A Room with a View: Some Geographic Perspectives on Dilettantism, Cross-training, and Scale in Hydrology

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In 1986, an invited paper appeared in the journal, *Water Resources Research,* titled, "Dilettantism in Hydrology: Transition or Destiny?" (Klemeš 1986). In this article, Vit Klemeš, a respected engineering hydrologist with a reputation for insightful, if not incisive, critiques of the discipline, argued that hydrology has been slow to emerge as a science in its own right and instead has an identity "only as an appendage of hydraulic engineering, geography, geology, etc." (177S). Because of this, Klemeš claimed, "the perspectives of hydrologists tend to be heavily biased in the direction of their nonhydrologic primary disciplines, and their hydrologic backgrounds have wide gaps which breed a large variety of misconceptions" (177S). "Hydrologists," charges Klemeš, "do not seem to be able to break free from the grip of their primary disciplines . . ." and, as a result, ". . . for hydrology as a whole, we are dilettantes who 'toy with the subject or study it lightly'" (178S).

I believe Klemeš's charge of dilettantism is especially relevant to this forum and the questions raised by Bauer, Veblen and Winkler because issues of methodology were at the crux of his critique. Using the metaphor of Bauer et al., dilettantism can be ascribed to those who are too comfortable in their favorite pair of disciplinary-based "methodological sneakers" to equip themselves for the "cross-training" needed to address the increasingly complex scientific questions that are emerging in hydrology. For example, Klemeš questions how much research interest "is really in the science of hydrology, in learning how it works," as opposed to an interest in "elaborating some pet concept from one's primary discipline which seems capable of performing a hydrologic trick" (1986:177S). These "pet concepts" are described in terms of favored mathematical tools, models, and other methods of analysis. Klemeš's charge of dilettantism further implies that there may be a much deeper problem in hydrology than a comfortable adherence to preferred methods. He describes it as an inability, or unwillingness, to move beyond a self-referential system that, for most hydrologists, is their primary discipline. Transferred to a geographical context, it is the tendency to stay isolated in one's primary physical geography subdiscipline, oblivious to the need for cross-training. Such a situation can evolve into a self-righteous ideology "which can recognize, and communicate with, nothing but itself, and be proud of it" (Klemeš 1986:179S).

As with his other thoughtful and challenging essays (e.g., Klemeš 1982, 1983, 1997), Klemeš's 1986 paper fostered both pondering and discussion among hydrologists (e.g., Beven 1987; Kundzewicz 1987; Klemeš 1987; Walling 1987; Anderson 1989).[1] This *Annals* forum on methodology in physical geography provides an opportunity to revisit some of the issues raised in Klemeš's paper. In what follows, I present a general overview of perspectives and methodologies in hydrology,[2] discussing them in the context of ideas put forth in Klemeš's essay. From this analysis, I develop a response to questions raised by Bauer et al., about how well current methodological approaches in both hydrology and geography equip us to analyze and understand hydrologic phenomena across an immense range of spatial and temporal scales. Finally, I address the readiness of geography to participate in the newly emerging "earth science" identity of the discipline of hydrology. The overarching message of this essay is that if we, as geographers, wish to exonerate ourselves from the charge of dilettantism, some mindful examination of how we approach hydrologic research is required. Klemeš's critique gives us a challenging framework for self-reflection and raises some important concerns about methodology in other areas of physical geography as well.

A Window in the "House of Science"

To describe the current state of methodologies and perspectives within hydrology, Klemeš developed an analogy of the "house of science." Many disciplines reside inside the house, each viewing and analyzing the real world through its own disciplinary window. Significantly, geography is mentioned as one of the scientific disciplines with such a window. In Klemeš's analogy, however, the *hydrologic* window has not yet been installed because hydrology has not been fully established as a science in its own right. Instead, hydrologic processes are viewed, understood, and analyzed from the methodological perspectives of other disciplinary windows. Klemeš does not fault hydrologists for having a particular disciplinary perspective. Rather, he charges those who are "so attached to their respective windows that, in trying to obtain the whole picture, they don't move to the other windows but rather try to reconstruct even the most remote scenes from the distorted perspective in which they see them from their own vantage points" (1986:178S). While his most pointed criticism is directed toward hydraulic and water-resource engineers, who tend to dominate hydrology, geographers do not emerge unscathed from his reproach. They are described as unable to "be stimulated by hydrology extending beyond rainfall-runoff correlations," and, in his house-of-science analogy, they are depicted as "looking through the wide-angle optics of the geography window" where they are "attracted by the broad outlines captured by multiple regressions" (1986:178S). This rather limited representation of geographical hydrology challenges us to reflect upon the nature of the "geography window" in the house of science. What *are* the research strategies through which geographers as hydrologists view the hydrologic components of the physical world? Are there identifiable dominant methodologies used by geographers as hydrologists, and, if so, do they play any role in fostering dilettantism, or a superficial approach to hydrology?

