AGU PUBLICATIONS

Water Resources Research

COMMENTARY

10.1002/2016WR020078

Key Points:
- Modern hydrology places nearly all its emphasis on science-as-knowledge
- Such emphasis is contrary to the productive and creative processes that facilitate fundamental advances in science as a process of discovery
- Discovery occurs via investigation whereby abduction leads to uberty, a kind of fruitfulness of inquiry, followed by deduction and induction

Correspondence to:
V. R. Baker,
baker@email.arizona.edu

Citation:
Baker, V. R. (2017), Debates—Hypothesis testing in hydrology: Pursuing certainty versus pursuing uberty, *Water Resour. Res.*, *53*, 1770–1778, doi:10.1002/2016WR020078.

Received 14 NOV 2016
Accepted 9 FEB 2017
Accepted article online 27 FEB 2017
Published online 29 MAR 2017

Debates—Hypothesis testing in hydrology: Pursuing certainty versus pursuing uberty

Victor R. Baker[1]

[1]Department of Hydrology and Atmospheric Sciences, University of Arizona, Tucson, Arizona, USA

Abstract Modern hydrology places nearly all its emphasis on science-as-knowledge, the hypotheses of which are increasingly expressed as physical models, whose predictions are tested by correspondence to quantitative data sets. Though arguably appropriate for applications of theory to engineering and applied science, the associated emphases on truth and degrees of certainty are not optimal for the productive and creative processes that facilitate the fundamental advancement of science as a process of discovery. The latter requires an investigative approach, where the goal is uberty, a kind of fruitfulness of inquiry, in which the abductive mode of inference adds to the much more commonly acknowledged modes of deduction and induction. The resulting world-directed approach to hydrology provides a valuable complement to the prevailing hypothesis- (theory-) directed paradigm.

Plain Language Summary This commentary suggests that a world-directed, investigative approach to hydrology may serve as a productive complement to the prevailing hypothesis- (theory-) directed, approaches. The emphasis of the former on discovery has the potential to be transformative for investigative hydrology.

> Remember, then, that scientific thought is the guide to action; that the truth at which it arrives is not that which we can ideally contemplate without error, but that which we can act upon without fear; and you cannot fail to see that scientific thought is not an accompaniment or condition of human progress, but human progress itself.
>
> William Kingdon Clifford, *The Common* Sense *of the Exact Sciences* (1885)

1. Introduction

The focus of this debate is on *hypothesis testing*. I have highlighted this phrase because it already entails implications as to what is meant by both *hypothesis* and *testing*. Moreover, the concern of the debate is presumably with *scientific hypotheses*, defined as "proposed explanations for a phenomenon that can be tested." This definition views a hypothesis to be a kind of proposition, that is, a potentially truth-bearing statement that needs to be evaluated as true or false. These concerns, in turn, lead to further, seemingly obvious implications as to what it is to be *scientific* and what constitutes a *scientific explanation*. Of course, a likely response from some readers to these questions might be that hydrologists already know what these terms mean, and that it is more important to get on with the substantive issues for advancing hydrological science, including the design of experiments for the "efficient falsification of hypotheses regarding hydrological processes" and the implementation of a "hypothesis-driven approach" in order to make "tangible scientific progress."

Already this discussion has moved to issues that are philosophical. However, the use of *philosophical* here does not mean some abstract lawyer-like discourse on trivia. As pointed out by the eminent philosopher *Nagel* [1987, p. 1], "The main concern of philosophy is to question and understand very common ideas that all of us use every day without thinking about them." This view of philosophy traces back to Aristotle, who recognized that many of the most basic of philosophical concerns lie with what is most commonly assumed without question as one goes about doing an activity, such as the testing of hydrological hypotheses. By being unquestioned, these basic philosophical concerns can be of a most pernicious kind, leading to numerous problems, the bases of which commonly go unrecognized.

Of course, a difficulty with thinking about first principles is that it can take quite a while to get going with the business at hand. Discussion of such perspectives can result in a much longer discourse than any audience (other than one of philosophers) would be likely to endure. The challenge is always to provide just enough philosophy to begin to do justice to the topic, without leading to problems of incomplete reasoning and/or the closing of inquiry.

