CUAHSI VISION PAPER

Hydropedology: Synergistic Integration of Pedology and Hydrology

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Outline

Abstract

This paper presents a vision for developing and promoting hydropedology as a new interdisciplinary science that embraces multiscale basic and applied research of interacting pedological and hydrological processes and their properties in the vadose zone. *Landscape water flux* is suggested as a unifying focus for hydropedology that is related to storages, pathways, residence times, and spatio-temporal organization of water in the root and deep vadose zones, and through which pedological and hydrological expertise can be better integrated. After illustrating multiple knowledge gaps that can be addressed by the synergistic integration of pedology and hydrology, we suggest twelve scientific hypotheses that require vigorous testing and concerted efforts from pedologists and hydrologists. Among them, six are critical concepts and challenges for advancing hydropedology and for enhancing the prediction of landscape water flux (i.e., a holistic conceptual framework, hierarchical structures, patterns, bridging multiple scales, elegant and robust models, and human impacts), and the other six are related to the unique contributions of hydropedology to the advancement of hydrology and pedology (i.e., soil morphology, genesis, classification, mapping, database, and future advancement of pedology). We then present three interlinked strategies for achieving the stated vision and the role of the CUAHSI. They are: 1) design of a set of scientific experiments to test the proposed hypotheses, 2) use of the CUAHSI's Hydrologic Observatories and natural soil laboratories, and 3) promotion and dissemination of hydropedology. We conclude this paper with statements on expected scientific and societal impacts from the proposed research vision. It is our hope that, by working together, hydrologists and pedologists, along with related discipline scientists (e.g., soil physicists, hydrogeologists, hydrogeophysicists, ecohydrologists, geochemists, and atmospheric

scientists) can better guide data acquisition, knowledge integration, and modeling-based prediction to advance hydrological science in the next decade and beyond.

1. Introduction

It is well recognized that the progress of science depends increasingly on an advanced understanding of the interrelationships among different fields and their components (AAAS Council, 2001). An interdisciplinary systems approach is a proven vehicle for addressing synergistically a wide array of environmental, ecological, agricultural, geological, and natural resource issues of societal importance. Over the past few decades, there has been a growing interest in a landscape perspective when dealing with cross-disciplinary issues such as non-point source pollution, whole watershed management, integrated agricultural systems, precision farming, sustainable land use, and ecosystem restoration and preservation. With a landscape perspective comes the need to address inherent variability in the field and to transfer knowledge and information across scales from the laboratory or small plot to the larger field and watershed scales. It also raises the need for field experimental designs and models that take into account the spatial scale triplet (i.e., spacing, support, and extent) and temporal scale triplet (i.e., sampling time interval, smoothing or averaging interval, and length of record) (e.g., Blöschl and Grayson, 2000). The changing factors that control abiotic and biotic processes in the continuum of a landscape should also be taken into account for effective modeling and reliable prediction.

Pedology and hydrology are scientific disciplines inherently associated with the landscape perspective. Pedology is a branch of soil science that integrates and quantifies the morphology, formation, distribution, and classification of soils as natural or anthropogenically-modified landscape entities (Wilding, 2000; Buol et al., 2001). Combining pedological and hydrological expertise can be particularly powerful in addressing complex environmental issues and policies (Bouma, 2005). Indeed, soil and water interaction creates the fundamental interface between the biotic and abiotic and thus functions as a critical determinant of the state of the earth system (Fig. 1). However, traditional solutions and approaches to measuring, modeling, and predicting the fluxes of water through soils and over landscapes (including the transport of chemicals and energy by the water flow) have long been plagued by discipline-limited efforts and "stereotype" visions on both sides of the fence. For example, the following limitations need to be overcome in order to truly ally pedology and hydrology (Lin et al., 2004a):

- To many hydrologists, pedologists use "strange" names to describe field soils and they make empirical statements about soil functions based on observations that are not necessarily supported by measurements. On the other hand, pedologists are taken back by the simplified representation of filed soils in terms of homogeneity and isotropy that hydrologists often assume in their models, which, to pedologists, clearly does not adequately reflect real-world conditions;
- Pedology has its roots in soil survey that considers *soil-landscape relationships* and *soil structur*e. These two aspects are critical for surface and unsaturated zone hydrology in order to improve quantitative characterization of flow regimes in the field. However, the pedological knowledge is often conveyed as semi-quantitative statements. Pedologists thus can benefit from flow theories in hydrology when transforming qualitative descriptions into quantitative expressions that are increasingly in demand from diverse users of soil survey information and providing inputs to environmental policy making.

There are multiple knowledge gaps that can be addressed by the synergistic integration of pedology and hydrology, as further exemplified in the following:

- Prediction of preferential flow dynamics and pathways at different scales, their interface with the soil matrix, their residence times, and their significance in different soils and landscapes remain unresolved (e.g., NRC, 2001d; Lin, 2003). Hydrologists may not have a clear picture of flow pathways in the unsaturated zone before starting modeling or field experiments. Pedologists routinely document *in situ* pedological features (such as clay films, ped coatings, soil structures, root distributions, macropores, and hydromorphic features) that often indicate preferential flow paths and soil moisture regimes. While qualitative or semi-quantitative approaches based on whole-soil interpretations have been successfully used (e.g., Boorman et al., 1995), a concerted effort is needed to quantify soil natural "architecture" (including soil cover, soil structure, and soil layering) in a manner that can be incorporated into models of flow and transport and their scaling.
- “Where, when, and how” water moves through landscapes and its impacts on soil processes and subsequently soil spatial patterns needs to be better understood. Conceptual and mathematical models of water movement through and over the landscape are key aspects of hydrological modeling, contaminant transport, and terrestrial ecosystem distributions. Currently, many hydrological models do a poor job in predicting subsurface lateral flow and baseflow vs. runoff in total streamflow (Wood, 1999). But sloping topography, stratification, and soil layering (especially water-restricting layers) all favor lateral flow (Richardson et al., 2001). The convergence of surface and subsurface lateral flows within a landscape results in the formation and

distribution of streams and rivers and contributes to the spatial heterogeneity of soil and vegetation across the landscape. Quantification of soil formation and soil spatial diversity is needed for different landscapes. Linking pedology to hydrology can facilitate the achievement of such a goal (Lin et al., 2004a).

- Bridging multiple scales remains at the heart of many hydrological and pedological studies. It is highly desirable to explore quantitative ways of bridging scales from microscopic (e.g., pores, aggregates) to mesoscopic (e.g., pedons, catenas) and to macroscopic (e.g., watersheds, regional, and global) levels for different hydrological and pedological properties and processes. Pedologists study both the *mechanisms* and the *magnitudes* of soil spatial diversity as a basis for broad generalizations about soil genesis, classification, and mapping; whereas hydrologists have also long been concerned with scaling and spatio-temporal variability of hydrological processes. However, the convergence of these efforts has not occurred. Joint efforts of pedologists and hydrologists will likely shed light on the fundamental processes upon which scale bridging might be possible. As an example, pedogenesis is an integrated phenomenon resulting from a series of physical, chemical, and biological processes, hence providing a holistic view of the system evolution and hydrological processes that have occurred or are occurring at the earth's surface and near-surface environment.
- Hydrologists need soil hydraulic parameters in their models and information to specify flow paths, but such data are often lacking or difficult to obtain in large volumes. In the mean time, many national and regional soil survey databases developed over the last century have been underused in addressing environmental and ecological issues. Improved procedures to extract useful information from the available databases and to

enhance soil survey interpretations for flow and transport characteristics in different soils are needed. Bridging data gaps through approaches such as pedotransfer functions and pedotransfer rules will be continuously in demand, which will enhance the value of soil survey databases and provide hydrologists with model input parameters. In addition, soil categorizations that differentiate various soil hydrologic units (e.g., in terms of flow patterns and transport mechanisms), and soil morphology quantification for inferring *in situ* soil moisture regime, water table behavior, soil drainability, flow paths, and soil hydraulic properties are essential research areas. The combined efforts from pedologists and hydrologists will open up promising opportunities for building mutually beneficial common databases.

- Hydrologists often believe that pedologists tend to view the soil as a static entity as they categorize soil characteristics into non-dynamic entities (such as grouping soil inherent drainage into 'well' or 'poorly' drained classes). This is yet another misperception and pedologists generally have a considerable understanding of the implications of these terms for predicting the height and duration of waterlogging within the soil as well as temporal changes in soil water regimes in the medium- to long-term. However, this is not always clearly communicated. Water table fluctuations in soils influence soil water storage capacity and runoff and thereby impact on such hydrological response as flood hydrographs, base flow, and solute concentrations in aquatic systems. Regular temporal sampling frameworks are becoming recognized in pedology, and concerted efforts from pedologists and hydrologists can lead to more complete datasets that include extreme events (e.g., sediment or solute concentrations in peak flow or sustained drought). A move towards continuous sampling or monitoring of the unsaturated zone will provide better datasets for hydrological modeling.

The developments in pedology and hydrology are now converging on multiple fronts, as illustrated in the above examples. This common ground leads to synergies that can be expected from integrating the two disciplines, as suggested in recent literature and professional activities (e.g., Lin, 2003; Lin et al., 2004a; Bouma, 2005; Wilding and Lin, 2005). We believe that integrating hydrology and pedology will give enhanced understanding and prediction of water fluxes and flow pathways in landscapes. It is in such a context that a vision of hydropedology is proposed in this paper. We hope that hydropedology becomes a common theme across the CUAHSI's hydrologic observatories.

