Hydrol. Earth Syst. Sci. Discuss., 6, 2931–2959, 2009
www.hydrol-earth-syst-sci-discuss.net/6/2931/2009/

Hydrology and
Earth System
Sciences
Discussions

Hierarchy theory in hydropedology

T. F. H. Allen[1], P. C. Allen[2], and D. L. Wixon[1]

[1]Department of Botany, University of Wisconsin-Madison, Madison, Wisconsin, USA
[2]Nelson Institute for Environmental Studies, University of Wisconsin-Madison, Madison, Wisconsin, USA

Received: 3 February 2009 – Accepted: 9 February 2009 – Published: 1 April 2009

Correspondence to: T. F. H. Allen (tfallen@wisc.edu)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The challenges that face scientists in the bourgeoning field of hydropedology include many of those that face investigations in complex systems. We suggest hierarchy theory as being particularly helpful in teasing through complexity in hydropedological investigations. We present a brief overview of hierarchy theory highlighting the importance of defining levels of analysis, the role of theory in prediction, and the importance of narrative in science. These concepts are highlighted by references from the hydropological literature. We point out several issues common to scientists faced with complex systems analysis, and suggest several strategies to help hydropedologists deal with them. In order to help bridge the gap between theory and application, we present several specific examples of how hierarchical treatments have helped scientists deal with the modeling and analysis of complex systems related to hydropedology. We conclude that hierarchy theory offers many powerful tools with which to tackle the complexity inherent in soil water interactions, and that its use would benefit a more systematic and robust integration of the hydrologic and soil sciences.

1 Introduction

Hydropedology is an exciting new interdisciplinary field of investigation that will likely offer significant contributions to both the hydrological and soil sciences (Lin et al., 2006). The challenges that face scientists in this field include many of those that face investigations in complex systems. We offer hierarchy theory as being particularly helpful in teasing through complexity in hydropedology.

A key question facing hydropedologists is how to determine appropriate measurements, and associated modeling parameters, for a spatio-temporal scale of interest (Lin et al., 2006). The belief that a single model or methodology will apply across scales has repeatedly been disproven; one recent example in the context of calibrating unsaturated zone soil moisture models (Shiekh and van Loon, 2007). Scales of importance here include time, space and soil depth. Soil hydrology is so notorious for its extreme variance in space that it is frequently modeled as being randomly spatially distributed, or stochastic in nature (Smart and Werner, 2007).

This example reveals that asking deceptively simple questions about, measuring, interpreting and modeling a complex system require a broader understanding. It is recognized that hierarchy theory in particular, and associated complexity theory in general, have much to contribute in both conceptual and operational terms towards the quantification of the structures of soil and hydrologic systems (Lin et al., 2006). However, the learning curve and addition of jargon can be effective deterrents to their application. Although the introduction of jargon will be unavoidable, the terms we describe come from the robust language of systems theory; a theory that seeks to define the structure and behavior of general systems. As opposed to the jargon generated as disciplines subdivide and become more specialized, systems terminology is purposefully general and interdisciplinary. Because the discipline of hydropedology is in the process of integrating two previously autonomous disciplines, we argue that systems terminology, due to this generality and interdisciplinarity, is particularly useful.

It is the purpose of this paper to elucidate some of the concepts of hierarchy theory so that they might benefit the field of hydropedology. Beginning by acknowledging the presence of complexity within the hydropedological discourse, we utilize hierarchy theory as a method of dealing with that complexity. This process begins by defining a level of analysis in order to delineate and simplify a system for predictive modeling. Recognizing, however, that models generally fail to achieve scale-independence, we introduce narrative as the principle means of understanding and communicating the diverse and multi-scale processes characteristic of complex systems. Along the way, we identify several problems common to scientific treatments of complex systems, including middle number systems, and semantic arguments, and provide tips on how to avoid such potential minefields. Finally, to help bridge the gap between theory and application, several examples are provided to demonstrate how concepts from hierarchy theory have been applied in the analysis of complex systems related to soil and water

interactions.

2 Hierarchy theory

Hierarchy theory is a device for helping scientists deal with complex situations. Hydropedology emerged from its parent disciplines to answer questions at the interface of hydrology and pedology that require the knowledge of both (Lin et al., 2006). Of course water flow anywhere is complex. And yes, soil is complicated in its types and in how it develops. But combine the two in soil water relationships and the resulting system exhibits behaviors typical of complex systems, including nonlinearity and strong dependence on initial conditions (Pietgen, Jürgens and Saupe, 1992). This makes both data collection and modeling singularly challenging, and the signature problems of complex systems arise: differing interpretations of the same data, challenges in determining which parameters to include in models, and scale-dependent results (Wixon, 2008).

In a complex system there is no uniformly best level of analysis (Giampietro, 2003), and this generates ambiguity that frustrates the modeler. A level of analysis can be defined as a focal view with an acknowledged context (Giampietro, 2003), a perspective, or boundary of an observer's interest. It is comprised of all the decisions and assumptions an observer must take in order to create a model. To make a model one needs to separate: 1) structure from behavior, 2) discrete from continuous, 3) significant change from incidental dynamics, 4) rate-dependent aspects from rate-independent. Making these decisions defines the scientist's perspective, what we call level of analysis. As those decisions are made complexity is stripped away and modeling is now possible. In a simple system, everyone agrees on the level of analysis necessary to make a model, and many may not realize that one even exists. In complex systems, however, it is absolutely necessary to explicitly define the level of analysis behind any model. The purpose of hierarchy theory in this context is to develop a set of rules and guidelines in order to make the process of defining a level of analysis in the face of complexity more orderly and consistent, thus increasing the quality of resulting models.

Analyzing messy situations involving many components of different size and type often benefit greatly from hierarchical treatments. Hydropedology is no exception. Ackoff (1974) utilized the term “mess” in order to explore its characteristics and the utility of a systems approach. In short, he determined that no mess is tidied by solving each of its component problems independently of the others because no mess can be decomposed into independent components (Ackoff, 1974). Hierarchy theory is a dialect of general systems theory (von Bertalanffy, 1968) taking a particularly set theoretic approach. It organizes elements into groups (or “levels”) by recognizing asymmetric relationships between them. To give a core example of what is meant by “asymmetric relationships”, a classification system may be better structured based on what is rate-dependent or rate-independent (O’Neill et al., 1986) than the state vs. process split common to hydrology.