So the reader will have to trust a bit, considering that the relevance will only emerge later in the paper. Nevertheless, the wait could be productive. While the focus of this debate is on hypothesis testing, there is an implicit assumption that the philosophy of science that underpins this concept will serve to justify (1) a methodology of experimentation that can successfully falsify hypotheses, and (2) a program of measurement, either in experiments or general monitoring, that will produce replication and generalization of the most satisfactory hypotheses. What if this view is not the best way to organize scientific research and make progress in advancing the understanding of hydrological phenomena? Given current presumptions that place immense emphasis on hypothesis testing in the conduct of hydrological research, in the evaluation of research proposals, in reviews of hydrological research articles, etc., perhaps it might be philosophically appropriate to question the basis for placing so much emphasis on this particular paradigm.

2. Science, Engineering, Systems, Theory, and Models

The word *science* drives from the Latin *scientia*, meaning *knowledge*. The meaning of *knowledge* is the subject of an entire branch of philosophy, that of epistemology. The classical meaning of knowledge comes from Plato: "justified true belief." This legacy is important when it comes to viewing aspects of testing, such as the increasingly popular Bayesian methodologies that presumably update scientific beliefs by incorporating additional evidence in a manner that is considered to be "scientific." It is also relevant to the commonplace modern view that "science" acts authoritatively as a repository of well-justified true beliefs (or at least beliefs with highly reduced uncertainty) that can be held to provide the trustworthy basis needed to underpin effective decision making. Of course, these views can also be used to justify a great deal of financial support for the scientific enterprise. However, there are also consequences to this science-as-knowledge concept [*Baker*, 2017] in that emphasis is placed on the epistemological issues of achieving truth and of the justification of that truth.

The history of hydrology has been envisioned [e.g., *Chow*, 1964] as one of progress through successive stages in which science-as-knowledge is achieved, by methods that progress from empirical, to rational, to theoretical. Increasingly, moreover, the theoretical phase of progress is being empowered by computational efficiency. Predictive computer modeling is revolutionizing the ability of scientists and engineers to consolidate theoretical knowledge into convenient conceptual packages that can be used to simulate the behavior of "systems" over ranges of conditions and processes that are presumed to operate in the real world. Given the increased ease of performing such modeling, the apparent rigor of the methodology, and the utility of the results in generating confident belief for decision-making, predictive computer modeling has become the principal operating paradigm for modern hydrology.

A hydrological theory can be considered to be an organized system of statements about things hydrological. The organization necessarily involves various assumptions, including rules of logic and axiomatic principles. A theory is both a system and a representation of a system. The system represented is a set of interrelated or interconnected elements, generally objects and processes. The whole arrangement is a human abstraction, deemed by its author(s) to be those interconnected elements that are most essential to the operation of the "real world." So defined, a system is a kind of reduction from the overly complex, incompletely understood totality of reality.

Models are human constructs that simplify the larger reality of the world. They may be analogies or abstractions that are drawn in verbal, mathematical, or physical terms for rationalizing the necessary connections between changes in a system [*Matalas et al.*, 1982]. They embody the elements abstracted from the world, defining systems that the modelers deem to be essential for the workings of the world. Such idealization creates a tentative construct that is both known and testable. Engineering hydrology incorporates the best available theory (science-as-knowledge) into models in order to achieve accurate representation (simulation) of the system of interest for some problem of control to be solved within limitations of time and available resources. The system is predefined by exact criteria for design, management, or control. A model is then constructed and applied to this system. Data can then be obtained to make initial estimates of the system parameters and to aid a progressive activity of modifying these parameters to reduce uncertainties in the prediction of processes. While this procedure serves to calibrate the model for making accurate predictions, that effectiveness only applies to the problem domain for which model was defined, including the initial criteria as well as the particular circumstances of time and space to which those criteria apply. A continually changing world will inevitably invalidate those criteria on magnitude and time scales that vary uniquely according to local and specific circumstances. Any "validation" for an engineering hydrological model is thus somewhat circularly confined to the idealized system of initial problem definition.

As with engineering models, scientific hydrological models must incorporate theory that relates to the empirical world, i.e., to facts and observations, measured, or sensed from the world of experience. However, while engineering models are viewed as the application of current science-as-knowledge to practical issues, scientific models are best viewed as hypotheses. They comprise part of an upward spiral between analogical reasoning and the testing of that reasoning with scientific observations. At some point, a model may begin to abstract from raw data the facts that its inventor perceives to be fundamental and controlling, placing these in relation to each other in ways that were not understood before, and thereby generating predictions of surprising new facts [*Judson*, 1980]. At this point, the model is beginning to qualify as a theory. True theories bind diverse consequences together in such an elegant manner that they compel belief by the larger scientific community. Such modeling is theory-directed. In conventional hydrology these models commonly employ first principles with the goal of achieving "physically based" predictions of hydrologic behavior with the precision of what Newton achieved for celestial mechanics.