Methodological approaches are determined in part by the nature of the phenomena being analyzed. The current most widely accepted definition of hydrology (see National Research Council 1991; Dunne 1998) illustrates the immense scope of properties and processes that are encompassed by the discipline:

> Hydrology is the science that treats the waters of the Earth, their occurrence, circulation, and distribution, their chemical and physical properties, and their reaction with their environment, including their relation to living things. The domain of hydrology embraces the full life history of water on the Earth. (Ad Hoc Panel on Hydrology 1962:2).

Opportunities in the Hydrologic Sciences (National Research Council 1991) further refined the domain of hydrologic sciences, focusing on *continental water processes* and including the spatial and temporal characteristics of the *water balance* (solid, liquid, and vapor) in all compartments of the global system: atmosphere, oceans, and continents. Hence the phenomena considered in hydrology occur over scales ranging from microscopic to global, and milliseconds to millions of years. To investigate water across these vast spatial and temporal scales adequately, it was recognized that hydrologic science must be an earth science that is integrative and multidisciplinary.

Given this broad definition of the domain of hydrology, it is not surprising that physical geographers from within several subdisciplinary specialties (e.g., water resources, hazards, geomorphology, climatology, biogeography, cryosphere) are engaged in hydrologic research. A cursory survey of the recent geographic literature on hydrologic topics reveals an enormous breadth of investigations: water-resource studies linking hydrology and humans; global and local water balance investigations; studies of land surface-atmosphere interactions; climatic studies of precipitation, evapotranspiration, soil moisture, and snowmelt; synoptic climatology studies of floods, droughts, and snow cover; hydrologic regionalizations of streamflow behavior; flood frequency studies linked to causes of floods; hillslope and catchment runoff studies based on field monitoring and modeling; water quality and groundwater studies; riparian vegetation related to river processes; paleoflood and stratigraphic studies linking flooding variability to climatic variability; dendrochronological studies revealing past floods and droughts, and so forth. Most of the conclusions in these investigations are empirically derived from various statistical methods, although many studies make use of deterministic and physically based models to arrive at their results. In Klemeš's "geography window" analogy, he implies that the dominant geographic analytical approach in hydrology is an empirical one, e.g., multiple regression. If there *is* a unique or favored hydrologic research strategy among geographers, however, it is difficult to pinpoint because of the scope of phenomena examined and the wide spectrum of scales that physical geographers investigate. Hence the portrayal of geography's window as having "wide-angle optics" may indeed be a valid characterization—and not necessarily a disparaging one.

Methodologies are also determined in part by one's philosophical perspective. Haines-Young and Petch remind us that tools and techniques are only one aspect of methodology: "In terms of theory and understanding, quantitative measures, statistical models and sophisticated apparatus have in themselves little to do with science" (1986:200–201). Unwin suggests that for most physical geographers, logical positivism forms a sound philosophical foundation for their research. Furthermore, its dominance is so great "that it simply passes under the guise of good scientific method"(1992:155). As scientists, however, we have a responsibility to examine the philosophical underpinnings of our methodological approaches and be aware of their implications. Klemeš's dilettantism critique provides one avenue for such an examination. The following sections explore this further by presenting some generalizations about methodological choices in hydrology and discussing some of the issues these choices raise for geographers engaged in hydrologic research. In what follows, I proceed through a set of italicized claims that are subsequently elaborated.