Hydropedology is a branch of soil science and hydrology that encompasses multiscale basic and applied research of interacting pedological and hydrological processes and their properties in the vadose zone (Lin, 2003; Lin et al., 2004a). Hydropedology could be viewed as a sister discipline of hydrogeology, with the latter traditionally looking at saturated systems. The synergistic integration of hydrology and pedology (along with other related bio- and geo-sciences such as soil physics, hydrogeophysics, and ecohydrology) into hydropedology suggests a renewed perspective and a more integrative approach to studying soil-water interactions across scales, and their relations to climate, ecosystem, land use, and contaminant fate. *Landscape water flux* is suggested here as a unifying focus for hydropedology that is related to storages, pathways, residence times, and spatio-temporal organization of water in the root and deep vadose zones, and through which pedological and hydrological expertise can be better integrated. Working together, we believe, hydrologists and pedologists, along with related discipline scientists (e.g., soil physicists, hydrogeologists, hydrogeophysicists, ecohydrologists, geochemists, and atmospheric scientists) can better guide data acquisition, knowledge integration, and model prediction.

2. Research Vision

Among many unresolved scientific issues in pedology and hydrology, some are fundamental. Advancement in these key issues can lead to significant improvements in our understanding, measurement, modeling, and prediction of water fluxes across landscapes in the next decade and beyond. In the context of hydropedology, we group such key issues into two categories: 1) six critical concepts and challenges for advancing hydropedology and for enhancing the prediction of landscape water flux changes induced by factors such as climate change and land use; and 2) six unique contributions of hydropedology to the advancement of hydrological science and pedology. We attempt to formulate one hypothesis in each of these twelve areas. These hypotheses require vigorous testing through concerted efforts of pedologists and hydrologists, along with related discipline scientists. Many of these key issues are applicable across the CUAHSI's hydrologic observatories.

2.1 Critical concepts and challenges for advancing hydropedology and for enhancing the prediction of landscape water flux

2.1.1 A holistic conceptual framework for integrated hydropedological studies

A holistic conceptual framework is called for defining quantitative relationships between *soil structure* and *hydrologic functions* at various *scales* and the incorporation of such relationships into robust *models* for prediction (Fig. 2). This framework, while generic in nature, requires considerable experimental data across multiple scales and geographic regions to test. In essence, four intertwined components are highlighted in this framework that could be used to guide the design and implementation of integrated hydropedological studies (Fig. 2):

- *Identification of structures*: Structure creates constraints and conditions in which processes act and interact. Thus, there is a need to identify the interrelationships between hierarchical structures of soil and hydrologic systems;
- *Characterization of functions*: Acting and interacting processes create preconditions and feedbacks that modify a system's structure. Hence, study of the functions and structures of soil and hydrologic systems needs to be integrated, including, for example, integration of soil-landscape relationships and hillslope processes, and integral characterization of a land unit in terms of pedological and hydrological functions;
- *Bridge of scales*: Soil structures and functions interact at a variety of scales that define scale-specific variability and pattern. Scales and scaling in soils need to correlated with scales and scaling in hydrology;
- *Systematic integrations*: Models integrate major (or dominant) properties and processes at a given scale (or across multiple scales). Variability or pattern determines suitable formulation and application of a model. Pedological predictive capacity needs to be integrated with hydrological predictive capacity.

A relevant hypothesis is thus suggested as:

- ***Hypothesis 1****: Systematically-designed and integrated hydropedological studies across multiple scales and geographic regions result in appropriate quantification of the proposed holistic conceptual framework.*

Hydrologists and pedologists use different sets of techniques at different scales. These techniques relate structures and functions at different spatial scales, as illustrated in Fig. 2. So far, they have not been combined systematically. In many cases, soil structures have been described in pedology without measurements of physical parameters such as hydraulic conductivity or moisture retention. Soil physical measurements, in turn, have often been made without any attention to soil structure or horizonation. Similar comments apply at larger scales, such as a field where processes and questions being raised are different. For example, in a hillslope, a soil scientist might define a soil sequence (catena) without paying attention to the spatial pattern of hydrological processes and properties; whereas a hydrologist might measure hydraulic conductivity without paying attention to distinctly different soil units. The watershed level poses a different set of conditions where geomorphologically-defined soil-landscape sections, that may contain several soil types and horizons, define a characteristic structure for this scale that can be characterized with geophysical techniques and remote sensing. Systematic integration of pedological and hydrological techniques across scales is likely to open new avenues to innovative sampling and measurement techniques that could contribute to the quantification of the proposed holistic framework and to provide the necessary integration.

2.1.2 Quantification of hierarchical structures of soil and hydrologic systems

A major difficulty in modeling flow and transport in soils – irrespective to the spatial scale – is the fact that nature is structured at any scale. This can be easily demonstrated by using images of soil structure obtained at various scales from soil thin sections to remotely-sensed data from satellites. As a consequence, any measurement taken will depend on the support scale of the instrument used. To achieve the goal of characterizing and modeling functions of soil and hydrologic systems across scales, we then need to find ways to quantify soil-landscape structures across scales. We need a probabilistic or fuzzy-logic discrimination of predominantly flow (or fast flow) and predominantly no-flow (or slow flow) domains forming a pattern that reflect the observed structures. Identification of soil-landscape structures allows enhanced understanding of flow pathways and processes (e.g., preferential flow). Thus, future investments should focus on spatial structure of material properties rather than on point measurements. This perspective is in line with our perceived need for studying patterns (see the next Section 2.1.3).

A hypothesis to be tested is proposed here:

- ***Hypothesis 2****: Soil systems exhibit hierarchical structures (discrete or continuous) that can be quantified using soil-landscape expertise, coupled with a set of measurement techniques (noninvasive and invasive).*

We need strategies to quantify spatial structures of soil and hydrologic systems at different scales. These include instruments and measurement techniques that are essentially noninvasive (e.g., tomography, geophysical tools, and remote sensing). All these tools are sensitive to some material properties and generate proxy measurements that can be related to those required by hydrologic models. An essential part of this is to further develop fundamental insights into such proxy-relationships or pedotransfer functions. One important issue is to identify critical and/or rare structural information that governs hydrological processes at different scales.

Direct detection and measurement of soil and hydrologic spatial structures is typically difficult and expensive. To make progress, we need to explicitly recognize that the observed structures are not an arbitrary outcome of some unknown random processes but the result of structure-forming processes that can be revealed and understood. Hence, an attractive approach is to use the existing knowledge on soil structure-forming processes, which exists and is continuously generated in various branches of soil science, especially pedology. Up to now, these disciplines find themselves separated from hydrology. Consequently, joining these disciplines in the hydropedological framework can lead to the fusion pushing our capabilities to quantitatively understand flow and transport processes and pathways to a higher level.

2.1.3 Identification and prediction of patterns (spatio-temporal organizations of structures and functions)

Identification and prediction of patterns or spatio-temporal organization across scales is becoming a leading area in soil science and hydrology (e.g., Grayson and Blöschl, 2000; Lin et al., 2004a). Patterns offer rich and comprehensive insights regarding the variability of structures and functions, as well as the underlying processes controlling hydrologic response (e.g., Grayson et al., 1997; Grayson et al., 2002; Lin et al., 2005). A number of recent catchment hydrology field investigations have demonstrated how the understanding and modeling of hydrological processes can be improved by the use of observed spatial patterns (e.g., Grayson and Blöschl, 2000). Some spatial patterns are temporally persistent (the notion of "time stability") (e.g., Vachaud et al. 1985; Kachanoski and de Jong, 1988; Mohanty and Skaggs, 2001), which may be a function of spatial scale and may vary across a landscape with different soil types (e.g., Kachanoski and de Jong, 1988; Zhang and Berndtsson, 1991; Lin et al., 2005). Western and Grayson (2000) found that combining spatial patterns with temporal responses added value to both observations in a modeling context and improved the confidence with which the spatio-temporal organization of soil moisture could be predicted.

There is a great need for innovative characterization and modeling of spatio-temporal patterns at different scales that are important to pedological and hydrological phenomena. Such approaches will use a combination of ground-based observations, digital geospatial data layers (e.g., digital elevation model or DEM, surficial geology, land cover), noninvasive geophysical/hydrogeophysical methods (e.g., electromagnetic induction, ground-penetrating radar, radiometry), and remote sensing imagery, along with 3-D landscape-soil-water dynamic modeling. The optimal combination, integration, and data assimilation of these multiple techniques and data sources will provide substantially better information regarding spatio-temporal organizations of pedological and hydrological phenomena across scales. For example, McKenzie and Ryan (1999) used a variety of data sources including topography, geology, climate, and airborne gamma radiometric data as predictors of soil properties. Techniques for combining remote sensing imagery with hydrologic models are also rapidly developing and are enabling better use of remote sensing observations at large (regional to global) scales. Some progress has been made in using remote sensing of hydrologic response to infer soil properties and vice versa (e.g., Hollenbeck et al., 1996; Jackson and Le Vine, 1996).

A suggested hypothesis here is:

- ***Hypothesis 3****: Storages, pathways, and residence times of water flux in the landscape exhibit identifiable spatial distributions and temporal patterns, with possible interacting spatial and temporal dimensions. This spatio-temporal persistence of water fluxes can be used to subdivide landscapes into similarly-functioning hydrologic units.*

The functional unit concept based on functional characterization of 4-D (3-D + time) soil units within fields allows reliable quantification of fluxes within those fields. Hydrologically similar soil-landscape units exist within watersheds and these can be identified using traditional and new techniques and data sources. Winter (2001) proposed the concept of "*fundamental hydrologic landscape unit*" as a means to break any landscape into its most basic forms: upland and lowland separated by a steeper slope. Each of these units has specific characteristics, including land surface form, geology, and climate, which control its hydrology. In the context of hydropedology, soil-landscape relationships and soil hydrologic characteristics are emphasized in defining similarly-functioning hydrologic units over a landscape.

Note that some differences within fields, as distinguished by pedologists, do not always correspond with hydrologic functional differences, for instance, in terms of different fluxes or water contents at particular pressure heads. Wösten et al. (1985) transformed soil patterns on detailed soil maps into patterns of "functional units" that each had distinctly different hydraulic conductivity and moisture retention characteristics. In doing so, the number of spatial units on the map was reduced by 30%. Breeuwsma et al. (1986) did the same but for cation exchange capacity and phosphorous adsorption capacity, resulting in reductions of 20% and 30%, respectively. A more sophisticated procedure was followed by Bouma et al. (2002) who delineated "management units" for precision agriculture on the basis of simulation runs for nitrogen transformations and pesticide leaching for point data, followed by interpolation. Knowing the internal variability within these "management units" allows estimates to be made of the variability obtained for simulation runs for the units.