The goal is to retain the expansiveness of the system in all its complexity, while making it manageable enough that effective discourse and meaningful models can exist. Hierarchy theory organizes elements into higher and lower levels according to a few general principles. Higher levels are higher because they: behave at a lower frequency; constrain lower levels by behaving more slowly; are the context of lower levels; consist of and contain lower levels; have lower bond strength. All of these principles may apply, but often only some of them do. The last two (consist of and bond strength) pertain to nested systems by virtue of containment. Lower level entities have a more powerful integrity and release more bond energy when they are broken (c.f. chemical versus nuclear explosives) (Fig. 1). For example, the watershed of the Mississippi River can be viewed at a higher level than the Ohio River watershed. The dynamics of the higher level behave at a slower frequency: the residence time of a water molecule is much longer. In this case, the higher level also physically contains the lower level.

Hierarchy theory deals with the danger of a simplistic application of the “levels of organization”, as in the watershed example, and is more broadly conceived than a

single series of levels. Its concern is reconciling the broad range of spatiotemporal scales involved in complex systems, a concern that is currently a focus of hydropedology research (Lin et al., 2006). A rate-structured rather than size-structured hierarchy applies, for example, in the definition of a rhizosphere. Root structures and associated fungal and bacterial communities sharply differ in size, but organizing them as a series of tangible objects of differing size and isolating water use of each independently is not useful. However, considering the soil water, microorganisms, soil invertebrates and associated roots as an entity distinct from bulk soil or aboveground processes is simple if rates of nutrient cycling define the asymmetric relationship instead (O’Neill et al., 1986).

2.1 Scalar versus definitional hierarchies

Ahl and Allen (1996) identified two sorts of hierarchy: scalar and definitional. Hydrologists often use scalar hierarchies such as basins, watersheds, catchments, and digital elevation models (Maidment, 2002), while pedologists often use definitional hierarchies such as the pedosphere, regional physiography, toposequences, and pedons (Wilding, 2000). Scalar hierarchies use levels of observation, where larger entities reside in upper levels. Definitional hierarchies assert levels of organization. The size that is so critical in scalar hierarchies is often spatial but it may also be temporal. Scalar hierarchies use levels where grain and extent pertain. Grain notes the finest distinction made in an observation (Allen and Hoekstra, 1992). For example, the general public cannot access Land-sat images of ocean at the grain as fine as 10 m because at that grain water can be distinguished from water with a submarine in it, one of the few state secrets that really matters. In definitional hierarchies, levels of organization are not particularly scalar, although they may exist inside a range of sizes. For instance, the organismal level of organization does not contain things that are of a particular physical dimension in principle, even though an organism falls in the size range from a bacterium to a redwood. In a definitional hierarchy, then, relationships between levels of organization are not size based, but are rather a matter of definition. Note that the population level of organization would appear bigger than organisms, except that many populations are smaller than many organisms, as when populations of parasites are smaller than their host organism. This is where definitions come in, because the population is only an aggregation of organisms that are, by definition, somehow equivalent.

Control hierarchies are a subset of definitional hierarchies where the asymmetry defining a level derives from what controls what. For example, a control hierarchy may have a small controlling element at an upper level that constrains a much larger entity, for instance the Watt governor that constrains and is the context of a steam engine. It takes this degree of precision to keep hierarchies straight. So the role of hierarchy theory is to make explicit those systems that are hierarchical, and to take responsibility for the decisions necessary to make them that way. Hydropedologists thus have the challenge of navigating between these different types of hierarchies in a cohesive way, and hierarchy theory can help.

It is usually an error to mix definitional and scalar hierarchies, since they represent two fundamentally different types of ordering. The relationship of organisms to populations seen as scalar invites confusion. Organisms can be large or small, but a given observed organism does appear at a particular size. It would be possible to translate entities defined by type to a particular observed set of scalar relationships, but the error of overgeneralization waits for the unwary. It might be helpful to compare two hierarchies, one scalar and the other definitional, but one cannot simply smear them together and be consistent. Hierarchical relations can be used as devices, but make the categories work for you. Do not work for the categories as if they were something imposed by nature. In soil science it might be possible and desirable to rank soils by grain of the particles, perhaps as a surrogate for percolation. However, there is usually not then a simple way to aggregate soil types within defined categories in a way that corresponds to soil grain size. The important thing to remember is that hierarchies are each created for a particular purpose (Fig. 2). Different processes at different scales may require the application of different hierarchies. For example, at a larger scale, hydrologic systems may constrain system behavior, and an associated scalar hydrologic hierarchy

may be appropriate. However, at a smaller scale, behavior may be constrained by soil properties, where a definitional hierarchy may be more useful.

There is much more to hierarchies than the examples that prevail in the literature of ecology and biology. The simplest examples move up time and space in lock step, a linear upward sloping trend in a log space and time plot; and these are favorites in ecology. Leaves live a short time, trees live longer, forests longer still, while biomes persist many millennia and so on. A biotic hierarchy may be compared to an atmospheric hierarchy that also locks time and space: boundary layers, diurnal temperature changes, seasonal changes, decadal weather cycles, local climate change, ice ages and so on. When biotic and abiotic hierarchies are compared there is something to be said for keeping them simple, but this is a somewhat crude and certainly not necessary arrangement. By contrast there are other entities that are not in lock step spatially and over time. For instance the whole planet shows diurnal change. Meanwhile the Meyer's line separates islands on either side only kilometers apart but it divides the flora and fauna of Asia from Australasia, a matter of evolution over hundreds of millions of years of continental drift (Fig. 3).

Hierarchy theory is thus a means of organizing diverse sets of information in a cohesive and useful way. Instead of relying on nature to organize observed data, hierarchy theory recognizes the role of the observer in organizing this information. Agreeing upon organizational structure allows science to carry forward more consistently and logically. In order for modeling to be useful and consistent, scientists must define their level of analysis, taking responsibility for the assumptions and decisions necessary to construct their model. This process is straightforward and largely taken for granted in simple systems, where everyone agrees on structure and function. However, defining a level of analysis is critically important in complex systems where observed data are not organized in any widely accepted way and there are often contradictory and incommensurate methods and metrics. In these systems, the appropriate level of analysis is rarely straightforward, and when multiple models are made of the same system from different levels of analysis, disagreement and confusion among the models' results necessarily arise. That is why hierarchy theory is so helpful in complex situations, although not always in an entirely intuitive way.