Problem-Solving versus Process Studies

Philosophically, a reductionist approach aimed at problem-solving has dominated in hydrology. In fact, due to hydrology's engineering heritage—which has been marked by the quest for operational solutions, predictable outcomes, decision-making, and optimized design criteria—reductionism may be far more pervasive in hydrology than in any other earth science. It has also helped to breed dilettantism by a desire to latch onto "quick and dirty" solutions to complex problems. Alongside its applied research activities aimed at problem solving and water-related societal needs (e.g., water supply, flood control), *hydrology also has had an identity as a natural science, with the goal of exploring various processes and components of the hydrologic cycle in all their complexities and uncertainties.* It is this latter activity that has most attracted physical geographers. Indeed, some sources even describe this line of research as having originated in geography: "in the early days, hydrology had just been derived from geography and so it carried the imprint of the natural sciences . . .. This Geographical Hydrology stage . . . laid the foundation for the development of hydrology"

(Jiaqi 1987:18). Approaching hydrology as a natural science demands a sophisticated understanding of processes from a more physically based perspective and hence discourages dilettantism. In fact one of Klemeš's proposed solutions to the problem is to acquire deeper knowledge of climatology, meteorology, geology, and ecology (Klemeš 1986). Physical geographers have become increasingly cognizant of the need to develop expertise in these areas to improve the science within individual subdisciplinary specialties. But the broad scope of hydrological phenomena calls for an expansive and integrated grasp of multiple earth-science disciplines. Geography's long tradition as a synthetic discipline has the potential of rising to this challenge, providing multiple disciplinary insights into hydrologic processes "through the lenses of place, space and scale" (National Research Council 1997:28). Recent advances in reformulating hydrology's identity as an integrated earth science (National Research Council 1991, 1998a) echo this legacy, but it is up to geographers to participate in hydrologic science in this context. Thus far, the involvement of geographers in this new vision of hydrology has been minimal at best.

Mathematical Models—Boon or Doom?

Mathematical modeling has been the predominant methodological tool in hydrology. According to Kundzewicz et al., "mathematical models are a means of representing essential aspects of reality (process, phenomenon, object, element, system, etc.) with the help of mathematical constructs" (1987:71). Mathematical models come in many forms, but all are based on crucial underlying assumptions required for the use of a particular mathematical tool (e.g., normality, time invariancy, linearity, stationarity, homogeneity of the data, etc.). In many cases, the assumptions are not valid or appropriate, given the natural behavior of the process being analyzed, but the model is used nonetheless. To perform efficiently, models also require some form of parameterization in order to represent complex spatial or temporal heterogeneities in the real world. In both their simple and complex forms, mathematical models have been enthusiastically embraced in engineering-dominated hydrology. Of course this is also true in other scientific disciplines, but I submit that the pre-eminence of mathematical modeling over other forms of scientific inquiry has become a defining characteristic of hydrology over the last half century. In classrooms, students are subjected to neatly derived "blackboard hydrology"[3] more often than they are faced with the complexities of physical processes as they are observed in nature. In journals, readers are confronted with scores of equations resembling sheets of "flute music"[4] to describe sophisticated mathematical constructs that balance precariously on easily invalidated initial assumptions about real-world hydrologic behavior. These mathematical models reign because they have the ability to provide numerical solutions to engineering problems, and they offer "convenience and cost advantage over other means of obtaining the required information on reality" (Kundzewicz et al. 1987:71). But not everyone has been convinced of their ultimate value to the discipline:

> For hydrology as a science, the invasion of mathematical modeling was nothing short of a disaster. It has retarded rather than advanced the development of hydrology because, with few exceptions, it focused all efforts on polishing the mathematical and computational aspects of methods and techniques, leaving the understanding of the substance at the 1930s level . . . (Klemeš 1997: 43).

Klemeš (1997:43) further accuses certain modelers of ignoring or avoiding the substance of hydrological knowledge and, instead, believing that the mathematical rigor of their models and their goodness-of-fit to empirical data are "the supreme guarantors of scientific objectivity and the key to true and reliable hydrologic understanding." In such instances, mathematical modeling is yet another form of dilettantism wherein investigators who are not themselves statisticians sometimes take the statistics and mathematics too seriously: "Overawed by what they do not understand, they mistakenly distrust their own common sense and adopt inappropriate procedures devised by mathematicians with no scientific expertise"(Box 1976:798).