2.1.4 Bridging multiple scales

Translating information about soil and hydrologic properties and processes across scales has emerged as a major theme in contemporary soil science and hydrology (e.g., Kalma and Sivapalan, 1995; Sposito, 1998; Hoosbeek et al., 1998; Western et al., 2002; Pachepsky et al., 2003). As remote sensing techniques for estimating large-area soil and hydrologic properties and *in situ* measurements for local areas continue to be developed, bridging multiple scales becomes even more essential. At present, no single theory emerges that is ideal for spatial aggregation (or upscaling), disaggreagation (or downscaling), and temporal inference (or prediction) of soils and hydrologic information. The major complementary approaches include scaling via defined hierarchies and continuous models of spatial variation as described by fractal theory and geostatistics (Lin and Rathbun, 2003). Further exploration of this topic is critical.

Hierarchical frameworks have been conceptualized by pedologists as a means for organizing soil systems from the soil pore scale to the global pedosphere (Fig. 3a) (Hoosbeek and Bryant, 1992; Wilding, 2000). Hierarchical complexity has been studied in pedology, which has long recognized self-organized complexity in the processes of soil formation, with taxonomic frameworks constructed to summarize that ordering (Buol et al., 2001). However, quantitative hierarchy of soil systems that could be integrated into models of flow, scaling, and rate processes is still lacking. Sommer et al. (2003) recently presented an integrated method for soil-landscape analysis, in which a hierarchical expert system was developed for multi-data fusion of inquires, relief analysis, geophysical measurements, and remote sensing data, as well as a combination of the soil-forming factorial model of Jenny (1941) with the scaleway of Vogel and Roth (2003) to address soil variability across scales.

There are several approaches in hydrology and soil physics to incorporate spatial heterogeneity into flow and transport modeling, including macroscopic homogeneity, discrete hierarchy, continuous hierarchy, and fractals (Fig. 3b). Vogel and Roth (2003) suggested a "scaleway" for predictive modeling of flow and transport in the subsurface at any scale. This conceptual approach is based on the explicit consideration of spatial structure that is assumed to present at any scale of interest, while the microscopic heterogeneities are replaced by an averaged, effective description. Some studies (e.g., Cushman, 1990; Vogel et al., 2002) have suggested a discrete hierarchy of representative elementary volume (REV), where the REV is a local property related to a given level of soil structural unit. This is consistent with the hierarchical organization of soil aggregates that is characteristic of most soils (e.g., Tisdall and Oades, 1982; Oades and Waters, 1991). However, quantification of soil structure and its impacts on flow and transport in field soils remain unresolved. A new and versatile geometric foundation for representing porous media (e.g., fractal geometry, percolation theory, and geometric modeling) is emerging as one of the possibilities for achieving improvements in media scaling, flow modeling, and soil hydraulic function characterization (e.g., Crawford et al., 1999; Jury, 1999; Gerke and van Genuchten, 1996). Further progress requires joint efforts of pedologists, hydrologists, mathematicians, and related discipline scientists.

A hypothesis is suggested here:

- ***Hypothesis** 4: Scale dependence in hydrologic parameters can be explained using hierarchical structures in soils, topography, and land cover. Scaling via structural hierarchies enables enhanced prediction of water fluxes across scales.*

Changing scale in soil and landscape studies means the changes in the type of information obtained about the system, in parameters used to characterize the system, in the system's variability, and in the observability and predictability of the system. Accordingly, scale transition unavoidably includes change of the flow model in hydrology (e.g., Navier-Stokes → Richards equation → water mass balance equation) and change in structure characterization in pedology (e.g., aggregate structure → profile structure → structure of soil cover). It is a system's structure that determines the processes or "physics" involved, and only when the physics is understood can a suitable flow model be developed. A triadic approach to scaling was suggested in which material properties from the finer scale are used to estimate model parameters values from the scale in question, whereas the system properties from the coarser scale are used to establish constrains for model behavior (Faybishenko et al., 2003). The exhaustive characterization of structure at each scale should describe rare structural features that, in actuality, may define the hydraulic behavior at the coarser scale (Pachepsky et al., 2004). Connected macropores that are rare at the soil horizon scale present an example of such a feature because they define soil hydraulic behavior under continuous water supply at the soil profile scale. Scale-specific delineation of rare structural features and characterization of their hydrologic role require a concerted effort from pedologists and hydrologists.

Hierarchy theory in ecology (O'Neill et al., 1986, 1989) presents some valuable philosophical and operational concepts pertaining to the quantification of hierarchical structures of soil and hydrologic systems (e.g., Haigh, 1987; Wagenet, 1998; Lin et al., 2004a). If properly constructed, a hierarchy of soil systems should reflect logical links and quantitative relationships among scales. It can be argued, however, that soil scientists' hierarchy of scales is often more an operational or observational device, based on the ability or feasibility to measure, rather than fundamental differences in basic processes (Wagenet, 1998). Hierarchy theory in ecology defines "*holons*," which are nested spatial units characterized by integrated biological, physical, and chemical processes (Haigh, 1987). In comparison, soil science uses entities that are less well defined and procedures that are less integrated. Further exploration in this area is worthwhile.

2.1.5 Need for elegant and robust models

Many current hydrologic models are either "too good to be real" or "too real to be good." In the first case, oversimplification undercuts the accuracy or generality of the results. In the second case, the need for detailed input data renders the model impractical to apply except in a research setting. Compromises between the quest for perfection and the complex reality, compounded by our limited knowledge, available modeling technology, and/or suitable data, plus natural uncertainty, are facts of life. Multiplicity and site-specificity of hydrologic models gain evidence and acceptance in hydrology (Beven, 2000) and it is therefore best to consider a broad range of reasonable alternative hypotheses and base the model on a variety of different types of data (NRC, 2001d). Armed with advances in categorizing soil-landscape relationships and cataloging existing structures, pedology has a potential to contribute substantially to building a range of hypotheses that should be considered in hydrologic modeling. Needs of hydrologic modeling, in turn, may catalyze efforts on organizing available soils information in a form relevant to modeling needs. Pedology has already provided a spectrum of pedotransfer functions to be used in model parameterization (Pachepsky and Rawls, 2005). More can be expected as information on soil structure and landscape features are being incorporated into pedotransfer functions (e.g., Rawls and Pachepsky, 2002; Lin et al., 2004a). In addition, as the importance of prior model parameter estimates along with posterior estimates from calibration becomes recognized, soil-landscape databases and pedotransfer functions can serve as useful sources of prior estimates. The need to use a broad range of data warrants efforts in developing a quantitative framework for linking soil moisture fields to climatic, pedologic, topographic, and vegetative processes and for linking data collected at different scales of spatial support. Such data assimilation and data fusion may improve operational use of hydrologic models at large scales by supporting model testing, verification, and refinement.

A hypothesis is suggested here:

- ***Hypothesis 5****: Soil-landscape relationships are essential elements in developing elegant and robust hydrological models. Hydrologically similar soil-landscape units exist within watersheds and these can be identified using traditional and new pedological and hydrological techniques.*

The most important step in any modeling is to determine what is important to system behavior. In modeling catchment response, determining the dominant processes and flow pathways that are responsible for controlling hydrologic response at different space and time scales enables development of good conceptual models that then form the basis of quantitative simulations of response. However, mixtures of different processes control hydrologic responses in different landscapes. At present hydrologic modelers struggle to determine what the dominant processes and flow paths are in a particular landscape unless they have been studied in detail. However, there is a potential to be better informed through more innovative use of soil survey data and through some modifications of the base data collected during soil surveys. It is important to note that as interest shifts to issues involving transport of solutes and sediments driven by flows of water that the hydrologic models need to get the flow paths and associated fluxes right, i.e., they need to be right for the right reasons, something that is not required to make a good prediction of integrated catchment runoff at watershed scales.

Another area where modelers are challenged is in developing system descriptions that work well across scales (Beven, 2002). This is partly because different processes become dominant at different scales, partly because the detail of information available typically decreases as one moves up in scale, and partly because the level of detail that can be represented reduces at larger scales due to the pragmatic constraint of computing. These effects have a number of implications that complicate modeling. At microscales, flow is controlled by capillarity and laminar flow through individual pores and around peds. As scale increases, flow often becomes controlled by impeding layers in the soil profile, then accumulation of water downslope leading to surface saturation, and finally routing of flow through the stream network. These changes in dominant process with scale mean that model structures change with scale of application. Data availability is also changing across scales. It is possible to characterize individual pores in a thin section but not for a soil profile; likewise, it is possible to characterize a soil profile in detail in a soil pit but not possible to characterize the 3-D soil entity to the same level of detail even in a first order catchment. This is fundamental because properties are spatially variable. This means that some form of average or statistical representation of small-scale detail may be required in models, even if the model resolves the system with a fine grid in space and time. Although limits on computing power will become less a concern in the next decade, larger spatial and temporal units are generally used for larger scale models. An implication of this is that clever algorithms are required that capture the effects of unresolved or unrepresented small scale processes, spatio-temporal variability of these processes, and the nonlinearities that typify environmental processes.

Besides the complexity of spatial scale, we also stress the critical importance of temporal dimension. The time scales over which soil and hydrological processes occur range from milliseconds for soil chemical reactions to decades or longer for transport of solutes to ground water, with some processes occurring only sporadically and also changing under different conditions. In addition, there is often a disjunction between soil and land use interactions and the subsequent impacts on aquatic systems. For example, nitrate is leached from soils in temperate agricultural systems largely during the winter but the impacts on aquatic ecology are often seen in summer and often at some distance away from the original source (Ferrier and Edwards, 2002). Therefore, measurement frequency must be aligned to the temporal variability and its structure (e.g., runoff events) inherent in pedological and hydrological processes. An adequate understanding and appropriate representation of temporal variability, the scales over which different processes operate, and the disassociations between sources and impacts, is vital to the development of robust models that can simulate hydropedological processes, watershed response, and environmental dynamics. Analogous to the REV, perhaps a concept of "representative elementary time-step" might be explored for characterizing temporal variability of pedological and hydrological phenomena.