There is another definition for science, one that is incompatible with that of science-as-knowledge. It can be stated as follows: Science is above all an activity and an attitude, held by a community of like-minded investigators, who are passionately driven by their desire to discover truths about the world. In order to pursue this inquiry, it is actually necessary to have uncertainty about the world, not to suppress it. How could one possibly do science, as just defined, if its subject matter consisted of facts and well-justified true beliefs, that is, knowledge? There would be nothing to pursue. This view of science holds it to be about the living, dynamic process of inquiry, not about knowledge that is a dead collection of presumed factual truths. This kind of scientific inquiry is open ended; we can view it as science-as-seeking. Questions (hypotheses) are pursued to generate understanding that ultimately makes for more and more reliable knowledge.

3. From "Saving the Appearances" to the *Two Dogmas of Empiricism*

The incompatibility of science-as-knowledge and science-as-seeking has been recognized for a long time. The great American geomorphologist *Gilbert* [1886] classified scientists as either theorists or investigators. Though Gilbert viewed the former to be those who seek to demonstrate the truth of their theories, many of today's scientists consider themselves to be theorists according to the philosophy of *Popper* [1959, 1963], which emphasizes the role of falsification rather than verification for the justification of scientific statements. However, those who ascribe to this view seem quite unaware of the rather devastating philosophical critiques that have been leveled against the abilities both verificationism and Popperian falsificationism to advance the goal of justifying science-as-knowledge. Moreover, despite the highly misleading title of his first book *Logic of Scientific Discovery*, *Popper* [1959] followed the views of his logical positivist contemporaries in sharply distinguishing between the logic of justifying scientific knowledge from what were inferred to be nonlogical modes for the discovery of that knowledge. Not being scientists themselves, and only being interested in the rational reconstruction of scientific knowledge, Popper and the logical positivists placed all their philosophical emphasis on justification, thereby misleading generations of practicing scientists, who looked to their writings for an underpinning for their methodologies, including those of hypothesis testing. Much of the confusion for practicing scientists revolves around the nature of inductive inference, a topic that has a little appreciated history.

There is a very old phrase from the earliest history of science that could well be resurrected in regard to the increasing use of predictive models in hydrology. This is the idea of "saving the appearances" (or "saving the phenomena") in which scientists (they were called "natural philosophers" in the late middle ages when this terminology was in common use) superimpose mathematical relations on phenomena. For the purpose of "saving the appearances," it sufficed that the deductive consequences of axioms (what today we would call model "predictions" that follow from assumptions) should agree with observations. This distinction was considered necessary at the time because it was realized that such agreement, while useful as a practical tool for predicting phenomena, nevertheless provided no insights for the full understanding of underlying realities. Though such a calculating tool might clearly work within a particular range of applications, that result did not show why or how that result came about, particularly when there were other ways of generating the same outcome.

The classical view, going back to the 17th century writings of Francis Bacon, was that the quest for understanding nature required a role for a scientific hypotheses to act as questions put to nature. This idea was associated with a view of inductive inference as a kind of interrogation of nature through experiments, not only to elicit answers to questions and also to suggest better questions. This viewpoint recognized a kind of mental element in the process, in which the mind of the questioner/interrogator became subjectively involved in the interaction with nature. In contrast to the modern logical view of induction, the view of Bacon, with roots going back to Aristotle, was that induction had two roles: the process by means of which the causes and laws inherent in nature could be discovered, and also the means by which the validity of those discoveries could be established. This early view of induction essentially blurred the distinction between fact and theory by allowing the facts (nature) to suggest the theory in such a way that the power of this suggestion was itself a kind of test of the theory.

During the 18th century subsequent empiricist philosophers, notably David Hume, came to propose a sharp distinction between the factual matters of the world, termed *synthetic* or *a priori*, that were considered to be contingent, empirical, and probable; versus the logical relationships among ideas, termed *analytical* or *a posteriori*, considered to be certain and necessary. This distinction later evolved into the notion of a sharp distinction between fact and theory. However, a great debate developed in the early 19th century involving, on one side, a very effective advocate for the new, logical approach to inductive reasoning, John Stewart Mill, who restricted induction/synthetic inference to the objective classification of facts. His adversary in the debate was the great Cambridge polymath William Whewell, who championed a revised version of the classical Baconian tradition of induction/synthetic inference. Whewell tried to reform the notion of induction in order to bring it into a more realistic accord with what scientists actually do, as evidenced in Whewell's own detailed studies of the history of science [*Whewell*, 1840; *Butts*, 1968]. Nevertheless, Mill's view of induction ultimately prevailed, becoming one of the bases for the logical positivist philosophical view of science that dominated for much of the twentieth century, a view that still is presumed by many working scientists. The logical positivists were not interested in science in order to find out about nature; they were interested in science in regard to its success that could be justified with good arguments in a logical sense. Deductive arguments were favored because they preserve truth with certainty. All other "good arguments" besides deductive ones were considered "inductive," but only in the narrow sense advocated by Mill, such that support is provided for conclusions, but without the guarantee that is provided by deduction. By excluding "discovery" from proper consideration in logic, viewed as the normative method of reasoning, the logical positivists came to pursue a project totally out of step with the general spirit of scientific inquiry, i.e., science-as-seeking.