Empirical and Causal Models

The development of empirical models has figured more prominently in hydrology than the development of causal models. Prediction is viewed by many as the ultimate aim of hydrology, but the majority of predictive models in the discipline have been developed on the basis of empirical relationships, defined mathematically, "that tell us what happens but do not derive the outcome from the dynamic mechanisms governing the process" (Klemeš 1982:95). Geographers, especially, have taken an empirical approach in their hydrological analyses more often than a causally or physically based modeling approach. Empirical models often provide insights about underlying causative mechanisms and process dynamics, but the models themselves are not theoretical constructs that provide causal explanations. They "do not, and are not meant to, explain what is behind the data, but merely describe their observed pattern" (Klemeš 1997:44). Misconceptions occur when empirical results are interpreted as physically based cause-and-effect "theories" or when mathematically derived theory is equated with an explanation of the real-world physical behavior of a hydrologic process. Other problems arise when the mathematical structure of the model used in the analysis has no underlying physical basis linked to the process being modeled, but often is interpreted as if it did. A classic example of the latter problem occurs in the broad use (and misuse) of probabilistic models, extreme-value theory, and curve-fitting techniques in flood-frequency analysis. Typically a record of flood peaks is parameterized and fitted mathematically to one of many probability distributions, and the curve is extrapolated to estimate the size of future rare floods. The exercise takes place without any implicit information or attention to what the physical causes of the largest, rarest floods might be, or whether the behavior of smaller, more common floods is even a good indicator of what to expect under extreme flooding scenarios: "No hydrologic, climatic, geologic, or other physical conditions are involved in the analysis. The floods are stripped of all hydrologic context down to bleached skeletons of numbers giving their peak flows and these numbers are then subjected to the most rigorous treatments regarding plotting positions . . . apparently in an unshakeable belief that the amount of this rigor determines the degree of hydrologic relevance of the results" (Klemeš 1986:184S). The ultimate consequence of this state of affairs in hydrology, according to Baker, is that flood "science," "is increasingly becoming the mathematical manipulation of idealized parameters that are assumed to have flood-like properties" (1994:139).

Flood-frequency analysis is an example of an empirical approach that uses stochastic mathematical principles to predict a hydrological phenomenon. A large branch of hydrology is involved in developing predictive models on the basis of deterministic relationships (e.g., rainfall-runoff relationships, hillslope process models, etc.) These models usually have some underlying physical basis and may reflect a theoretical understanding of certain hydrological processes, but as Klemeš (1978) points out, determinism is not synonymous with causality. Causal relationships exist whenever one thing happens *because* of another, while a deterministic relationship is one that can simply be determined from the other, whether or not one caused the other. Hence even deterministic models need not be causal- or theory-based (in the sense that physically based explanation is provided). Haines-Young and Petch (1986) provide a critique specific to geography that echoes Klemeš's dismay over the dearth of causal models in hydrology: "in physical geography there have been very few advances in our theories about, or our understanding of, the natural world . . .. In addition, the vast majority of journals and advanced texts still contain material which is either merely descriptive or an attempt to model some phenomenon by statistical or simple mathematical equations akin to those employed by engineers" (1986:199).

"Theory" and "Practice"

In hydrology, a tension between "theory development" (often equated with mathematical modeling) and "practice" (often equated with field observation and experiments) manifests itself on many levels. A dissociation between these two pursuits can lead to dilettantism in the form of "mathematistry" (see Klemeš 1986). According to Box, "Mathematistry is characterized by development of theory for theory's sake, which, since it seldom touches down with practice, has a tendency to redefine the problem rather than to solve it" (1976:797). Collins suggests that, in hydrology, "field measurements and models appear to have lived separate existences, and the scientists forming these individual groups have tended to remain apart" (1987:95). One reason put forward is a lack of cross-training, i.e., that there are not many scientists with interest and expertise in both field and modeling techniques.