We are now entering a predictive age (e.g., predicting future changes due to land use and climate change). With prediction comes a critical issue of uncertainty quantification in modeling. There has been substantial growth in research directed at quantifying and reducing the uncertainty associated with predictive modeling in the vadose zone (e.g., Holt and Nicholl, 2004). Most existing research on vadose zone uncertainty has focused on various components of the modeling process (e.g., uncertainty due to spatial heterogeneity and parameter estimation), while other important aspects have received limited attention (e.g., implicit conceptualization and global uncertainty) (Holt and Nicholl, 2004). Implicit conceptualization includes imposed assumptions regarding process, scale, geometry, and even numerical solution techniques, whereas global uncertainty refers to cumulative uncertainty that occurs via uncertainty propagation through the modeling process (Holt and Nicholl, 2004). New conceptual and quantitative approaches are needed to characterize the magnitude of various uncertainties inherent in soil and hydrologic modeling predictions.

2.1.6 Human impacts and the concepts of soil "*genoform*" and "*phenoform*"

With increasing emphasis on human impacts and land management practices, the arising interest in dynamic soil and water properties require more attention to hydropedology. Anthropogenic influences on soils have resulted in distinct characteristics that can be used to classify and model naturally-formed soils under different land management scenarios. Concepts of "genoform" (for genetically defined soil series) and "phenoform" (for soil types resulting from a particular form of management in a given genoform) facilitate the incorporation of management effects into pedological and hydrological characterizations and enhance pedotransfer functions that involve soil series and land uses as carriers of soil hydraulic information.

A hypothesis in this area is suggested as:

- ***Hypothesis 6****: The concept of "genoform" and "phenoform" combined with the use of pedotransfer functions can improve the efficacy of soil series and land use as carriers of soil hydraulic information under different human impacts.*

Any given soil can be changed significantly by land use management practices. For example, Droogers and Bouma (1997) studied a prime agricultural soil in the Netherlands and found that the organic matter content of a tilled variant had significantly increased as a result of organic manuring for many years. Also, grassland had significantly higher organic matter contents even though soil classifications of these two so-called phenoforms of the given genoform were identical. Modeling crop growth and nitrate leaching to the ground water yielded significantly different results, which indicated that just taking the standard soil descriptions (for the genoform) when characterizing a land mapping unit may produce erroneous results. Pedotransfer functions often use organic matter contents and bulk densities as input parameters and these vary significantly among different phenoforms. Distinguishing different phenoforms for a given genoform (or soil series) can refine the dynamic characterization of soils and pedotransfer functions under different human impacts, which will undoubtfully enhance hydrologic modeling and prediction.

2.2 Unique contributions of hydropedology to the advancement of hydrology and pedology

Hydropedology is a timely addition in this exciting era of interdisciplinary and systems approaches for developing comprehensive prioritization of science and applications in pedology and hydrology. Seizing this opportunity requires that we develop a vision of hydropedology and explore its unique contributions to the overall hydrological science as well as soil science. As a new interdisciplinary science, the domains of hydropedology have been suggested as (Lin et al., 2004a): a) *Landscape-soil-water systems* – Taking a holistic view of the landscape, with roots in pedology and a focus on water as a driving force, hydropedology emphasizes the vadose zone system linkages, the state and pattern of its component storages, interfacial fluxes, and dynamic changes (including those caused by human activities); and b) *Soil-water interactive processes across scales* – Hydropedology aims to characterize integrated physical, chemical, and biological processes of soil-water interactions at all scales, including chemical elements and energy transport by the water flow, and the interrelationships between soil distributions/functions and hydrologic and geomorphic processes. The fundamental scientific issues of hydropedology include at least (Lin et al., 2004a): a) Soil structure and layering as indicators of flow and transport characteristics in field soils; b) Soil morphology as signatures of soil hydrology; c) Water movement through the landscape as related to the soil cover; d) Hydrologic cycle as a factor of soil formation and a driving force of dynamic soil systems; and e) Human impacts on soil-water interactions as reflected by land use and management.

Unique contributions of hydropedology to enhanced understanding and prediction of *landscape water flux* include: 1) providing better soils data and water flow pathways (e.g., those related to soil-landscape structures, preferential flow, and lateral fluxes over slowly permeable soil horizons), 2) enhancing the understanding of mechanisms and magnitudes of soil spatio-temporal variability (e.g., soil spatial diversity as a function of soil-forming factors and processes), 3) improving the quantification of structural hierarchies and pattern identifications of soil and hydrologic systems (e.g., soil-landscape relationships and soil hydrologic units as portrayed by soil maps of various scales), and 4) enhancing model structure formulation and selection of suitable model for hydrologic prediction. For example, short- and long-term hydrologic responses are controlled by different soil characteristics (e.g., infiltration capacity and rapid subsurface flow pathways for short-term response, while recharge to ground water and subsequent release as baseflow via deep slow flow pathways for long-term response). Hydrologically key soil characteristics can be identified at different spatial and temporal scales, and identification and characterization of such key soil properties will require continued joint efforts from soil scientists and hydrologists.

In the following, we further discuss unique aspects of pedology and their contributions to understanding and predicting *landscape water flux.* Six additional hypotheses are formulated to suggest future work that needs to be done in order to advance pedology, hydrology, and hence hydropedology.

2.2.1 Soil morphology including soil structure

Soil morphology is the foundation of pedology. It is a basis for interpreting soil genesis, a key component for classifying soils, and an essential aspect in soil survey and mapping. Soil morphological attributes such as pedogenic diagnostic horizons or features, soil profile horizonation, color, hand-texture, structure, consistence, roots, pores, redoximorphic features, concretions, and ped/void surface features are routinely described by field soil scientists. These descriptions, however, are generally qualitative or semi-quantitative, categorical assessments of visible and tactile qualities of the soil. Nevertheless, significant volumes of soil morphological data available within many national and regional soil survey databases offer considerable potentials to develop rule-based relationships between soil morphology and soil hydraulic properties and to improve equation-based pedotransfer functions (e.g., Lilly and Lin, 2005).

Furthermore, soil morphology offers clues to predicting potential occurrence of preferential flow. Frequency and importance of preferential pathways can be inferred using pedologic information and methods. For example, a well-developed soil structure indicates interpedal pore space that likely conducts water preferentially, which often exhibits characteristics such as clay films that provide supporting evidence. Worm channels may conduct large volumes of water under saturated or near-saturated conditions but only when they are vertically continuous and hydrologically connected. Staining techniques can help show macropore continuity and connectivity. Once preferential flow has been indicated to occur, new measurement techniques can be used to express it as a function of flow rate and time (e.g., Booltink and Bouma, 2002). Soil structure descriptions in pedons can be quantified with morphological techniques and data obtained can, in turn, be used to calculate hydraulic conductivities by using physical relationships between pore sizes and fluxes of water (e.g., Bouma, 1990; Lin et al., 1999). Because soil morphology provides clues as to the hydrologic history of a site by integrating long-term effects of water movement and storage in observable features of soil color (including redox features), structure, density, horizonation, and other features, efforts to interpret and quantify soil morphologic information can elucidate seasonal high water table fluctuations, soil moisture regime in the past and present, and soil hydraulic properties.

A hypothesis is suggested here:

- ***Hypothesis** 7: Soil morphological features and their spatial arrangement over the landscape can be used to aid in determining dominant flow pathways and water fluxes through different soils and landscapes.*

We realize that predicting preferential flow from soil morphologic information still has a long way to go, and that preferential flow may be caused by a multitude of processes, including some that are not immediately evident from classic pedologic studies (e.g., unstable flow). One of the key issues is the need to quantify soil structure in a manner that provides direct information for inclusion in hydrologic models. We envisage the appearance of innovative methods for quantifying *in situ* soil structure and linking such information to hydrologic processes/properties in a quantitative manner.

2.2.2 Pedogenesis

Soil genesis is essentially an integrated weathering phenomenon resulting from a series of physical, chemical, and biological processes. It provides a holistic view of the processes that have occurred, or are occurring, in the vadose zone. Besides conceptual understanding of soil-forming factors and processes (e.g., Jenny, 1941; Simonson, 1959), quantitative models that describe the impact of environmental variables on rock/sediment weathering and soil formation are lacking. Nevertheless, soil genesis provides insights regarding the processes involved (including hydrological processes) and soil-geomorphology evolution over time.

The essential role of water in soil formation is apparent in the Simonson's (1959) theory of soil formation, where four general soil-forming processes are recognized (i.e., additions, deletions, transformations, and translocations). All these four soil-forming processes involve water in significant ways: Water adds material through deposition of eroded sediment and precipitation of dissolved minerals; water can also entirely remove soil materials through leaching and erosion; water transforms soil material through weathering reactions; and water translocates solid and dissolved materials in mass flow within soil profiles (Lin et al., 2004a).

A relevant hypothesis is:

- ***Hypothesis 8****: Pedogenesis provides valuable information regarding hydrological processes involved in soil-landscape evolution over time. Hydrology/hydropedology provides a potential means of quantifying soil-forming processes.*

All soil-forming factors affect and are affected by hydrology. The flux factors of soil formation (climate and vegetation) as well as site factors (topography and parent materials) can be linked to landscape hydrology, which is further modified by soil internal hydrologic environment (Lin et al., 2004a). For instance, climate influences the amount and timing of soil water availability and soil moisture in turn influences climate. The biota growing on and in soils are strongly influenced by water's presence, both directly because organisms require water to live, and indirectly because the amount of soil water influences oxygen availability, the temperature regime, and nutrient transport in soils. Topography frequently directs and controls the flow of both surface and subsurface water over the landscape. Parent materials affect the flow of water because they are the sources of the matrix through which surface water infiltrates and may reflect the materials through which ground water flows. Time is required for both soil development/change and for water to flow through soils and landscapes. Much like "*one cannot ignore the role of ground water in performing geologic work*" (Domenico and Schwartz, 1998), water in the unsaturated zone cannot be ignored in soil formation and soil dynamic changes.