The point of this historical digression is that this view of absolute separation of fact from theory, an assumption that underlies what can be productively learned from either the verification or the falsification of hypotheses, became ingrained into thinking, even though it was subsequently discredited by later philosophical work that seems still not to have been understood by many practicing scientists. One of the newer philosophical realizations again came from the historical studies of the scientific process, recalling the approach of *Whewell* [1840]. This new work was that of *Kuhn* [1962], who clearly demonstrated the role of theory-laden facts in the practice on what he termed "normal science." However, a much more devastating critique came in what many consider to be the most important philosophical paper published in the last century: The *Two Dogmas of Empiricism* by *Quine* [1951]. This work showed that it is not possible to isolate individual hypotheses and theories when making real world tests. Whether done in the field or in a laboratory, any concrete test of a theory, model, or hypothesis involves numerous auxiliary assumptions about boundary conditions, the nature of instruments, potential sources of interference, etc. Moreover, many of these auxiliary assumptions will be unstated, highly theoretical, poorly understood, or even completely unknown. Because it will never be clear from a failed prediction whether the primary hypothesis (or model) produced the result, or whether the failure resulted from one or more of the myriad of auxiliary hypotheses, it will always be the case that the test cannot be absolutely conclusive in regard to any particular hypothesis or presumption. This is a matter of logic, and it has immense consequences for predictive modeling [*Oreskes et al.*, 1994].

4. Hydrosemiosis and the Pursuit of Uberty

So what is the alternative to the hypothesis-testing framework in which theories (hypotheses) are evaluated for mirroring nature, and data are substituted for phenomena? The alternative involves inference-laden signification and a world-directed point of view. It is *semiotic* in that it understands the world, not in a detached manner as a mere source of data, but as a complex interpretive structure, in which the investigator is immersed. This is a world mediated and sustained by *signs* that exist in a continuous, connected flow, a *semiosis*, in which the signs are things that stand for something else (their object) in relation to something else (their *interpretant*). A scientifically fruitful aspect of this view is the recognition of indexical signs in which the relationship to objects is one of causation. Although the world contains, or is composed of a semiotic structure (a *semiosis*) of indexical signs, the interpretant aspect of these signs is what is triggered in the investigator, whose thoughts, in turn, become new signs, constituting a continuity of the signs in human thought with those in the world [e.g., *Baker*, 1999]. Thus, it is in through this semiosis, or action of signs, that the world "speaks" to the investigator [*Baker*, 2000].

Instructive illustrations of the role of semiosis in the investigative process are provided by considering the methods of an experienced medical doctor, interpreting the symptoms of a disease, or the investigations of a master detective, interpreting clues at a crime scene. As an example of the latter, Sherlock Holmes studies numerous clues (indexical signs) that relate to other clues, developing them into an interconnected web. Eventually a picture emerges that becomes a working hypothesis, binding all the clues together into a kind of narrative that possesses an overall consistency and coherence. Note that the key element in this process is not the correspondence testing of individual hypotheses as propositions. Rather, it is the overall consistency and coherence of the narrative, as a working hypothesis, that adds confidence to process of inquiry.

The relationship of crime detection to semiotics is described in a book by the semioticians, *Eco and Sebeok* [1988], entitled *The Sign of Three: Dupin, Holmes, Peirce*. The analogy between science and crime scene investigation is not exact, however. The crime case can be resolved, at least in principle, by identifying a unique culprit. In the science investigation, the inquiry commonly remains open with each new sign leading the investigator to new levels of understanding.