Nevertheless, according to Dunne, the "value of theoretical models can be greatly enhanced if they are developed in close cooperation with field studies. Such cooperation ensures that the physics of the problem is well understood and that the model is an adequate description of field conditions" (1983:27).

Field studies of hydrological processes combined with modeling have resulted in some important contributions to hydrology by geographers (e.g., see Dunne 1983). This is especially true for those investigations that have provided a strong link between hydrology and geomorphology, although field-based investigations and modeling of the hydroclimatic components of the water balance, especially evapotranspiration and soil moisture, have also involved geographers. As Baker and Twidale (1991) point out, however, a self-enhancing relationship between physical theory and observable process measurements can only be realized for processes operating within certain observable spatial and temporal scales of activity. To study hydrological processes outside this range (e.g., paleofloods, long-term droughts, global-scale processes), other approaches must be used.

Beven (1987), who writes from the perspective of catchment-scale hydrological processes, suggests that the relationship between theory, as defined by mathematical models, and process studies, may be facing a critical juncture within hydrology. He points out that many models used in hydrology have been applied in ways that are inconsistent with what is now known (based on new evidence from isotopes and remote sensing) about the hydrological response of catchments to storm rainfall. Moreover, while models are extensively calibrated by adjusting parameters to improve model results, in practice, there is rarely any hypothesis testing of model performance to evaluate the validity of the underlying theory. In light of these factors, Beven maintains that the branch of hydrology dealing with flow processes in catchments faces a theoretical crisis:

> We know that the assumptions underlying our macroscale theories are inconsistent with reality, but we have ways of protecting them through the process of calibration that has enabled us to avoid questioning them in a serious way. If hydrology is not to stagnate as a science, then it is time to consider seriously the limitations of our theoretical heritage. It is not sufficient that we can prove a correspondence between predictions and observations in terms of numbers, if the theory is incompatible with our perceptual knowledge of the operation of hydrological systems (Beven 1987: 400).

Shutters, Blinds, and Window Washing

The generalizations above provide a framework for stepping back from the "geography window in the house of science" to take it in as a whole and reflect on some of the questions raised by Bauer et al. Have geographers, through our methodological choices, shut out part of the view, leaving some things undetectable from the geography window? Have geographers put up blinds that distort or filter our understanding of nature, especially its scalar dimensions? Finally, what can geographers do to refit ourselves for an era of cross-training, avoid dilettantism, and clarify and sharpen our methodological view of hydrologic processes in the real world?

Consider, first, a wide-angle geography window that is composed of multiple small panes arranged in the row-and-column framework depicted in table 1 of Bauer et al. As these authors suggest in their essay, the empirical analytical techniques that are so widely used by geographers in hydrologic research represent only the upper left-hand side of this window. Moreover, such empirical approaches shut out that part of the view containing a theoretical emphasis on underlying causes in our science. There is a preponderance of geographical literature in hydrology that is absorbed in describing spatial and temporal patterns statistically, and often the analysis ends there. Although explanations for the patterns are usually discussed or speculated upon, the physical basis for the patterns and their underlying causative mechanisms are often given less attention than matters addressing the reliability of the model used or its goodness-of-fit. Of even greater concern is a tendency to interpret results as cause-and-effect without a critical examination of the explanatory limits of the analysis, e.g., the quality and nature of the data, the assumptions attached to the use of a particular technique, or the real-world behavior of the physical processes involved. Recently the analytical view from geography's window has been widening toward the right-hand side of table 1 (Bauer et al.). Newer analytical techniques aimed at more accurately modeling nonlinear dynamical relationships, such as chaos theory, neural nets, and fuzzy-rule-based models, are emerging as useful methodologies in hydrology that can better capture the way processes and relationships occur in nature (e.g., Rodríguez-Iturbe et al. 1989). Yet I have observed that an eagerness to incorporate the latest trends in methodology can often "blind" the researcher to the need for a serious examination of the critical assumptions involved in the technique. Each of the above situations may foster dilettantism. As physical geographers, we can counteract such tendencies by sharpening our knowledge of the natural phenomena we are analyzing, as well as the theoretical implications of the statistical analyses we use, even if this involves moving to another disciplinary window to gain a new perspective or a deeper understanding of a process.