2.2.3 Classification

Soil classification offers a hierarchical system for organizing, modeling, and transferring knowledge about different soils across geographic regions. While a huge success in its own right, the exclusive focus on *Soil Taxonomy* (Soil Survey Staff, 1999) in the U.S. pedology community over the last four decades or so has become an introspective exercise and resulted in some unintended consequences, including: 1) lack of relation between soil taxonomic units and landscape features; 2) lack of consideration of dynamic soil properties such as hydraulic functions; 3) lack of simplicity for non-pedologists to apply; and 4) lack of quantification of variability (or specific range of soil properties) within taxonomic categories and soil map units, thus leading to a common assumption of "homogeneity" within soil taxa and map units by non-pedologists (Lin et al., 2004a). Despite such shortcomings, however, considerable soil characteristics (including morphological, physical, chemical, and pedogeneric properties) are contained in soil taxonomic classifications and in soil taxonomic names, thus providing opportunities to infer and/or group diverse soils into hydrologically similar units.

A related hypothesis is suggested here:

- ***Hypothesis 9****: Soil taxonomic systems can be utilized or modified, particularly when used in combination with landscape features, to aid in categorizing diverse soils into hydrologically similar groups.*

Soil categorizations that differentiate various soil hydrologic units are possible. For example, Quisenberry et al. (1993) have devised a preliminary system of classifying soils in terms of water flow pathways and patterns (uniform flow vs. different types of preferential flow) using soil texture, structure, and clay mineralogy. The work of Quisenberry et al. (1993), however, has been limited to partial soils in South Carolina and is descriptive in nature. A soil hydrological classification (termed Hydrology of Soil Types or HOST) has also been developed in the UK based on soil attributes to predict water movement through soils and substrates (Boorman et al., 1995; Lilly et al., 1998), in which 29 groups of soils are identified with distinct flow pathways and flow rates. The attributes used in the HOST include the presence or absence of an organic surface layer, substrate hydrogeology, the depth to a slowly-permeable layer, the depth to gleying, and air capacity value (volume of pores that drain under the influence of gravity). Pedotransfer rules underpin much of the HOST classification, which are not linked to landscape features. A more comprehensive and quantitative approach to grouping hydrologically similar soil types across scales is desirable.

Being able to group and even classify soils prior to, during, and after the development of pedotransfer functions also enhances the accuracy and reliability of pedotransfer function applications (e.g., Lilly and Lin, 2005). A description of the groups in terms of both soil morphology and hydraulic properties is a valuable means of developing simple predictive pedotransfer functions for field soils. Furthermore, a grouping of soils (particularly when linked to soil map units) for flow and transport characteristics will enable estimation of the magnitude of expected hydraulic properties and determination *a priori* of how important preferential flow is in a given soil and location. Such grouping will allow capturing "big picture" (e.g., flow mechanisms and pathways) before a specific water flux is derived.

2.2.4 Mapping

Soil mapping provides a foundation for understanding soil-landform relationships and soil variability over the landscape. The purpose of soil mapping is to partition soils and landforms into stratified subsets that are less variable (Soil Survey Division Staff, 1993). Soil maps currently available are often considered as one of the very best data one usually can obtain at the present time in environmental and natural resource assessments as compared to many other available data (Merchant, 1994). However, the proper use of existing soil maps is not necessarily warranted if the map scale and within-map-unit variability are not well understood. Quantification of map unit purity for different scales of soil maps is an area needing improvements in modern soil surveys (Arnold and Wilding, 1991; Lin et al., 2004b). An understanding of how soil maps are made, the map scale involved, and the variability within map units is required for effective integration of pedology and hydrology.

A hypothesis to be tested is suggested here:

- ***Hypothesis 10****: Pedodiversity as portrayed by soil maps is indicative of hydrological heterogeneity of soil-landscapes. Hierarchy of soil hydrologic units can be put in correspondence to the hierarchy of soil cover.*

It is possible to define landscape elements consisting of groups of soil horizons with a defined range of hydrological properties as essential building blocks for hydrologic modeling. Quantitative soil hydrologic properties/processes and their variability within soil map units can be related to pedologic features mapped. Such mapping can aid in providing quantitative estimates of system parameters required for hydrologic prediction. In addition, current digital soils databases (e.g., Soil Survey Geographic Databases or SSURGO, State Soil Geographic Databases or STATSGO, Major Land Resource Areas, and Common Ecological Regions) have been developed as separate and independent products at various map scales. A new scalable data model linking geo-referenced locations of soil measurements (e.g., point data) with soil components on soil maps of various scales is needed for developing the hierarchy of soil hydrologic units.

To advance hydropedology and hydrologic modeling, we need new ways of mapping soils over the landscape in greater detail and with higher precision. Traditional soil maps have been created using mental models of soil variation based often on air photo interpretation and collated information on the soil and its relations with landform, geology, vegetation, and land use (Dijkerman, 1974; Soil Survey Division Staff, 1993). Field observations are made at a selected number of locations chosen by soil surveyors using formal knowledge and intuitive judgment (Dijkerman, 1974; Hudson, 1992). These methods generally result in qualitative models that produce broad schemes that discretize and classify the soil continuum (Cook et al., 1996). With the emergence of quantitative pedologic measurements and modeling techniques including pedometrics, pedologists have sought more quantitative approaches to modeling the spatial distribution of soil types and soil properties (e.g., McBratney et al., 2000; Heuvelink and Webster, 2001; McBratney et al., 2003). Promising approaches include environmental correlation modeling (e.g., McKenzie and Ryan, 1999; Ryan et al., 2000) or landscape-guided soil mapping (Heuvelink and Webster, 2001), where landform and environmental attributes such as DEM, land use/land cover, parent materials, and others serve as additional information in kriging and mapping. Another encouraging alternative to conventional soil mapping is the combined use of Geographic Information Systems (GIS), expert knowledge, and fuzzy logic, as used in the soil-land inference model (e.g., Zhu et al., 2001). This model is based on a similarity representation of soils, soil-landscape relationships, and a combination of local soil scientists' knowledge with GIS under fuzzy logic.

2.2.5 Database

Soil survey databases provide a wealth of information that hydrologists could utilize for various applications. For example, the National Cooperative Soil Survey Program in the U.S. has provided over 100 years of soil inventory, measurement, and evaluation, and has maintained several national databases (e.g., digital soil maps of multiple scales and associated attribute tables, official soil series descriptions, soil characterization database that includes over 25 physical and chemical properties for over 20,000 soils sampled throughout the U.S., soil moisture and temperature monitoring network, and hydric/wet soils monitoring database). These data can be coordinated and well utilized in the development of pedotransfer functions, hydrologic grouping or classification of soils, and testing of hydrologic models.

A hypothesis in this area is suggested as:

- ***Hypothesis 11****: The accuracy of pedotransfer functions for hydrologic model parameterization can be improved by using structural parameters of soils and linking to soil cover and landscape features.*

Most data in traditional soil survey databases have been collected at a window in time. Dynamic soil properties, including land use-dependent soil properties, are increasingly in demand. Hence, a database containing dynamic soil properties will be desirable to enhance the value of classical soil survey databases and to facilitate the integration of pedology with hydrology. We believe hydropedology offers a useful framework for bridging traditional soil survey and future database of dynamic soil properties. In such an integrated database, a minimum set of hydropedological data should be collected in order to characterize a catchment and its hydrologic flux response, land use and land management information, and various landscape features, along with location and time for various measurements.

2.2.6 Future pedology

The emphasis of pedology is now shifting from classification and inventory to understanding and quantifying spatially-temporally variable processes upon which the water cycle and ecosystems depend (Lin et al., 2004a). Hence, the contributions of hydropedology to the advancement of pedology are multi-faceted, as illustrated in the above discussions. In essence, hydropedology proposes to realign geology-rooted classical pedology with a hydrology-driven approach based on a landscape perspective, reflecting the crucial role of water in wide array of issues. Hydropedology adds quantitative information to classical pedology through measuring water flux, modeling soil dynamic behavior, and making soils databases hydrological relevant.

We suggest a hypothesis that can be tested in the next decade or so:

- ***Hypothesis 12****: Hydropedology is a promising direction for future pedology.*

Bridging disciplines, scales, and data signifies potential unique contributions hydropedology can make to integrated soil and water sciences (Lin, 2003). Hydropedology also plays a unique role in advancing the frontiers of soil science towards a geoscience (Wilding and Lin, 2005). Historically, soil science has followed a complex path in its evolution from a descriptive discipline with foundational roots in geology, to an applied agricultural and environmental discipline, and now to a bio- and geo-science through the earth's critical zone investigations.

Future pedology mandates systematic, quantitative, and dynamic characterizations of soil natural "architecture," soil spatial diversity, and soil-landscape relationships, which are fundamental underpinnings of pedology. As an example, soil maps can no longer be static documents. Rather, derivative and dynamic maps, created for specific purposes or functions, must be generated from original soil maps and tailored to particular applications. Thus, pedotransfer functions, in combination with computer models and geospatial databases, need to be integrated into expert systems to derive such maps. Up to now, there is a lack of appropriate means of producing derivative and dynamic maps such as soil hydraulic properties through space and time. In this regard, hydropedology offers considerable opportunities.

3. Strategies for Achieving the Vision

The strategies for achieving the above stated vision and the role of CUAHSI are multi-faceted and mutually indispensable. We group the strategies into the following three interlinked components (Fig. 4): 1) Design of a set of scientific experiments to test the proposed hypotheses, 2) Use of Hydrologic Observatories and natural soil laboratories, and 3) Promotion and dissemination of hydropedology.