2.2 Theory and prediction

Hierarchy theory is a special sort of theory that may not meet criteria for what many would have theory be, because of its relationship to hypotheses and predictions. It does not make predictions per se, but rather explicitly extracts the functional structure of the system from the data, rather than relying on an arbitrary designation of components (O'Neill et al., 1986). This opens the way for hypotheses that can better parallel system behavior, yielding predictions that can be accurate for novel situations. Although making a prediction is largely taken for granted, the nature of prediction is counter-intuitive. Ken Boulding once said that all predictions are that nothing happens. It would appear that a pool player predicting "Black ball, corner pocket" is saying what will happen but in fact the prediction refers to a set of things that do not change. The player is still skillful, the cue will effect motion in the cue ball like it always does, the balls will interact as they always do, the cushions will interact with the balls as usual, the table will stay flat, and nobody will move the pocket. If any of those things change, the prediction will almost certainly fail. Furthermore predictions are relative to a time frame. "Black, corner pocket in ten years" will not come true because there is a good chance the pool hall may be knocked down, perhaps in a San Francisco earthquake. In other words, if you wait long enough at least one of the things that need to remain constant will not. On a pool table, during a short time span, prediction is pretty straightforward. In hydropedology, however, many different processes and patterns interacting at many different spatial and temporal scales makes prediction a much messier ordeal. The idea that only factor will change while others remain constant, such as temperature causing only evaporation and reducing soil water content, is not correct; increase temperature will also impact the plant and microbial use of soil water.

Hierarchy theory can help by pointing to what questions can be answered, and what questions cannot. Weinberg (1975) distinguished three sorts of system specification:

small, middle and large number systems. Small number systems, such as solar systems, may be modeled and predicted with one equation for each part. Large number systems, such as radioactive chain reactions or the gas laws, have more than Avogadro's number of particles in the system. In the case of the gas laws perfect gas particles are invoked, which have no volume, no mass and no friction. Clearly these are false assumptions, but with so many particles predictions are achieved regularly using some representative values. Systems with millions or even trillions of particles have too many to parts to model each one separately, but also have too few to offer representative average values for predictions. For instance, in 1923 German police shot into a Nazi mob, killing one of them. Standing next to the slain man, unhurt, was an unknown Austrian house decorator who turned out to be Adolf Hitler. Clearly the world would be a very different place had Hitler been the one killed, but that difference would have appeared incidental at the time. One would need Avogadro's number of Germans to get a prediction there. In these middle number systems, as they are called, one cannot predict which particle will take over and govern whole system behavior. If there were an opportunity to run the system again, it would turn out differently. Careful experimentation is therefore no defense against a middle number specification, since prediction is in principle impossible.

The only thing to do with middle number specification is to change the question at the crux of the prediction. One simply has to change the investigation so it gives a predictable answer to a question that can be answered. Changing expectations in a new question may well give something adequate. Hydropedology invites many middle number specifications. The approach of hierarchy theory is to search for the rate structure that already exists in the system (O'Neill et al., 1986). It is important to realize that the inability to predict is not a data problem, it is a matter of system scaling and assignment to type, both arbitrary considerations. Hierarchy theory is of great utility in scaling and assigning system parts to a type, and that can rescue many discourses, including those that frustrate hydropedologists.

For example, soil water content alone is rarely a meaningful metric; the interaction between water content and soil hydraulic properties determine how tightly it is held in the soil matrix (Del Grosso, 2005). The data is not the problem. The problem depends on the purpose for which the soil water measurement is to be used, the matter that might invoke hydropedology in the first place. The situation is made stickier as these issues surrounding soil water are addressed. Consider which metric to use when addressing soil water available for microbial decomposition. Soil moisture effects on decomposition are often expressed in incompatible terms in models (Rodrigo et al., 1997), which then lead to contradictory results. How do we measure how much water is in the soil? There are a surprising number of answers, including water filled pore space, volumetric or gravimetric soil moisture, matric potential, depth to water table, all hydropedological measures. Hydraulic conductivity, the tool of hydrologists, is rarely of direct applicability to soil carbon cycling. The volume of water-filled pores (WFPS) may be favored (Linn and Doran, 1984), as it is considered estimator of limitations to microbial activity (Robertson et al., 1999) and incorporates bulk density. WFPS may be estimated by simple measurements of bulk density and gravimetric water content, and is used by large-scale models (Kucharik et al., 2000). However, it has limitations; for example, air diffusivity better explains net nitrification compared to WFPS in wet soils, while solute diffusivity may better explain aerobic respiration in dry soils (Schjonning et al., 2003). Modelers have noted that percentage saturation is less consistent with nutrient diffusion models than volumetric soil moisture (McGuire et al., 1995). Some models use the volumetric fraction for the soil moisture metric as well as for field capacity definitions (Izaurralde et al., 2006). Other authors have found that considering the depth to water table has an important effect on soil respiration (Smith et al., 2003). Still others find that matric potential is more appropriate than either volumetric or gravimetric (Davidson et al., 1998), as it expresses water available to organisms across soil textures. Ultimately many metrics can be interconverted using correlated factors such as soil bulk density, but there is no convention for modelers or experimenters.

Attempts to find scalars of soil water content that function consistently across soil types have been made, but the utility of most of these functions remains site-specific

(Davidson et al., 2006). Convention is useful for cross-investigation comparison, but there are good reasons for the failure of one best measure to emerge. Each investigation must take responsibility for the adequacy of the measure they choose. Everyone comparing results must moderate what they say with an announcement of the consequences of the inconsistency of measures used on each side of the comparison. There is no solution except transparency and common sense. More data will not force consistency.