I would argue that geographers involved in nonempirical physically based modeling of hydrological processes have a better view of the underlying theoretical structure of physical processes in nature than most empiricists. Nonetheless, the need to parameterize breaks up this view, blocking out or oversimplifying the details of process interactions at various spatial and temporal scales. Hence, instead of a panoramic view that integrates hydrologic processes continuously across spatial and temporal scales (suggested by figure 1 in Bauer et al. 1999:684),[5] the analytical view from most disciplinary windows is either extensively partitioned, or filtered to focus on only the broadest outlines. As Beven (1987) and Klemeš (1997) point out, an exclusive focus on parameterization and calibration to "improve the fit" of the model diverts the researcher from seriously questioning the model structure or its underlying assumptions from the standpoint of real-world processes. To move hydrology forward from this state of affairs, Beven (1987) suggests a new perspective on physically based models that views parameter values, input data, and model structures, not as "physical" values or theories, but as sources of uncertainty. Rethinking current theories from within this new framework and using it to test hypotheses and initiate new lines of thought would make prediction "a far more intellectually honest process than our current delusion-ridden methodologies" (Beven 1987:401). Ultimately, such an approach would allow hydrology to transcend its reductionist heritage and rediscover its roots as a natural science that "confronts and even gains energy from its own uncertainties" (Dunne 1998:13).

I suggest that this call for a reexamination and revisioning of hydrologic theories and their underlying assumptions illustrates one of the most important ways of advancing science. According to Brown (1996:13), theories can function as part of the methodology of a discipline when they serve as "guiding assumptions" that provide criteria for "deciding what questions are worth asking, what observations are worth making, what phenomena are problematic, and what counts as a legitimate solution to a problem." These guiding assumptions (theories), however, can be challenged empirically and replaced. In fact, according to Brown (1996:14), "we must get beyond the view that valuable scientific work consists only in the production of true results. In many cases, the most important outcome of scientific work is found in the contributions it makes to undermining the guiding assumptions on which it is based." Haines-Young and Petch offer a similar insight when they suggest that physical geographers must develop "the tradition of criticism" (1986: 201) instead of merely applying "new techniques to old questions" (Unwin 1992:156). The best "window-washing" we can do is to sharpen our critical stance toward our chosen methodologies, especially their underlying assumptions, the uncertainties they breed, and the conceptual frameworks from which they emerge. Bauer et al. call for such a critique toward the issue of integration across scales, which I will consider next.

The Need for a Telescopic View

Hydrologists have been grappling with scale issues for many years, particularly in the context of spatial scales in catchment hydrology (e.g., Pilgrim 1983; Gupta and Waymire 1983; Gupta et al. 1986; Wood et al. 1988), but also with respect to such issues as rainfall dimensions in hydrological modeling (e.g., Hamlin 1983; Rodríguez-Iturbe 1986); global-scale hydrology (see Eagleson 1986); soil moisture (e.g., Vinnikov et al. 1996; Mahmood 1996), the representation of hydrologic processes in climate models and vice versa (e.g., Hostetler and Giorgi 1993; National Research Council 1998b), and the discordant scales at which hydrologic and atmospheric processes operate (see Hostetler 1994). In 1983, a special issue of the *Journal of*