Thus, the hydrologist, as an investigator seeking understanding by making discoveries about the world, needs to be involved in a *hydrosemiosis*. The key inference employed in this process is neither the induction nor the deduction that are most often distinguished in modern discussions of logic. Rather, the key mode of inference is *abduction*. Just as the master detective is attracted to clues, the attention of the hydrosemiotic investigator is attracted to particular processes or to particular circumstances that lead to productive effect-to-cause inferences. Of greatest interest, given the investigator's broad experience with similar sign systems, is something surprising that seems particularly important. Based on this observation, it can be inferred that, if such and such were the case, then this surprising fact would follow as a matter of course. This is what the great 19th century American logician and practicing geophysicist, Charles Sanders Peirce, defined as an abductive inference. Thus, as envisioned by Peirce, and recently summarized by *De Waal* [2013, p. 66], a short statement of scientific reasoning is the following: "...*abduction* furnishes us with explanatory hypotheses, or theories, *deduction* draws out their logical implications, and *induction* verifies (or falsifies) these implications, and by doing so verifies (or falsifies) the hypothesis."

Charles Peirce considered the role of logic (where logic is viewed as a normative science of correct reasoning, as opposed to being a branch of mathematics) as twofold: (1) to bring out a kind of security, i.e., an approach to certainty, in the three forms of reasoning, and (2) to bring out a possible and hopeful kind of productivity or fruitfulness, which he termed *uberty* in the three kinds of reasoning. Much attention in modern philosophy of logic is devoted to (1), and deduction is obviously the reasoning mode that gets highest marks for this, while induction, as noted above, is subject to lots of controversy. However, while deduction is best for achieving security, it is the worst form of logic in regard to uberty. The opposite is true for abduction, which Peirce holds to have been miserably confused with induction by nearly all philosophers of science other than William Whewell, who, like Pierce and unlike most, was himself a practicing scientist.

Why use "uberty" instead of "fruitfulness"? The reason for Peirce has to do with how abduction differs from induction. Induction for Peirce is focused on purely objective observations as a run of some kind of experience, as might be dealt with by statistical inference. Observations can be fruitful in this way, but to have uberty, which is a kind of value in productiveness, there must be a component of reasoning combined with the objective observations. That reasoning must also have a kind of instinctive sense of meaning, or a kind of feeling for the beginnings of truth to it, which might be termed "the scent of truth" [*Houser,* 2005; see also, *Baker*, 2009].

Although abductive inference is commonly applied and even explicitly mentioned in paleohydrological research [*Baker*, 1996, 1998, 2014], use of the term "abduction" is rare in conventional hydrological literature. One exception is *Pomeroy et al*. [2013], who, for their predictive study of the ungauged portion of the Smoky River Basin in Alberta, Canada, invoke a combination of "deductive, inductive, and abductive reasoning for developing appropriate model process structure, basin discretization, and parameterization." Even though the terminology may not get mentioned, abductive inferences clearly form portions of many hydrological investigations. An example is the study of *Sidle et al*. [2000], who describe hydrometric, applied conservative tracer, dye staining, tensiometric, piezometric, and subsurface thermal response tests conducted at the Hitachi Ohta Experimental Watershed in Japan. These studies led the authors to propose "a conceptual hydrogeomorphic model" for steep, deeply incised headwater catchments. Their model seems to have been based on abductive inference, and *Sidle et al*. [2000] describe how their conceptual model is consistent with findings from other studies, i.e., that its consequences were proving fruitful for further work, thereby exhibiting uberty. The next step would be to formalize a mathematical model to deduce ("predict") specific outcomes, which then could be tested by inductive comparison to measured results.

5. Testing for Uberty

Testing for uberty relies less on the correspondence logic of theoretical/experimental sciences, like physics, and more on the logic of consistency, coherence, and consilience that characterizes the investigative and historical sciences of interpretation exemplified by geology.

In the experimental methodologies of physics and chemistry the testing of hypotheses, which are set up as logical propositions, occurs by the correspondence of theoretical statements to specific measurements in highly controlled circumstances that allow the experimental conditions to exactly conform to the "system" that had been presumed to hold for the complexities of the natural world. However, unlike classical physics or chemistry, much of geology and many parts of hydrology cannot rely upon controlled experimentation in regard to their subject matter, which commonly cannot be restricted to those simplified aspects of natural phenomena that get predefined as "physical systems." Without such simplification of the specificity and complexity of the real world, these sciences must engage alternative means to test or corroborate the various hypotheses that are generated by analogy. This testing or corroboration is accomplished first by adopting the hypotheses and then by exploring their consequences, i.e., by making of them into "working hypotheses", often as multiple candidates [*Chamberlin*, 1890, 1904] that can be compared to their alternatives. These comparisons do not rely so much upon the logic of correspondence, which involves a kind or agreement with accurate measurement from controlled experiments, but instead involve the logic of consistency, coherence and consilience.