2.3 Semantics and logical types

Beyond the nightmare of middle number specification there are many semantic arguments that arise because of conflict in scale specification: hierarchy theory can often clear up those problems. Once semantic arguments are identified, they can be considered for what they are. Those differences that are more than semantic can then be set up as proper competitive models and tested. Predictions would come from the results of those tests. Hydropedology is rife with situations that may be equivalent for some purposes but not for others. The conflicts and tensions above in how to measure soil water are a case in point. The default setting for scientists is that more data will solve most problems, but quite often it is not a data issue but one of hidden conflict between incompatible levels of analysis. Hydropedologists will still be responsible for making their own predictions, but hierarchy theory may help them get to that point by identifying what is and what is not equivalent.

By identifying what is contextual to what, relationships can be made unambiguous by hierarchy theory even if there is still not a formula for easy translation of one to another. For instance, depth to water table and potential air spaces in that soil type are the context in which the volume of water filled pores is set. Sometimes measurements may even be in the same units but still be incommensurate, in which case the strategy and systematic approach of hierarchy theory can anticipate potentiality for inequivalence. Human social settings can give intuitive examples. For instance, the amount of food consumed by the average American will come out in calories whether or not the amount of food thrown away by the average family is or is not included in the estimate. It depends on the definition of "consumed". Some differences in expression of measurements may be well established so that critical meaning can be extracted, as in absolute versus relative humidity. It is no accident that nightly weather reports use relative humidity since it addresses likelihood of precipitation and how the air feels to the listener. When investigating a complex system such those in hydropedology, often researchers will develop a new ad hoc measurement scheme tailored for a particular situation in order to produce a mechanistic model. The ordering strategy of hierarchy theory can expect likely errors in such unfamiliar situations, especially in the form of semantic arguments.

Semantic argument mistakes models as competitive when in fact they can be reconciled when it is recognized that they address different logical types (Whitehead and Russell, 1910; made accessible by Bateson, 1980). To define logical type by an example, the concepts of carnivore and herbivore belong to the same logical type – animal assigned to a class by what it eats. However, carnivore and cat are of different logical types because the former is a superset of the latter. There is great potential for getting muddled when more than one logical type is present in a discussion. We turn to an intuitive human setting once more, so we can make our way across a minefield of misconception.

Consider the question, "Why does a mirror switch your image from left to right but not from up to down?" An engineering colleague recently admitted not seeing how a mirror switches the subject left to right in the image, so let us be careful here. To see the left right switch one must give identity to the image as a thing in itself. The "person" in the image may not be a three dimensional material being, but in the conceptual realm, which is the issue here: we can see an equivalence to the actual person. An observer of all this can see the person and see the image of the person in the mirror so they can be considered in equivalent terms. If the actual person raises its right arm, the image appears to raise its left arm. Since measurement in hydropedology is some version of what we "see" with some instrument, the mirror situation is in fact relevant.

The relationship between up/down as opposed to left/right might appear simply that they exist at right angles. Indeed they are when one is making the sign of the cross. In that specific case up and left are forced into the same logical type, that is, a direction relative to the center of some being. But in the questions about the mirror that unity breaks down. Up refers to an external context while the left side is possessed internally by each individual. Thus up belongs to a different logical type, a level of analysis that is more inclusive as compared to the left side of a person. Being differently inclusive, up and left would not be expected to be explicitly related, and indeed they are not. The left right switch comes from using a lower level of analysis where the image in the mirror is given its own identity. It moves its left side in correspondence to the actual person's right side. But moving up scale takes away the identity of the reflection. At that upper level of analysis one does this by simply making the reflected image part of a mirror reflecting. It is not a "person" any more it is simply a reflection. At this upper level the head of the person reflected is opposite at the top of the mirror, where the head is reflected, so there is no change. The feet are reflected at the bottom of the mirror, again no change. More significant is that there is also no change on the left side of the body being reflected in the left side of the mirror. At that upper level of analysis, where the more inclusive type of "up" resides, there is no switch.

Things belonging to different types are easily mistaken as being directly comparable when they are not. The last amount of water in a soil is much more tightly bound to the soil particles because the phenomenon of surface tension reigns in such thin layers. Water is much more loosely associated with soil particles in waterlogged soil – lift it up in a porous bag and the water gushes out. Certainly it is still water, but the phenomena that govern it are different than those that constrain the last one percent of water in a soil. It is these differences that lead to complex phenomena such as hysteresis in soil wetting versus drying as well as the complexity in interpreting depth to water table. With its care in scaling, bounding and assigning entities to types, hierarchy theory can sort out those problems so that everyone knows what the scientist analyst is saying.

The point of this discussion is to highlight the common problem of semantic arguments in science. This issue could be particularly problematic for hydropedology, as it combines two disciplines, each with its own terminology, assumptions, and levels of analysis. Care must be taken throughout the integrative process in explicitly defining logical types in order to avoid semantic arguments. Once logical types are defined and agreed upon, scientists can compare models confident that the data, and not semantics, lie at the root of their model's results.

2.4 Post-normal science and the importance of narrative

Funtowicz and Ravetz (1993) developed the idea of post normal science. One might like science to be unambiguous and confident, but sometimes the important problems do not invite such tidiness (Allen et al., 2001a). How does one respond to a system with high intrinsic variability when the time is short, the stakes are high, and the values are in conflict? Use post-normal science. Medicine is faced with those situations all the time. "I want to get my confidence limits down to p=.05" "Yes but he will be dead by Tuesday, so give me your opinion now." Such is the lethal importance of landslides and the short lead-time on critical conditions. Such are the conflicts between extracting forest products and erosion. Such is the intrinsic variability of the behavior of water in soil that hydropedology invites a post-normal approach. Post-normality turns to quality narratives, and hierarchy theory is a useful tool for making evaluations that go into crafting compelling stories.

Developing high quality narratives is a key process when dealing with complexity (Zellmer et al., 2006). Models are definitive and internally consistent but that is not the be all and end all of science. Narratives can normalize across scales and incorporate models at different levels of analysis (McCormick et al., 2004). Narratives are the bottom line in science even though they need not be internally consistent. Tolerance of inconsistency gives narratives the power to move up scale and grasp the whole. Stories are not in themselves about verity, but are rather statements of beliefs embodied in a set of decisions as to what matters and when it counts (Cronon, 1992). Models improve our trust in a narrative by inserting an understanding in which we may have

confidence by virtue of the internal consistency of models. But to achieve that consistency, models are forced to be relatively local so that inconsistencies may be avoided. Because different processes dominate at different scales, hydropedological models are necessarily bounded in space and time (Lin et al., 2006), and are therefore relatively local. These models break down at higher and lower scales, as other processes take over. It is important that each process be explicitly bounded by appropriate spatial and temporal scale (Samouelian and Cornu, 2008), defining its location relative to other processes. Once a sequence of processes has been mapped at different scales, narrative becomes the only tool to grasp and communicate the relations between them. Models of these processes improve the quality of the narrative.