Hydrology (Rodríguez-Iturbe and Gupta 1983) was devoted to "Scale Problems in Hydrology." Klemeš's contribution to this volume, entitled "Conceptualization and Scale in Hydrology," argued that "in nature, scales of things are not arbitrary but arise as a function of their material substance and of the balance between the interacting forces . . . . we cannot impose scales but have to search for those which exist and try to understand their interrelationships and patterns" (1983:1). He further claimed that the range of meaningful scales is not continuous: preferred scales tend to "have concentrations around discrete states which seem to be rather far apart" (1983:2). Foreshadowing issues he would later raise in his "Dilettantism" paper, Klemeš took hydrologists to task for an arbitrary use of spatial and temporal scales in their analyses and for behaving in the following manner: "instead of *searching* for feasible ways of conceptualization of hydrological processes, they *postulate* the structures of their models on the basis of arbitrarily embroidered high-school diagrams of the hydrologic cycle with little concern for testability. The customary test, based exclusively on a fit of the model output to the recorded hydrograph, is hardly any better than reaching the exit from a labyrinth not by walking through it but through an artificial labyrinth of one's own construction built outside the real labyrinth's walls" (1983:3). Many model-based scale studies in hydrology have taken this approach by building numerically constructed multiscaled catchments over which rainfall events occur that are designed as identically distributed and mutually independent random variables that can arbitrarily be scaled up or down. While it is recognized that mathematical rainfall (or runoff) models are simplistic conceptualizations of a very complex reality, some have argued that such models work, despite their averaging and parameterization, because they mimic how nature manifests itself: "their success in hydrologic applications depends on the fact that in nature different laws governing the same physical phenomenon emerge at different scales and the laws at higher scales retain only the averages of the details of the phenomenon at a lower scale" (Rodríguez-Iturbe 1986:36S). But using nature to validate the behavior of a postulated model structure is contrary to the approach advocated by Klemeš, wherein the researcher searches hydrologic phenomena telescopically, identifies and focuses on scales as they exist in nature, and then tries to understand their interrelationships and patterns. For example, flood events recorded in the Santa Cruz River Basin of southern Arizona do not share the same seasonality, relative magnitude, or frequency of occurrence at all gauges (Hirschboeck 1985). By examining the different types of storm systems that produce flooding at each gauge in the basin hierarchy, I have been able to identify the scale of catchment size that experiences flooding more readily in response to summer convective thunderstorms, as opposed to winter synoptic-scale precipitation events. This is a scale limit defined by nature, rather than one emerging mathematically from a model simulation. While this result could be tested or reproduced in a mathematical model, it is initially based on processes as they occur in nature, and not on a derivation emerging from postulates and assumptions chosen because of their mathematical tractability. I would suggest that this process-based approach to scale analysis is less prone to the hazards of mathematistry and dilettantism. In addition, it is inherently geographic and fits well with the methodological framework depicted in Bauer et al.'s figure 2 (1999:685). In the case of the flood study described above, figure 2 could be modified by replacing the air photos at times t_1, t_2, t_3, etc., with weather charts or satellite images. Temporal records at gauging stations could be indicated on the figure to illustrate the occurrence of floods over a range of increasing spatial scales. Paleoflood data might be added to expand the temporal scale in both small and large basins, but there would be no corresponding "paleometeorological" information to assign a storm type to these older events. Paleoclimatic information from tree rings might provide an indication of the climatic background from which individual flood-producing weather events emerge, but until such records can be interpreted at meteorological time scales (see Hirschboeck et al. 1996), the analysis of flood causes and spatial scales would be constrained by the historically observed record. Since flood events tend to be discontinuous and episodic in time, and clustered in space, in response to the closing query of Bauer et al.'s essay (p. 686), I would not expect this approach to yield a "seamless integration" across all spatial and temporal scales. According to Hostetler (1994), the difficulty in reconciling the discordant scales at which hydrologic and atmospheric processes operate, remains a central problem in hydrologic research. Even if these methodological limitations were to be solved, the possibility that preferred scales of phenomena concentrate around discrete and disparate states may dictate that a seamless integration will never be achieved. Only by searching for the existence of preferred scales in nature will we draw closer to answering the question.

Geography and the "New" Hydrologic Science

Returning to the "house of science" theme of this essay, I would like to pose some additional questions about the significance of the "geographic window" for the future of hydrology. Throughout the twentieth century, many hydrologists have argued for a more scientific hydrology, especially in the U.S. (e.g., see National Research Council 1982). As the century ends, these efforts appear to be coming to fruition in the form of a "new" hydrology that vigorously asserts its identity as an earth science in its own right (National Research Council 1991; 1998a). How will geography—once considered a progenitor to hydrology—participate in this new and independent earth science? Will our geographic disciplinary and subdisciplinary perspectives sustain us methodologically in the future as we strive to make meaningful scientific contributions to increasingly complex hydrologic problems defined by this emerging new discipline?