We would like to point out that, while devising more detailed experimental and modeling work as proposed in the following, a useful first step in hydropedology is to link existing soil and hydrological data (such as grouping hydrologically similar soil units and enhancing pedotransfer functions) to generate interests, and to develop case studies on the use of pedological data for improved hydrological applications (such as knowledge of flow pathways at the pedon and field scales and of hydrological responses at the watershed scale) (e.g., Dunn and Lilly, 2001). The knowledge gaps thus identified can then be used to guide more detailed fundamental research.

3.1 Design of a set of scientific experiments to test the proposed hypotheses

Designing a set of scientific experiments that can test the suggested hypotheses is a logical and fundamental step in achieving the proposed research vision. The proposed hypotheses can be used to guide the design and implementation of such experiments. These experiments can be conducted in the CUAHSI's Hydrologic Observatories as well as smaller-scale natural soil laboratories as described in the next section. In addition to the desired infrastructure supports, available funding, coordinated efforts, new instruments, innovative technologies, integrated databases, and multidisciplinary communications are also needed to carry out the suggested experiments in a more comprehensive and fruitful manner.

An iterative loop of "understanding, sampling, and modeling" is essential to integrated hydropedological studies. This requires a concerted program of systematic and integrated experiments, analyses, and modeling on watershed-scale dynamics. Soil science and hydrology have a fundamental need for multiscale, multidisciplinary, and long-term field experiments. Hydropedology can contribute uniquely in this regard in ways that include a) the use of the state-of-the-art techniques in soil mapping, vadose zone monitoring, and variably-saturated modeling, and b) attention to field soil morphology and soil cover patterns to guide the selection of monitoring sites, optimal experimental designs, interpretations of hydrologic measurements, and flow and transport modeling in the vadose zone.

Much progress has been made in 1, 2, and 3-D modeling, in terms of integrating various processes at different scales and incorporating preferential flow dynamics (van Genuchten and Šimunek, 2004), but much remains to be done, especially in bridging scales, feeding inputs, quantifying uncertainties, and integrating processes from a systems perspective in the context of the earth's critical zone. Integrated models are the future, where overland flow (including rivers and lakes), ecohydrology, vadose zone flow and transport, and ground water hydrology are tightly coupled. Running models of this type for various applications will give hands-on guidance of what hypotheses are fundamental and what data are critical.

To make a quantum leap, we need to embrace a holistic framework such as the one discussed in Section 2.1.1 and to find ways to build up comprehensive datasets for quantifying such a framework. Beyond problem-solving needs, we have to address fundamental concepts and first principles involved in landscape and watershed hydrology, and to take full advantage of signatory information recorded in soils (such as soil morphology and pedogenesis). One way to follow such a path is to advance our understanding of a system's logical connections such as "structure – physics – flow model."

3.2 Use of hydrologic observatories and natural soil laboratories

One critical need for advancing hydropedology is a network of well-designed and carefully maintained natural laboratories across geographic regions for systematic (in both space and time) field data collections. The proposed CUAHSI's Hydrologic Observatories will provide such an essential support. In addition, we suggest the development of smaller-scale natural soil laboratories across Hydrologic Observatories as well as in other watershed testbeds for conducting coordinated field experiments.

Leading-edge instrumentation and innovative measurement techniques will be an integral part of each Hydrologic Observatory, such as:

- Networked arrays of state-of-the-art sensors (ground-, air-, and space-based platforms) for measuring states and fluxes in the critical zone at point, hillslope, catchment, and regional scales and at critical time-steps (e.g., *in situ* real-time soil moisture sensors, optical and microwave imagery, radiometry, hyperspectral imagery, and others);
- A suite of noninvasive tools (e.g., computing tomography, geophysical tools, and remote sensing) for characterizing soil-landscape structures across multiple scales and for linking such structural information to water fluxes in a block of land of various sizes;
- Advanced soil and landscape mapping that captures spatial and temporal organization (patterns) of hydropedological properties and processes;
- A set of natural and anthropogenic tracers for tracking the movement of water through landscapes and ecosystems.

We propose to develop commonly accepted and adhered to protocols for establishing natural soil laboratories within each CUAHSI's Hydrologic Observatory as well as in representative Major Land Resource Areas (MLRAs) using hierarchically-nested watershed testbeds. As MLRAs are becoming a new direction for the U.S. national soil survey and mapping program, the MLRA concept (and the related Common Ecological Regions) provide a useful means of establishing natural soil laboratories in contrasting landscapes.

Hydropedology blends the field work, laboratory investigations, and computer modeling into an integrated systems approach to understanding landscape-soil-water dynamics across scales. Field work (observations, monitoring, experiments, and verifications) ultimately serves as the initial drive of identifying the real world problems, formulating theories of processes and events, and validating models and their predictions. Field survey and mapping of landscape features (including soils, geology, topography, vegetation, and others) is a foundation for conducting integrated hydropedological research over a block of land and for extrapolating results from intensively studied sites to unstudied watersheds.

We believe there is a minimum set of hydropedological data that should be collected in the CUAHSI's Hydrologic Observatories and natural soil laboratories in order to characterize a catchment and its hydrologic flux dynamics. Determination of such a core dataset is to be guided by the scientific hypotheses to be tested, interpretation techniques required for the collected dataset, improvements for quantitative modeling, as well as the needs for the overall integrated monitoring network. Research conducted at these Hydrologic Observatories and natural soil laboratories will also allow for the testing and refinement of pedometric approaches to mapping critical hydropedological variables and scaling pedon data to the landscape scale.

It is important to point out the need for process-based modeling in conjunction with the data gathering. Data are only good if they are used, not just by users or policy makers, but even more so by peer scientists including those interested in advancing hydrologic modeling. Future modeling needs could provide both justifications and guidelines for all the measurements to be made by the CUAHSI Hydrologic Observatories and natural soil laboratories, including "what, where, and when" data should be collected, at what resolution, for how long, and for what purpose. Systematic field data collections must contribute to enhanced understanding at a hierarchy of scales and to the advancement of quantitative modeling and prediction.

3.3 Promotion and dissemination of hydropedology

3.3.1 Integrated hydropedological information systems

To integrate knowledge, databases, and models of interactive pedological and hydrological processes and properties across scales and geographic regions, and to streamline information capture, storage, sharing, comparison, visualization, syntheses, modeling, hypothesis testing, and decision-making, an *Integrated Hydropedological Information System* (IHPIS) is suggested here.

There is a clear need for integrating knowledge, databases, and models to address forcing, feedbacks and coupling, and to ensure appropriate spatial coverage, temporal frequency, and data resolution. Within the *HydroView* framework, *Hydrologic Information Systems* (HIS) provide a comprehensive data model, thus making them more useful to scientists and identifying gaps that are hindering scientific advances. While *ArcHydro* for hydrological data has been developed (Maidment, 2002), a similar one for soils data is desirable so as to provide a systematic, cohesive, and yet flexible enough set of toolboxes to help advance our science. Besides data models, integrated process-based modeling system is also needed that allows systematic examination of various processes at different scales. In doing so, code standards (such as algorithm transferability, modularization, and object-oriented design) and inter-code comparison (especially against field data collected in watershed testbeds) need to be considered (e.g., Šimunek et al., 2003). We recognize the need for balancing standardizations and innovations in both field data collections and modeling system developments so as to provide commonly adhered protocols for data gathering and sharing and model comparison and yet not to constraint new ways of data collection and modeling.

Hydropedoinformatics is coined here from hydroinformatics and pedometrics, both have attracted growing interest in recent years. Hydroinformatics is the study of the flows of knowledge and data related to water and all it transports, together with its interaction with both natural and man-made environments (Abbott, 1991). It is a discipline that has a strong ancestry in computational sciences and artificial intelligence, where GIS and data mining (artificial neural networks and genetic algorithms specifically) are the prevailing technologies (Savic and Walters, 1999). Pedometrics is the application of mathematical, statistical, numerical, and artificial intelligence methods to soil science in general and soil surveys in particular (McBratney, 1986; Webster, 1994). Innovative syntheses of hydrological and pedological data with new tools/methods for data mining and knowledge discovery are important for advancing hydropedology once systematic and comparable datasets are collected.

3.3.2 Effective communications of hydropedology

Adequate and effective communication with other discipline scientists, the general public, stakeholders, and policy-makers is needed to advance hydropedology. Effective means of communication and dissemination of hydropedological knowledge also includes education and outreach activities such as course offering, field camps, and workshops.

Rather than just reporting results of studies having been made, it is often more effective to take part in interactive processes between, for example, policy-makers and citizens dealing with water or land-use problems by providing relevant information at the right time. Being part of the learning process is better than being an outsider who provides data but is never sure whether it will be used. As often as not, potential users have little affinity with what is being offered, because researchers have not bothered to really investigate the wishes of the users or of the policy-makers. The Internet offers as yet largely unexplored possibilities to present hydropedological expertise, building on the natural affinity of many people with the earth and its critical zone and many cultures with soil and water resources (e.g., Bouma, 2001a, b, 2003).

4 Expected Impacts

4.1 Scientific impacts

HydroView and its four infrastructure elements will provide a springboard and long-term support for the advancement of hydropedology, which, in return, will contribute significantly to the CUAHSI's Science Agenda (Fig. 4). As highlighted by Lin et al. (2004a), seven working models or perceptions of soils can be used to evaluate the relevance of hydropedology to the study of the earth's critical zone (Fig. 1)—within each of these models, soil-water interaction plays a critical role. The U.S. National Research Council has identified integrated studies of the earth's critical zone as a compelling research area for the 21st century (NRC, 2001a).

Hydrogeoscientists are facing a new intellectual paradigm that emphasizes connections between the hydrosphere and other components of the earth system. While hydroclimatology, hydrogeology, and ecohydrology are now well recognized, an important missing piece of the puzzle is hydropedology that focuses on the interface between the hydrosphere and the pedosphere (Fig. 1). Hydropedology closes this gap and emphasizes flow and transport processes in field soils as occurred in landscapes (i.e., soils that have distinct characteristics of structure, layering, and soil-landscape relationship). We believe hydropedology can contribute significantly to the study of the hydrologic cycle, the pedosphere, the earth's critical zone, and the earth system as a whole.