A narrative is a description that compresses a system down to those events that the narrator decides matter for the story (Cronon, 1992). In the humanities, narratives are woven by researching documents describing events taken place in the past. In science, narratives are composed of models describing collections of data. Paradigmatic vocabulary, methods, and relationships of components, usually assert a scale for the players and relationships involved. They compress the universe of interest down to common interests and beliefs that generate a set of favored definitions. Predictions are made inside what a paradigm leads the group to expect. A narrative takes the scale and events of interest, provides an arbitrary start to the story and after it has finished nothing happens. Moving the story forward, as it is told, is what matters. Hierarchy theory is a set of devices for achieving that compression or changing the compression to one that asserts a more useful frame of reference. Once told, narratives have the unique ability to communicate complex phenomena in a cohesive and compelling way. Probably the most powerful property of hierarchy theory is its ability to reconcile confusion and contradiction, and fix it by suggesting new narratives, new intellectual frames and ways of getting to them.

For those who prefer science to be objective and unambiguous it feels uncomfortable to assert that the power of scientific advancement lies in telling stories, but a change in narrative can open up new research arenas. Beland and Allen (1994) suggest a primitive genetic code that reads both DNA strands in both directions. If both strands in both directions must mean the same thing, then there are only 20 separate meanings, which correspond with the number of amino acids on the modern code. That old code remarkably enough lies perfectly at right angles to the modern code charted out in rows of shared meaning (e.g. a row of CC-anything means proline, while GG-anything means glycene). The new code has stop codes going for it along with its capacity to code for 20 amino acids. It appears that the move to the new code may have resulted from the modern code using its stop codes not so much as punctuation, but as weapons to jam any misreading, including the old code. The prevailing narrative is that stop codes are punctuation, but if we erect a story where they are seen as weapons against any rival reading of DNA then new options appear. If stop codes are weapons: we can ask, "Is cancer using stop codes as weapons against us?"; or we can ask, "Can we use stop codes as weapons against cancer?" By changing the narrative, the scientist opens up new avenues of investigation with the potential of sparking new paradigms (Fig. 4). Hierarchy theory is one of the few scientific devices inviting new narratives to open up novel research possibilities.

Narrative thus serves several purposes for science in the realm of complexity. First, it allows scientists to communicate diverse phenomena existing at multiple and often incommensurate scales. Because they must remain internally consistent, quantitative models, being constrained to a specific scale, cannot grasp the relations between processes at multiple scales. But they do increase the quality of the narrative that weaves the models together into a convincing story. Another use for narratives, are their ability to open up new lines of research by re framing conventional wisdom. In both hydrology and pedology there are many models of many diverse processes that hydropedologists must integrate and understand cohesively. We suggest that hierarchy theory, in its care for organization, logic, and consistency, can assist hydropedology in constructing high quality narratives of their systems, even in the midst of complexity.

3 Experimental examples

3.1 Wind and plant growth

Schneider and Kay (1994) suggest that quite the opposite of challenging the second law of thermodynamics, life actually depends upon it to generate emergent structures. Life shortens those gradients and exploits the flux, as when food is degraded rapidly as it gives up its high quality energy that is then used to drive life's processes. They argue that the gradient on land that drives life is warm planet to cold outer space. Plants use the latent heat of evaporation of water to perform the work of moving water and nutrients from roots to the canopy. As a result, the more work the plants perform, the more they exploit the heat gradient and the colder is the upper surface of the vegetation. Cool vegetation means fully functional vegetation. Hydropedology pertains here in that the gradient is exploited by taking water from the soil. In a set of experiments Allen, Havlicek and Norman (2001b) measured vegetation to see the emergent property of life under the second law that is actively cooling to do work.

Allen, Havlicek and Norman (2001b) grew plants in different wind speeds and found that plants were coolest, that is they are doing more work, when they were situated in the environment in which they had been grown. They were warmer, doing less work, when placed in some other wind speed. Complexity theory suggested to the experimenters that mixed vegetation would be cooler because of increased complexity. The plants reared in slow wind were taller because they had to invest less in stems to resist the wind. The mixed vegetation was warm because the slow wind plants were up in the wind, while the fast wind plants were down out of the wind. By growing plants so that fast wind plants had longer to grow tall, the reverse arrangement was achieved with fast wind plants up in the wind, while young slow wind plants were down in the vegetation. This is a more natural arrangement since the oldest tallest plants indeed do grow in the wind in nature. The vegetation immediately was cooler, indicating it was more functional.

The even and uneven aged experiments were compared directly by subtraction of results of the experimental outcomes. It appeared that the plants grown in faster wind were functionally the same temperature whether they are up in the wind of down in the vegetation. However, the slow wind reared plants were significantly cooler if they were out of the wind, down in the vegetation in the mix that more resembled natural vegetation. This result showed not only the functionality of correct placement according to rearing environment, but also how the increased functionality worked. The slower growth of the fast wind reared was the price of entry paid for living in wind. In or out of the wind was a comparable situation for them. Those canopy plants appeared to protect the slow wind reared under story, increasing the functionality of the whole mix when the faster wind reared plants were in the place they would have been in natural vegetation. Complexity works by one part of the system taking a hit such that it protects the functionality of the whole system: when a big tree falls it is replaced by another that may be much younger but is not much shorter, since the younger tree has been protected by larger and so has grown faster.

These experiments in vegetation complexity and functionality imply a hierarchy. The concern with what were the proper constraints on the vegetation is an example of using the precision of hierarchy theory to tease apart complex functioning. Being about whole plants taking up soil water and then displaying the emergence of complexity, the experiments of Allen, Havlicek and Norman (2001b) are as close to an experiment in complexity and emerging hierarchies as we could find relative to hydropedology. We admit it is a bit of a stretch, but experiments on complexity and emergence are rare. It is however an indication as to how, in an arena close to hydropedological concerns, emergence and complexity might be developed and investigated. There is lots of complexity and emergence in soil water relations just waiting to be addressed in explicit terms. There are many issues across hydropedology that will yield similar benefits to a hierarchical approach.