Consistency entails a lack of contradiction, such that a causative hypothesis for a phenomenon is not contradicted by known physical principles, any indicated spatial associations with related phenomena, the historical sequence of development into which the phenomenon fits, the causal nexus in which it is embedded, and/or similar relationships. Coherence requires an explanation that is sufficiently comprehensive to align with other known explanations of closely related phenomena.

Finally, and perhaps most importantly, a tentative hypothesis achieves consilience, literally, a "jumping together" of knowledge [*Whewell*, 1840], if it leads to a kind of "explanatory surprise" in which a completely different set of phenomena from that being tentatively explained is discovered or recognized, such that (1) the newly recognized phenomena are clearly related to the phenomena under investigation, and (2) that they are adequately explained by the tentative hypothesis that was originally proposed in a more limited context. Though consilience does not confer truth via formal logic, its operation is commonly associated with the most fruitful of scientific investigations.

Coherence operates as a kind of consilience that happens over time. As the investigation of the working hypothesis proceeds, its connections to consequent phenomena are further extended, resulting in the recognition of new classes of facts that either differ from or are subsumed by the working hypothesis. In the latter case, the hypothesis may be falsified, but in the former one is given confidence as to the continued productivity of that hypothesis.

6. Discussion and Conclusions

Many years have now passed since the late Vit Klemeš raised many philosophical issues critical to achieving a scientific hydrology [e.g., *Klemes*, 1986, 1997], Though Vit Klemeš himself was praised by some for being "the conscience for hydrology," it can be argued that there has been relatively little change in the attitudes and practices that he criticized. Can what aspires to be scientific hydrology come to be absolved from the charge of "dilettantism" that *Klemes* [1986] laid upon it?

Much of the modern scope of hydrology is focused on either the deductive procedures of predictive modeling or inductive procedures for characterizing and reducing uncertainty. These are all appropriate for engineering and science-as-knowledge versions of hydrology. However, as noted in discussions of Newtonian versus Darwinian hydrology [e.g., *Harman and Troch*, 2014], this emphasis has also been viewed as producing a kind of crisis for modern hydrological science [see also, *Blöschl and Zehe*, 2005; *Beven*, 2006; *Kirchner*, 2006; *Wagener et al*., 2010].

This commentary suggests that a world-directed, investigative approach to hydrology may serve as a productive complement to the prevailing hypothesis- (theory-) directed, approaches (Table 1). The emphasis of the former on discovery has the potential to be transformative for investigative hydrology.

7. Postscript: Comments on the Other Papers in the Debate

The other articles in this debate contain much that is consistent with the views expressed herein. *McKnight* [2017] relates her personal experiences in formulating explanatory hypotheses, how she used them in the design of field studies, and how surprises can arise during those studies. She describes three types of hypotheses, all of which are pragmatic in that their meaning lies in those effects or outcomes with practical bearings to which their consequences might conceivably lead. Moreover, they all involve abductive inference in that they require creativity in (1) recognizing the surprising effects that are encountered, and (2)

Table 1. Comparison of Theory-Directed Versus World-Directed Approaches to Hydrology

	Theory- (Hypothesis-) Directed	World-Directed (Investigative)
Basis	Define elements of nature (systems) capable of controlled study	Take the world (nature) as it is
Goal	Develop theories that explain	Make discoveries to advance understanding
Emphasis	Idealizations: general principles that apply at all times to all places	Real phenomena: concrete particular happenings (events), including past
Character	Experimental, predictive, mathematical	Observational, historical
Methods	Theoretical model simulation/prediction Controlled experimentation	Observations to stimulate hypothesis generation via analogy
Testing	Correspondence	Consistency, coherence, consilience
Role of Hypotheses	Propositions or conjectures to be tested	Working guides to possibilities
Viewpoint	World as a system that favors the application of deduction (through mathematics) to provide certainty	World as a semiosis in which the connectivity of signs favors the use of abduction to provide uberty
Role for Data	Verification or falsification of model predictions	Indexical signs for the understanding of causative processes
Types of Inference	Deductive analysis (truth-preserving) followed by inductive synthesis (for theory confirmation and/or reduction of uncertainty)	Abductive synthesis, followed by deductive analysis of consequences, followed by inductive synthesis of observations to test conclusions
Role of Logic	To underpin valid reasoning about what can be said about the world	To assess the uberty provided by the semiosis of what the world says (conveys) to the investigator
Reasons to Justify Research	Formulate and test predictive models (hypothesis-driven testing)	Make fundamental discoveries about world to advance understanding

applying the knowledge of past results that allow an investigator to infer what can be envisioned in regard to what would have brought those results about.