Beyond the earth's system, hydropedology also poses potential contributions to extraterrestrial explorations in search for water signs through soils, rocks, and landforms, such as that on Mars. The recent formation of the *Weathering System Science Consortium* demonstrates the need to answer a fundamental scientific question: "*How does the Earth's weathering engine transform the protolith into soils and solutes in response to climatic, tectonic, and anthropogenic* *forcing*?" (Anderson et al., 2004). Answers to this question will likely shed light on weathering processes on Mars and the potential role of water in the genesis of Martian soils.

4.2 Societal impacts

Soil-water interaction creates the fundamental interface between the biotic and abiotic and thus is a critical determinant of the state of the earth system. Through its influences on the physical, chemical, and biological processes in the root and deep vadose zones, soil-water interactions at different scales play a significant role in many societally important issues (Fig. 5). These include leaching of chemicals to ground water, non-point sources of pollution, gas exchange between soil and the atmosphere, carbon flux and carbon sequestration, nutrient dynamics in agroecosystems, crop yield, drainage and irrigation related to land use and agricultural practice, flood/drought and landslide preventions, contaminant fate in the environment, and many others.

Soil moisture is the life-giving substance, and is directly linked to the function of the earth's critical zone. Nolan and Fatland (2003) summarized this adroitly: "From Napoleon's defeat at Waterloo to increasing corn yields in Kansas to greenhouse gas flux in the Arctic, the importance of soil moisture is endemic to world affairs and merits the considerable attention it receives from the scientific community. This importance can hardly be overstated, though it often goes unstated." The spatio-temporal pattern of soil moisture is critical for hydrological forecasting, erosion prediction, carbon flux determination, contaminant transport modeling, nutrient cycling, pedogenic processes, and geomorphic processes. A better understanding of the spatio-temporal distribution of soil and water interactions contributes to improved land components of climate and global circulation models.

A number of recent reports of the U.S. National Research Council have highlighted the significance of integrated soil and water studies in the context of agriculture (NRC, 1993a), ground water vulnerability (NRC, 1993b), watershed management (NRC, 1999), earth sciences (NRC, 2001a), water resources (NRC, 2001b), and environmental sciences (NRC, 2001c). Water fluxes into and through soils across the landscape are the essence of terrestrial life, resembling in a way the manner in which blood circulates in a human body (Bouma, 2005). We could even compare blood pressure with the pressure potential of water in soil – when it is too high or too low soil functioning is clearly hampered. We can envisage a pulsating landscape in which water enters and leaves on hourly, weekly, yearly, and long-term bases. Once water regimes have been characterized, physical, chemical, and biological processes in the unsaturated zone can be properly approached as they depend strongly on the water regime. Indeed, the hydrologic cycle is viewed as the integrating process for the fluxes of water, energy, and chemical elements (NRC, 1991).

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List of Figures

Fig. 5. (A) Relevancy of hydropedology to the study of the earth's critical zone—within each of the issues illustrated, soil-water interaction plays an important role. (B) Water is a main driving force of many environmental issues; hence soil-water interaction is critical to problems concerning nitrogen, phosphorus, carbon, pesticides, heavy metals, pathogens, and other nutrients or contaminants in the environment. Biogeochemical cycle is inseparable from the hydrologic cycle.

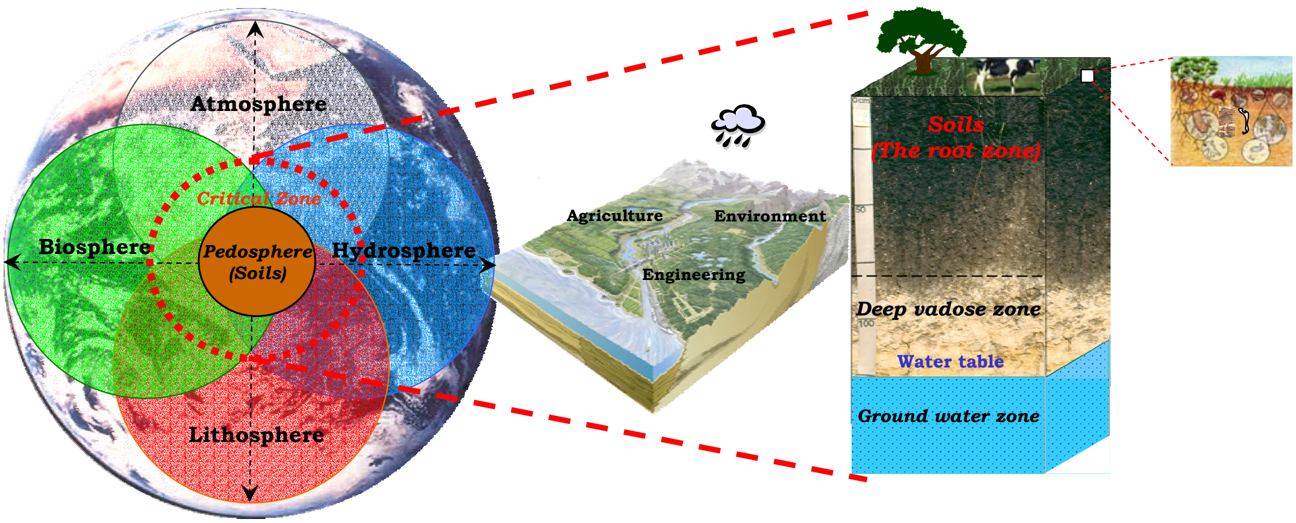
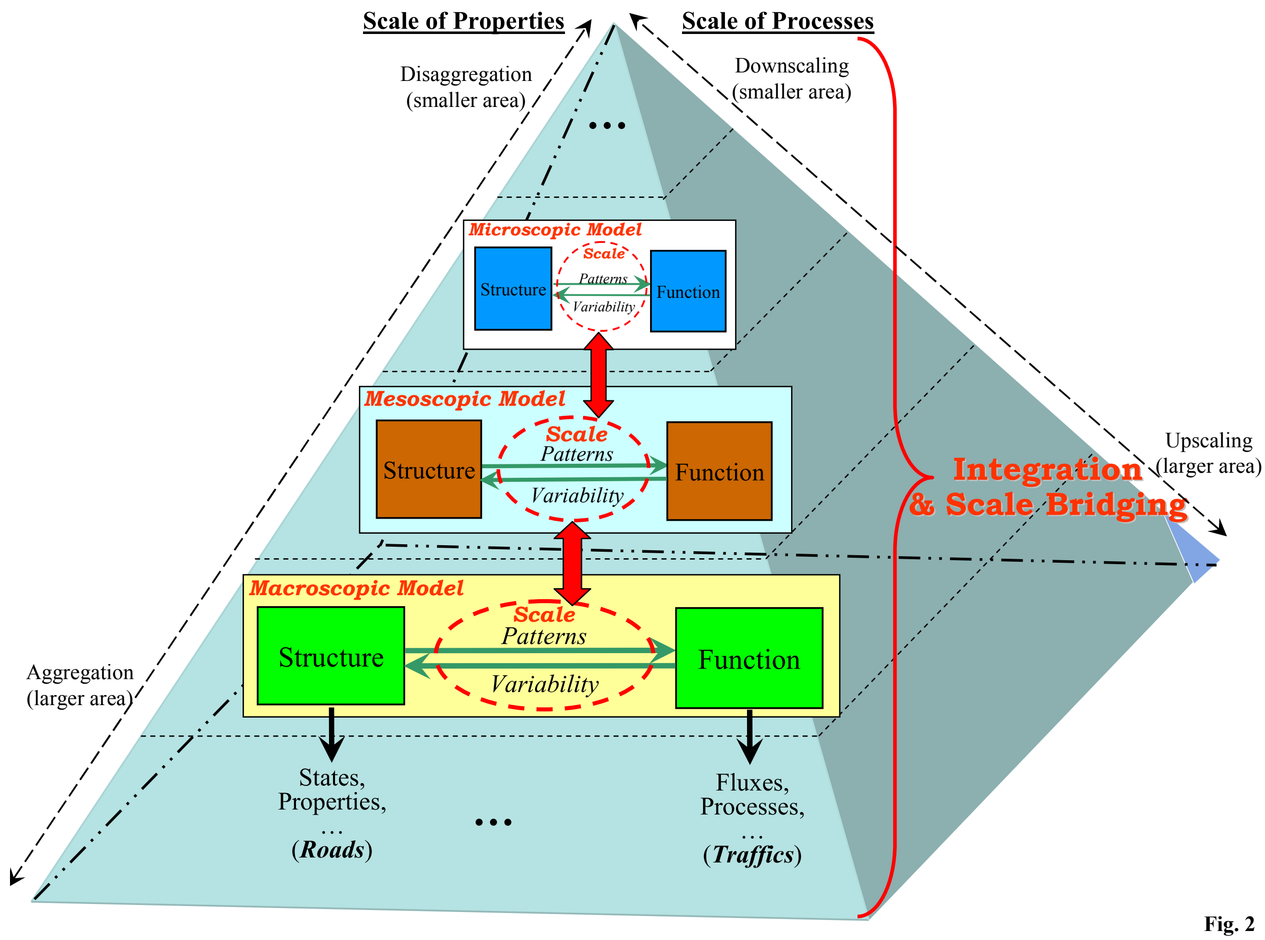

Atmosphere
Critical Zone
Biosphere
Pedosphere
(Soils)
Hydrosphere
Lithosphere
Agriculture
Environment
Engineering
Soils
(The root zone)
Deep vadose zone
Water table
Ground water zone

Fig. 1

1


Scale of Properties
Scale of Processes
Disaggregation
(smaller area)
Downscaling
(smaller area)
• • •
Microscopic Model
Structure
Scale
Patterns
Variability
Function
Mesoscopic Model
Structure
Scale
Patterns
Variability
Function
Upscaling
(larger area)
Integration
& Scale Bridging
Macroscopic Model
Structure
Scale
Patterns
Variability
Function
Aggregation
(larger area)
States,
Properties,
…
(Roads)
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Fluxes,
Processes,
…
(Traffics)