3.2 Reframing the question: soil water and carbon utilization

Hydropedology suffers the curse common to complex systems of correlated parameters; the many processes and patterns exhibit strong interactions. The list of potential factors controlling flux behavior is long and includes soil morphological attributes such as redoximorphic features, structure and ped/voide surface features (Lin et al., 2006), parent material, soil texture, age, management regime, topography, and climate. Even earthworm density and the resulting channels can impact flux pathways. Other factors besides soil texture, such as soil organic matter (SOM) content, and degree of aggregation, influence soil hydraulic properties but are often ignored, to the detriment of models (Del Grosso et al., 2005). Pedo-transfer functions, for example, may fail to give satisfactory predictions of soil hydrology because information of impermeable layers or other factors such as parent material are not taken into account (Schnieder et al., 2007). An effective model therefore requires a step into hierarchy theory in order to structure the appropriate framework and specify the system correctly as it pertains to the question.

For example, asking if soil water impacts carbon utilization is not effective, as a wealth of contradictory data proves: it depends, and the factors it depends on are myriad (Davidson et al., 1998). Hierarchy theory suggests that an approach organizing the factors, and properly determining a question that can be answered by considering the whole system, is in order. A relational database model organizing the factors was created (Wixon, 2008) using a control hierarchy. Time duration, the metric of water content (as discussed above), the quality of the carbon and the variability of water content typically experienced in the soil turn out to be key regulating factors. To better address the middle number situation, hierarchy theory allows us to organize the question at the scale of interest and isolate factors relating to this scale. An example of a more useful resulting question is: does short-term, (time scale) acute water stress (magnitude scale, metric) impact labile carbon efflux (quality) in a well-drained system that does not typically experience water stress (contextualize in variability of system)? In this example, earthworms are outside the bounds of interest due to the time scale, and well-drained puts us out of the wetland context, where labile carbon may change its meaning. Without a concrete hierarchy of control, too few or too many factors are typically involved in an experiment or a model. It cannot be that to construct a predictive model, we must make these measurements over the nearly infinite space of combinatorial perturbations in all environmental factors; such a model would have little certainty or predictive utility (Oreskes, 2003). This potentially immense matrix is reduced by the fact that many factors only interact, and only limit key processes, at particular scales and system conditions. In this example, the scales are addressed but left imprecise ("short-term", "acute", "typically") in the question partially in order to delineate the study's intent rather than its methods. However, this highlights another advance that can be made from the hierarchy framework: magnitudes can be quantified by a range of experiments designed to isolate the thresholds of behavior associated with the specific factors identified as key controls. Given the complexity of soil water relationships to decomposition rates (Saiz et al., 2007), determining what matters when, and the feedbacks and interactions involved, is no small achievement.

4 Conclusions

As it integrates and combines knowledge and understanding from hydrology and pedology, and as it carries out its own unified investigations, hydropedology will face many challenges associated with the study of complex systems. We offer hierarchy theory as being particularly helpful in teasing through complexity in hydropedology. First, we suggest that scientists must acknowledge and define their level of analysis, so that models may be understood in their proper context. Hierarchy theory provides a consistent and robust guide to this process by providing: (1) a set of general principles by which to organize information according to higher and lower levels, (2) a definition of middle number systems and strategies to avoid them, and (3) a method of avoiding semantic arguments by defining logical types. Once models are constructed, however,

scientists must understand how diverse sets of local models of different local phenomena relate to one another across multiple scales; a particularly challenging process for hydropedologists. We suggest that narrative, because of its ability to navigate between scales and because it is not constrained by being internally consist, is the means with which to achieve this understanding. We also suggest that reframing traditional wisdom with a new narrative has the potential to open up exciting new avenues for research. Armed with these tools, hydropedology can carry forward more systematically and robustly, avoiding many of the problems endemic to scientific discourses confronted with complexity.

References

Ackoff, R.: Redesigning the Future: Systems Approach to Societal Problems, John Wiley & Sons, New York, USA, 1974.

Ahl, V. and Allen, T. F. H.: Hierarchy Theory: A Vision, Vocabulary and Epistemology, Columbia University Press, New York, USA, 1996.

Allen, T. F. H. and Hoekstra, T. W.: Toward a Unified Ecology, Columbia University Press, New York, USA, 1992.

Allen, T. F. H., Havlicek, T., and Norman, J.: Wind tunnel experiments to measure vegetation temperature to indicate complexity and functionality, in: Advances in Energy Studies, 2nd Intrenational Workshop: Exploring Supplies, Constraints and Strategies, edited by: Ulgiati, S., Brown, M. T., Giempietro, M., Herendeen, R. A., and Mayumi, K., Padua, Servici Grafici Editoriali, 135–145, 2001b.

Allen, T. F. H., Tainter, J. A., Pires, J. C., and Hoekstra, T. W.: Dragnet ecology – "Just the facts, ma'am": The privilege of science in a postmodern world, Bioscience, 51, 475–485, 2001a.

Bateson, G.: Mind and Nature, Bantam Books, New York, USA, 1980.

Beland, P. and Allen, T. F. H.: The origin and evolution of the genetic code, J. Theor. Biol., 170, 359–365, 1994.

Cronon, W.: A Place for Stories: Nature, History and Narrative, J. Am. Hist., 78, 1347–1376, 1992.

Davidson, E. A., Belk, E., and Boone, R. D.: Soil water content and temperature as independent or confounded factors controlling soil respiration in a temperate mixed hardwood forest, Glob. Change Biol., 4, 217–227, 1998.

Davidson, E. A., Janssens, I. A., and Luo, Y. Q.: On the variability of respiration in terrestrial ecosystems: moving beyond Q10, Glob. Change Biol., 12, 154–164, 2006.

Del Grosso, S. J., Parton, W. J., Mosier, A. R., Holland, E. A., Pendall, E., Schimel, D. S., and Ojima, D. S.: Modeling soil CO_2 emissions from ecosystems, Biogeochemistry, 73, 71–91, 2005.

Funtowicz, S. and Ravetz, J.: Science for the post-normal age, Futures, 25, 735–755, 1993.