As a preface to answering these questions, five points of interest to geographers about the "new" hydrology can be noted. First, hydrology has undergone a radical shift in point of view from an operational stance that viewed climate as stationary and time invariant (see Hirschboeck 1988) to a new perspective that is actively incorporating spatial and temporal climatic variability into hydrologic research strategies. Second, geographic information systems (GIS) are playing an increasingly important role in the analysis of surface and subsurface hydrology. Third, remote sensing has become an essential tool in hydrologic research, especially in multidisciplinary research initiatives (e.g., GEWEX, GCIP, see National Research Council 1998b) that are currently underway to address global-scale hydrology and the role of hydrologic processes in land surface-atmosphere interactions. Fourth, issues of scale are at the forefront of many of the critical and emerging areas of hydrological research, especially in land surface-atmosphere interactions and in attempts to reconcile the discordant scales of hydrologic and atmospheric models. Fifth, environmental-societal dynamics are gaining attention in hydrology because human activity is recognized as an active and increasingly consequential element of the hydrologic cycle. Although no single discipline "owns" any of these research areas, geography has a strong tradition of involvement in each of them. Provided we have attended to our "shutters, blinds and window washing," physical geographers *should* stand poised and ready to make significant contributions to hydrology from the perspective of our "geography window" in the house of science. But will we rise to the challenge?

Dilettantism Revisited

Before closing, let me return once more to the critique of dilettantism. Geographers are not immune to practices that foster a superficial understanding of hydrology, and certainly there are dilettantish leanings in many of us, when viewed in the context of Klemeš's critique. I propose that one way we, as geographers, can supplant dilettantism, is by contributing a distinctive methodological approach to hydrology in its place. It will require a concerted effort to acquire an integrated and sophisticated understanding of the full range of hydrologic processes, and to combine this with a sensitivity to place, scale, and human/environment interactions. This approach should be characterized by a critical stance toward the guiding assumptions in hydrology, one that is informed by an integrated knowledge of hydrologic processes, especially those that operate at the interfaces of the domains of geomorphology, climatology, biogeography, and so forth. This approach should also incorporate geography's long tradition in environmental/societal dynamics (e.g., flood hazards, water-resources policy) by aligning it more directly with the physical processes involved. In addition, it should attune expertise in the use of geographic information systems and remote sensing to hydrologic applications. Finally, this approach should employ the best analytical tools geography can develop to address the issues of scale integration raised by Bauer et al., and to explore and analyze the natural temporal and spatial scales of hydrological phenomena as they emerge in nature. It is clear that such a scientific contribution to hydrology cannot be accomplished within any one subdisciplinary specialty of geography. Cross-training and cross-communication would need to increase among geographers of all types. Hence Klemeš's critique on how one's "primary discipline" influences one's hydrologic perspective should also be directed within geography—that is, to geographers who cling to their primary *subdisciplinary* geographic perspectives (e.g., geomorphology, climatology, biogeography, hazards, quantitative methods, remote sensing, GIS, etc.) when addressing hydrologic subjects. As Dunne reminds us: "experienced scientists repeatedly emphasize that scientific breakthroughs commonly arise when scientists break out of their disciplinary isolation and collaborate in the unexplored territory between specialties" (1986:29). For hydrologic research in geography, a great deal of unexplored territory awaits.

Notes

1. The paper also provided a springboard for self-reflection among physical geographers engaged in hydrologic research during a stimulating panel discussion on "Geographers as Hydrologists: Are We Guilty of Dilettantism?" which was sponsored by the Water Resources Specialty Group (WRSG) at the 1992 Annual Meeting of the Association of American Geographers in San Diego. The panel, composed of physical geographers with various hydrologic interests, deliberated over the question without reaching a definitive answer.
2. The focus of this essay is on *hydrology* rather than water resources, although research efforts in these two areas are closely related and frequently interconnected.
3. J.E. Nash, personal communication, cited by Klemeš (1986:187S).
4. The "flute music" metaphor is attributed to Walter Langbein, the eminent U.S. Geological Survey hydrologist and former editor of *Water Resources Research,* who used it to refer to the general appearance of manuscripts submitted to him that involved elaborate mathematical modeling.
5. See figure 2.9 in National Research Council (1991) and figure 1 in Hirschboeck (1988) for similar scale diagrams depicting hydrologic processes, specifically.

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