Valid deductive inferences (misleadingly termed "predictions") yield logically (not temporally) subsequent results that follow from premises that include both rules (laws) and cases. The cases of concern to *Neuweiler and Helmig* [2017] are subsurface hydrological model concepts, particularly what must be presumed to be actual flow and transport processes. Part of the uncertainty associated with such cases is aleatory, i.e., represented by random processes and random fields. Such considerations are inductive and probabilistic, including increasingly popular applications of Bayesianism. More problematic, however, are epistemic uncertainties that arise from not knowing the actual processes relevant to the model application. It is not sufficient to know what is probable for what has been presumed, i.e., what can be inferred inductively; it is also necessary to know what is possible in terms of the processes actually operative for the particular circumstances to which the model is being applied. Abductive inference infers what is possible, and abductive inferences result one or more *working hypotheses*, where "working" is directed toward uberty in regard to generating increased understanding. The deduced consequences of these hypotheses can then be compared (inductively) to their consequences, leading to various kinds of testing, but, perhaps more importantly, when combined with the investigative skills of the experienced hydrologist, to further abductive inferences.

Based on a random sampling of recent research papers, *Pfister and Kirchner* [2017] conclude that much conventional hydrological practice does not follow the idealized scientific method. Common deviations include "HARKing" ("Hypothesizing After the Results are Known") and confirmation bias. Yet, despite these and other disfunctions, hypothesis testing seems essential for effective hydrological research. Pfister and Kirchner provide examples of inconsistencies where hypothesis generated from currently prevailing theories have demonstrated anomalous results, which, of course, are exactly the situations that lead to abductive inferences.

Finally, I completely agree with Pfister and Kirchner's highlighting of exploratory research aimed at the generation of hypotheses, i.e., a primary focus on promoting abductive inferences, rather than deduction and induction. The current overemphasis of grant funding agencies on requiring a silly game of hypothesis statement and rigorous testing as necessary for successful proposals is anathema to the most important aspect of all science: that of the unexpected discovery. Good science involves developing fruitful hypotheses during in the course of exploratory investigations.

Acknowledgments
Readers can find supporting information regarding this essay's conclusions in the cited references listed below. No direct funding was received for this work, but the author thanks The University of Arizona for providing the opportunity to write the essay. There are no conflicts of interest for the author.

References

Baker, V. R. (1996), Discovering the future in the past: Palaeohydrology and geomorphological change, in *Global Continental Changes: The Context of Palaeohydrology*, edited by J. Branson, A. G. Brown, and K. T. *Gregory, Geol. Soc. Spec. Publ.*, *115*, 73–83.
Baker, V. R. (1998), Paleohydrology and the hydrological sciences, in *Palaeohydrology and Environmental Change*, edited by G. Benito, V. R. Baker, and K. J. Gregory, pp. 1–10, John Wiley, Chichester, U. K.
Baker, V. R. (1999), Geosemiosis, *Geol. Soc. Am. Bull.*, *111*, 633–646.
Baker, V. R. (2000), *Let Earth speak! in The Earth Around Us: Maintaining a Livable Planet*, edited by J.S. Sneiderman, pp. 358–367, W. H. Freeman, New York.
Baker, V. R. (2009), Charles S. Peirce and the "Light of Nature," in *Scientific Revolution in Geology from the Renaissance to the Enlightenment*, edited by G. D. Rosenberg, Geol. Soc. Am. Mem., 203,pp. 259–266.
Baker, V. R. (2014), *Paleohydrology, IAHS Benchmark Papers in Hydrology*, vol. 9, 494 pp., Internat. Assoc. of Hydrol. Sci. Press, Wallingford, U. K.
Baker, V. R. (2017), Interdisciplinarity and the Earth sciences: Transcending limitations of the knowledge paradigm, in *Oxford Handbook of Interdisciplinarity*, Second Edition, edited by R. Frodeman, J. T. Klein, and R. C. S. Pacheco, pp. 88–100, Oxford Univ. Press, Oxford.
Beven, K. (2006), Searching for the Holy Grail of scientific hydrology: Qt = (S, R, 1t) A as closure, *Hydrol. Earth Syst. Sci.*, *10*, 609–618.
Blöschl, G., and E. Zehe (2005), On hydrological predictability, *Hydrol. Processes*, *19*, 3923–3929.
Butts, R.E, (1968), *William Whewell: Theory of Scientific Method*, Hackett Publ., Indianapolis, Indiana.
Chamberlin, T. C. (1890), The method of multiple working hypotheses, *Science*, *15*, 92–96.
Chamberlin, T. C. (1904), The methods of Earth-sciences, *Pop. Sci. Mon.*, *66*, 66–75.
Chow, V. T. (1964), Hydrology and its development, in *Handbook of Applied Hydrology*, edited by V. T. Chow, pp. 1.1–1.22, McGraw-Hill, New York.
De Waal, C. (2013), *Peirce: A Guide for the Perplexed*, Bloomsbury, London.
Eco, U., and T. A. Sebeok (1988), *The Sign of Three: Dupin, Holmes, Peirce*, Indiana Univ. Press, Bloomington.
Gilbert, G. K. (1886), The inculcation of scientific method by example, *Am. J. Sci.*, *31*, 284–299.
Harman, C., and P. A. Troch (2014), What makes Darwinian hydrology "Darwinian"? Asking a different kind of question about landscapes, *Hydrol. Earth Syst. Sci.*, *18*, 417–433.
Houser, N. (2005), The scent of truth, *Semiotica*, *151*, 455–466.
Judson, H. F. (1980), *The Search For Solutions*, Holt, Rinehart and Winston, New York.