Giampietro, M.: Multi-Scale Integrated Analysis of Agroecosystems, CRC Press, London, UK, 2003.

Itzkovitz, S. and Alon, U.: The genetic code is nearly optimal for allowing additional information within protein coding sequences, Genome Res., 17, 405–412, doi:10.1101/gr.5987307, 2007.

Izaurralde, R. C, Williams, J. R., McGill, W. B., Rosenberg, N. J., and Jakas, M. C. Q.: Simulating soil C dynamics with EPIC: Model description and testing against long-term data, Ecol. Model., 192, 362–384, 2006.

Kucharik, C. J., Foley, J. A., Delire, C., Fisher, V. A., Coe, M. T., Lenters, J. D., Young-Molling, C., Ramankutty, N., Norman, J. M., and Gower, S. T.: Testing the performance of a dynamic global ecosystem model: Water balance, carbon balance, and vegetation structure, Global Biogeochem. Cy., 14, 795–825, 2000.

Kuhn T.: The Structure of Scientific Revolutions, University Chicago Press, Chicago, USA, 1970.

Lin, H. S., Bouma, J., Pachepsky, Y., Western, A., Thompson, J., van Genuchten, R., Vogel, H. J., and Lilly, A.: Hydropedology: Synergistic integration of pedology and hydrology, Water Resour. Res., 42, W05301, doi:10.1029/2005WR004085, 2006.

Linn, D. M. and Doran, J. W.: Aerobic and anaerobic microbial-populations in no-till and plowed soils, Soil Sci. Soc. Am. J., 48, 794–799, 1984.

Maidment, D.: Arc Hydro: GIS for Water Resources, ESRI, Redlands, California, USA, 2002.

McCormick, R. J., Zellmer, A. J., and Allen, T. F. H.: Type, Scale and Adaptive Narrative: Keeping Models of Salmon, Toxicology and Risk Alive to the World, in: Landscape Ecology and Wildlife Habitat Evaluation, edited by: Kapulstka, L., Biddinger, G., Luxon, M., and Hector, G., ASTM International, 69–83, 2004.

McGuire, A., Melillo, J. M., Kicklighter, D. W., and Joyce, L. A.: Equilibrium responses of soil

carbon to climate change: empirical and process-based estimates, J. Biogeogr., 2, 785–796, 1995.

O'Neill, R. V.: A Hierarchical Concept of Ecosystems, Princeton University Press, Princeton, New Jersey, USA, 1986.

Oreskes, N.: The Role of Quantitative Models in Science, in: Models in Ecosystem Science, edited by: Canham, C. D., Cole, J. J., and Lauenroth, W. K., Princeton University, Princeton, New Jersey, USA, 13–31. 2003.

Pietgen, H., Jürgens, H., and Saupe, D.: Chaos and fractals, Springer-Verlag, New York, USA, 1992.

Sheikh, V. and van Loon, E. E.: Comparing Performance and Parameterization of a One-Dimensional Unsaturated Zone Model Across Scales, Vadoze Zone Journal, 6, 638–650, 2007.

Robertson, G. P., Coleman, D. C, Bledsoe, C. S., and Sollins, P.: Standard Soil Methods for Long-Term Ecological Research, Oxford University Press, New York, USA, 1999.

Rodrigo, A., Recous, S., Neel, C., and Mary, B.: Modelling temperature and moisture effects on C-N transformations in soils: comparison of nine models, Ecol. Model., 102, 325–339, 1997.

Saiz G., Black, K., Reidy, B., Lopez, S., and Farrell, E. P.: Assessment of soil CO_2 efflux and its components using a process-based model in a young temperate forest site, Geoderma, 139, 79–89, 2007.

Samouelian, A. and Cornu, S.: Modelling the formation and evolution of soils, towards an initial synthesis, Geoderma, 145, 401–409, 2008.

Schjonning, P., Thomsen, I. K., Moldrup, P., and Christensen, B. T.: Linking soil microbial activity to water- and air-phase contents and diffusivities, Soil Sci. Soc. Am. J., 67, 156–165, 2003.

Schneider, E. D. and Kay, J.: Life as a manifestation of the second law of thermodynamics, Math. Comput. Model., 19, 25–48, 1994.

Smart, J. S. and Werner, C.: Applications of the random model of drainage basin composition, Earth Surf. Processes, 1, 219–233, 2007.

Smith, K. A., Ball, T., Conen, F., Dobbie, K. E., Massheder, J., and Rey, A.: Exchange of greenhouse gases between soil and atmosphere: interactions of soil physical factors and biological processes, Eur. J. Soil Sci., 54(4), 779–791, 2003.

von Bertalanffy, L.: General Systems, Braziller, New York, USA, 1968.

Weinberg, G.: An Introduction to General Systems Thinking, John Wiley & Son, New York, USA, 1975.

Whitehead, A. N. and Russell, B.: Principia Mathematica, Volume 1, Cambridge University Press, 1910.

Wilding, L. P.: Pedology, in: Handbook of Soil Science, edited by: Sumner, M. E., E-1-E-4, CRC Press, Boca Raton, Flordia, USA, 2000.

Wixon, D. L.: Black boxes and complexity: Factors controlling the temperature response of microbial decomposition, MS thesis, Univeristy of Wisconsin, Madison, USA, 2008.

Zellmer, A. J., Allen, T. F. H., and Kesseboehmer, K.: The nature of ecological complexity: A protocol for building the narrative, Ecological Complexity, 3, 171–182, 2006.