Fig. 2

1

A) Pedology Model

B) Hydrology/Soil Physics Model

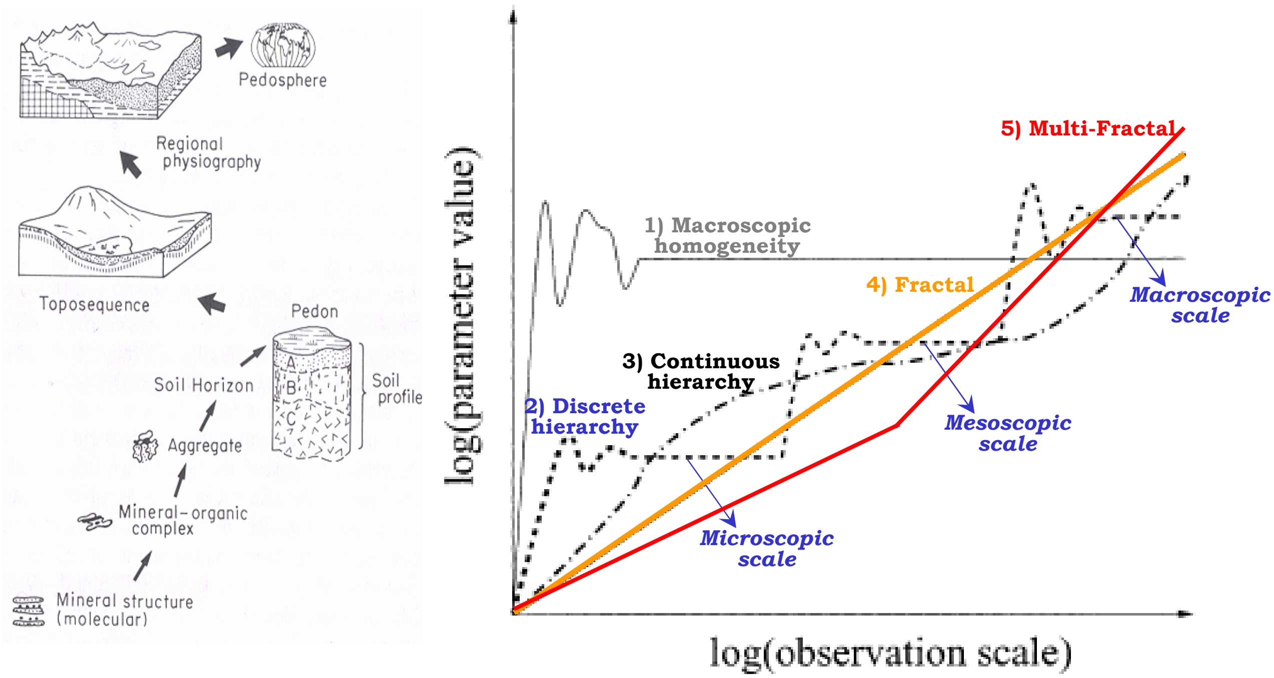

Fig. 3

1

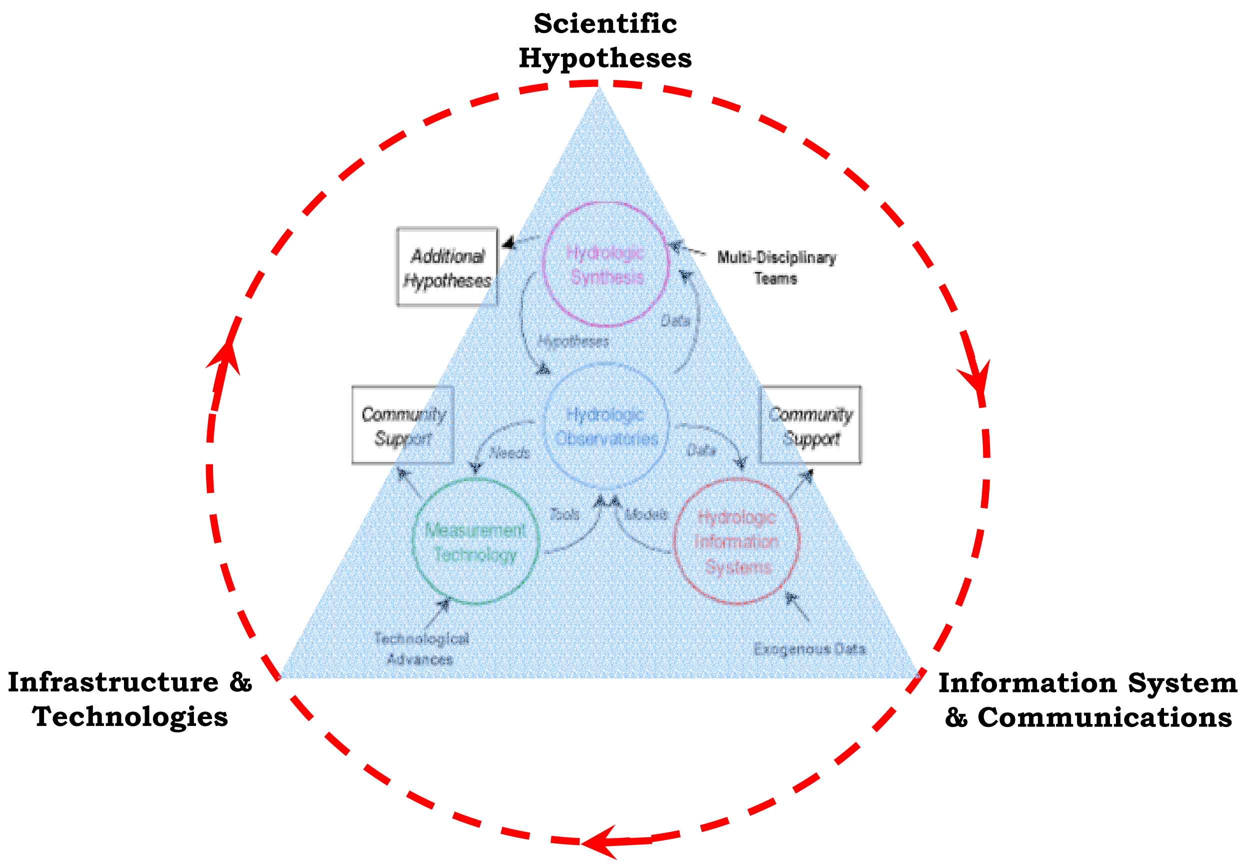
Scientific Hypotheses
Additional Hypotheses
Hydrologic Synthesis
Multi-Disciplinary Teams
Data
Hypotheses
Community Support
Hydrologic Observatories
Community Support
Needs
Data
Tools
Models
Measurement Technology
Hydrologic Information Systems
Technological Advances
Exogenous Data
Infrastructure & Technologies
Information System & Communications

Fig. 4

1

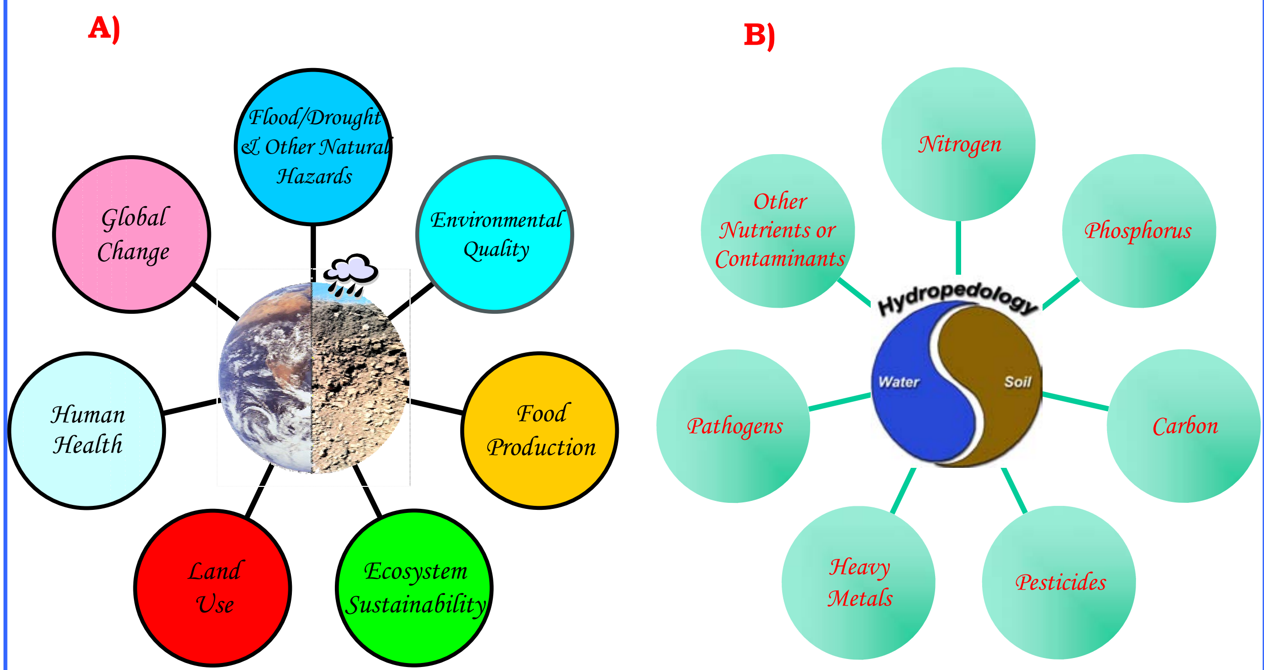
A)
Flood/Drought & Other Natural Hazards
Global Change
Environmental Quality
Human Health
Food Production
Land Use
Ecosystem Sustainability
B)
Nitrogen
Other Nutrients or Contaminants
Phosphorus
Hydropedology
Water
Soil
Pathogens
Carbon
Heavy Metals
Pesticides

Fig. 5