Kirchner, J. W. (2006), Getting the right answers for the right reasons: Linking measurements, analyses, and models to advance the science of hydrology, *Water Resour. Res.*, *42*, W03S04, doi:10.1029/2005WR004362.

Klemes, V. (1986), Dilettantism in hydrology: Transition or destiny? *Water Resour. Res.*, *22*(9), 177S–188S.

Klemes, V. (1997), Of carts and horses in hydrologic modeling, *J. Hydrol. Eng.*, *1*, 43–49.

Kuhn, T.S. (1962), *The Structure of Scientific Revolutions*, Univ. of Chicago Press, Chicago.

Matalas, N. C., J. M. Landwehr, and M. G. Wolman (1982), Prediction in water management, in *Scientific Basis of Water-Resource Management*, pp. 118–127, Natl. Acad. Press, Washington, D. C.

McKnight, D. M. (2017), Debates—Hypothesis testing in hydrology: A view from the field: The value of hydrologic hypotheses in designing field studies and interpreting the results to advance hydrology, *Water Resour. Res.*, *53*, doi:10.1002/2016WR020050.

Nagel, T. (1987), *What Does It All Mean? A Very Short Introduction To Philosophy*, 101 pp., Oxford Univ. Press, Oxford.

Neuweiler, I, and R. Helmig (2017), Debates—Hypothesis testing in hydrology: A subsurface perspective, *Water Resour. Res.*, *53*, doi: 10.1002/2016WR020047.

Oreskes, N., K. Shrader-Frechette, and K. Belitz (1994), Verification, validation and confirmation of numerical models in the earth sciences, *Science*, *263*, 641–642.

Pfister, L., and J. W. Kirchner (2017), Debates—Hypothesis testing in hydrology: Theory and practice, *Water Resour. Res.*, *53*, doi:10.1002/2016WR020116.

Pomeroy, J. W., X. Fang, K. Shook, and P. H. Whitfield (2013), Predicting in ungauged basins using physical principles obtained using the deductive, inductive and abductive reasoning approach, in *Putting Prediction in Ungauged Basins into Practice*, edited by J. W. Pomeroy, P. H. Whitfield, and C. Spence, pp. 43–63, Can. Water Resour. Assoc. and Int. Assoc. of Hydrol. Sci., Cambridge, Ont.

Popper, K. R. (1959), *The Logic of Scientific Discovery*, Basic Books, New York.

Popper, K. R. (1963), *Conjectures and Refutations: The Growth of Scientific Knowledge*, Routledge, London.

Quine, W. V. O. (1951), Two dogmas of empiricism, *Philos. Rev.*, *60*, 20–43.

Sidle, R. C, Y. Tsuboyama, S. Noguchi, I. Hosoda, M. Fujieda, and T. Shimiz (2000), Stormflow generation in steep forested headwaters: A linked hydrogeomorphic paradigm, *Hydrol. Processes*, *14*, 369–385.

Wagener, T., M. Sivapalan, P. A. Troch, B. L. McGlynn, C. J. Harman, H. V. Gupta, P. Kumar, P. S. C. Rao, N. B. Basu, and J. S. Wilson (2010), The future of hydrology: An evolving science for a changing world, *Water Resour. Res.*, *46*, W05301, doi:10.1029/2009WR008906.

Whewell, W. (1840), *The Philosophy Of The Inductive Sciences, Founded Upon Their History*, Cass, London.