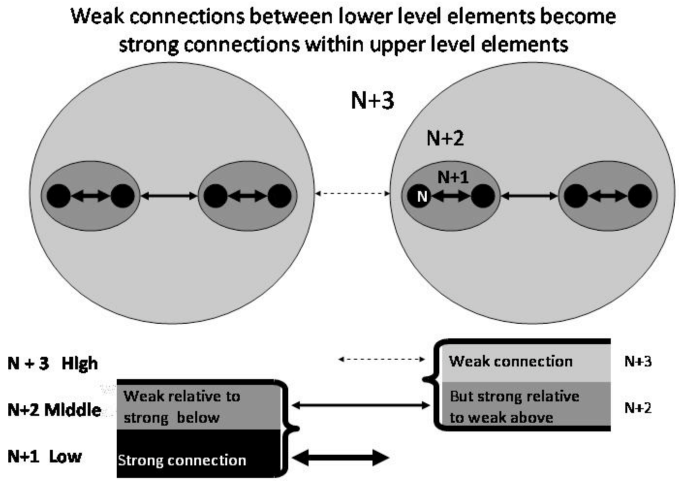

Fig. 1. This figure shows entities at different levels in a nested hierarchy, one where upper levels contain and consist of lower levels. Bond strength is a relative matter in hierarchies. The lowest level entities have the strongest bond strength. They are united with bonds to make upper level entities that may themselves be united at yet higher levels. The weak bonds in the second level may become the relatively strong bonds that hold the yet higher-level entities together. Hand grenades are chemical as their bonds are broken in an explosion. Nuclear material breaks atomic bonds and so the explosion is greater because such bonds release more energy when broken. The hierarchy here may also work on upper levels constraining, being contextual or behaving at a lower frequency.

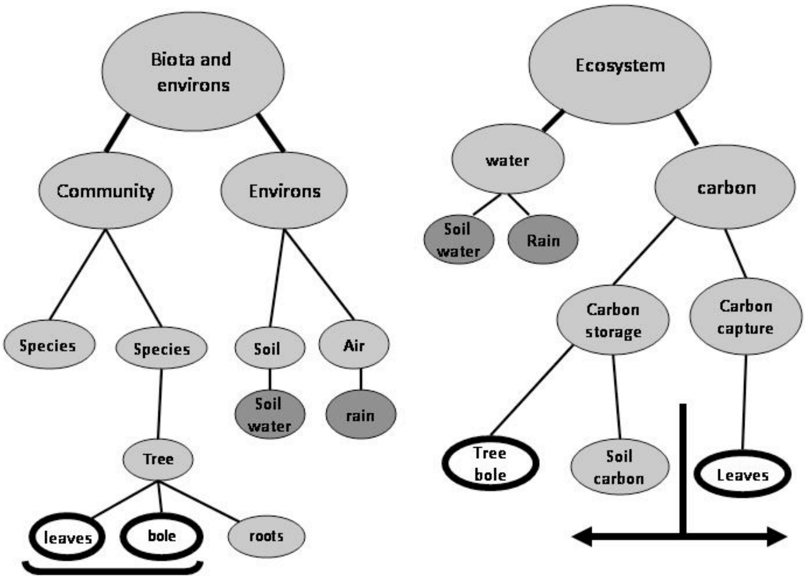

Fig. 2. Two hierarchies are shown from two different perspectives. Plant community and organismal structure unites the bole of a tree with its leaves in the organism. The alternative is a hierarchy of ecosystem flux where tree bole is united with soil carbon as ecosystem carbon storage. Note too how soil water and rain come together differently in the two hierarchies.

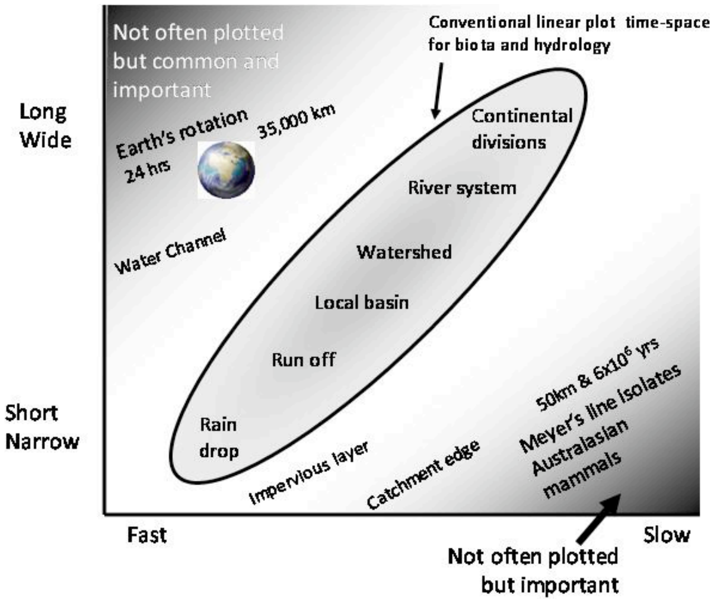

Fig. 3. Favorite hierarchies in ecology often are ordered to move increased spatial size in lock step with longer time frames and periodicities. Here we move up a hydropedological hierarchy in the conventional way, from small fast raindrops to wide slow continental regions. But also note other hydropedological entities off the diagonal that mix fast and wide (water channel) or narrow and slower (narrow impervious layer slows flow; or narrow catchment edge such as the ridge of the continental divide that diverts water over months at least).

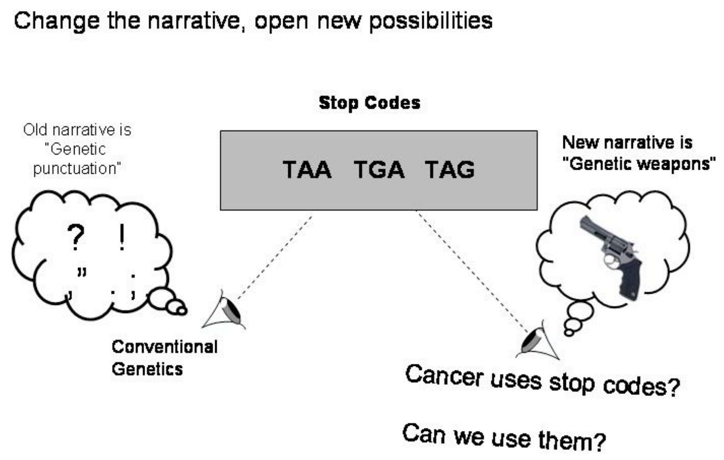

Fig. 4. While the material situation may remain the same the narrative can shift. Itzkoitz and Alon (2007) compared the real code to random alternatives. They found it to be one of the very best for creating stop codes when by mistake it read nonsensically out of frame. Nonsense reading is stopped early. By questioning the centrality of stop codes being punctuation new narratives are invited. One is that stop codes are for shutting down alternative coding: stop codes as weapons. That new narrative as to the significance of stop codes opens avenues for addressing say the genetics of cancer.