societal priorities from economic livelihood to environmental recovery (Kandasamy et al., 2014). However, if hydrology begins to embrace humans as part of the system, then there is a possibility that hydrological science may take on features of economics and social sciences. This means that we will be in a better position to explain phenomena involving humans, but may not be able to make predictions of those phenomena in the traditional sense. But predictions may still be used to trigger or encourage innovations even if their truth or falsity is undecidable (Srinivasan et al., 2017).

3.2. Analysis Approaches and Breakthroughs

Newton, Darwin, and Wegener would of course explore these phenomena in different ways. Newton would look for universal laws underpinning these phenomena, building on evidence collated by other industrious hydrologists. She would, for example, seek universal laws through generalizing the water management typology compiled by Srinivasan et al. (2012). Darwin would look at phenomena from a comparative perspective, exploring what makes phenomena at two places similar, and explaining them in terms of their common history. She would make inferences from the legacy of processes and archival records and try to build a consistent narrative on phenomena such as the pendulum swing of water consumption. Wegener would look at spatial patterns of vegetation, for example, and explain their formation and migration, including the role of human modification. Even as we would envisage all three to be world-class hydrologists, it is possible that in the coevoluion era, it is Darwin who might have the best chance of achieving breakthroughs. This is because her natural history approach resonates better with the nature of the era.

One thing is for sure. Regardless of their traditional bent, in one aspect of their research they would be identical: all three would be synthesizers. Their historical counterparts all synthesized information from diverse sources to find common ground and to “connect the dots,” and this is exactly what they would do now.

They would perform meta-analyses of published research to overcome fragmentation, assemble data sets from different places to find out about similarities and differences, and perform model intercomparison studies. They would combine different pieces of evidence by abductive reasoning (Baker, 2017). They would reconcile the diverse concepts that exist for representing evaporation/transpiration (e.g., energy balance, combination method, vegetation optimality) under a single unified theory. Likewise, they would combine the representations of different runoff generation mechanisms (e.g., infiltration excess, saturation excess, tile drainage, urban drainage) into one unified model. And they would explain the levee effect, the efficiency paradox and the pendulum swing by appealing to the same common principles underlying human-water interactions.

4. Lessons for the Future

If one believes, as we have argued here, in the cycle of euphoria and disenchantment that stimulates progress in hydrologic science, one wonders where the disenchantment would come from at the end of the last, i.e., coevolutionary, era. We can only speculate.

It seems to us that in an increasingly interconnected, globalized world, water management is going to be much more complex than before. Water security challenges and other societal problems related to water are going to be addressed through multilateral approaches, including interbasin (or international) transfers of real water and regional and global exchanges of virtual water (i.e., water embedded in commodities, such as food and energy). Failure to address water shortages is likely to generate not only local problems but also regional and global problems, including border conflicts, migration and global political instability. We could perhaps refer to the next period as the Globalization Era (2030–2050).

It is likely that the understanding acquired in the Coevolution Era will prove inadequate for addressing these new global challenges. It seems to us that the main disenchantment will come from the inability of local or even regional scale models of coupled human-water systems to predict long-term dynamics in an increasingly globalized world, and the inability to address, let alone predict, these problems before they even appear on the horizon (Srinivasan et al., 2017). The increasing pressures will force us to look for more technical and social solutions to enhancing the access and quality of terrestrial waters and, given the vanishing margin between supply and demand as we experience a variable climate, there will be a need to drastically improve predictability of climate and human induced variations in hydrology, which will lead us to yet newer lines of inquiry (Lall, 2014).

There will surely be exciting new technological opportunities that assist in addressing these needs—higher resolution remote sensing products, the *internet of things* that captures the dynamics of human demand and consumption, and sophisticated trade networks that connect people regionally and globally. Social networks will help connect and track people, and in this way propagate information fast across the globe. There have been amazing advances in machine learning in the last decades that open the door for the identification of pattern/form and space-time evolution from data, and in our staircase context, a new wave of empirical discovery requiring new causal insights is on the verge.

These new technologies, along with bright new ideas that we cannot even imagine now, will help understand phenomena arising from climate changes and global virtual water trade and other spatial teleconnections of people and ideas. An example is how demand for food in one part of the world contributes to the depletion of groundwater resources in another part of the world (Marston & Konar, 2017). Feeling at home in this era, Wegener would look at global virtual water trade patterns. In order to understand better how water and people are connected spatially, she would link virtual water trade patterns with trade patterns of other commodities in the same way as her historical counterpart linked different variables to confirm his continental drift theory.

5. Conclusions

On the basis of our tracking of hydrological progress over the past century and speculating about future progress through the eyes of hypothetical modern-day Newtons, Darwins, and Wegeners we (mere mortals in this regard) are drawn to the following tentative conclusions:

1. *Progress in understanding sandwiched between societal needs and technological opportunities*: The progress brought about by Newton, Darwin, and Wegener came through an iterative combination of ideas and technology to explain phenomena. These were also important for progress in hydrology, but because water is so central to human civilization, addressing societal needs has also been a strong motivation in hydrology. In contrast to concerns sometimes voiced, we think that having to address societal needs has in fact been beneficial to the growth of our science, and will continue to be so in the future. While we, as hydrologists, may not be able to control the evolution of societal needs and the broader technological advances, being aware of the connections may help us align our research agendas with these external changes and even have an influence over them.
2. *Euphoria-disenchantment cycle*: We believe that the cycles of euphoria and disenchantment have been the stimuli for the progress in hydrological understanding. Hydrology would not be the vast and rich field that it is today if not for the periods of disenchantment that contributed to the motivation behind subsequent innovations and breakthroughs.
3. *Need for leaders and community efforts*: For hydrology to progress as a science we need a community, observing and analyzing, predicting and practicing, succeeding and failing, and interacting through cooperation and competition. This community effort is how ideas are generated and propagated. Only a few leaders pick up the ideas that are "in the air" and raise them to the level of great transformative ones, as Newton, Darwin, and Wegener did in their times. Hydrology too has this community and has this class of leaders.
4. *What would Newton, Darwin, Wegener do if they were hydrologists today?* One major lesson we have learned from looking over the successes of Newton, Darwin, and Wegener is the critical role of synthesis, or the emphasis on "connecting the dots." Regardless of the differences between what they did (physics, biology, geoscience), Newton, Darwin, and Wegener were great synthesizers. They had the right idea, or asked the right questions with which to see order in the apparent disorder, or as Bronowski (1956, p.23) said, "to create order." If there is one thing we want to say in conclusion it is that hydrology would benefit from more "connecting the dots"!

Acknowledgments
The ideas behind this paper were formed through discussions with many colleagues over the years. The paper also benefited from constructive comments from Marco Borga, Gemma Carr, James Jawitz, Megan Konar, Upmanu Lall, Peter Loucks, Charlie Luce, Kathryn McCurley, Hari Rajaram, and Stan Schymanski. We are also grateful for valuable comments from the Editor Martyn Clark, and reviewers Keith Beven, Hoshin Gupta, Marc Bierkens, and an anonymous reviewer, which helped to substantially improve the paper. We are, however, responsible for any errors that remain. The authors would like to acknowledge financial support provided by the Austrian Science Funds (FWF) as part of the Vienna Doctoral Programme on Water Resource Systems (DK-plus W1219-N22).

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