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Earth's Critical Zone and hydropedology: concepts, characteristics, and advances

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Abstract

The Critical Zone (CZ) is a holistic framework for integrated studies of water with soil, rock, air, and biotic resources in terrestrial environments. This is consistent with the recognition of water as a unifying theme for research on complex environmental systems. The CZ ranges from the top of the vegetation down to the bottom of the aquifer, with a highly variable thickness (from <0.001 to >10 km). The pedosphere is the foundation of the CZ, which represents a geomembrance across which water and solutes, as well as energy, gases, solids, and organisms are actively exchanged with the atmosphere, biosphere, hydrosphere, and lithosphere to create a life-sustaining environment. Hydropedology – the science of the behaviour and distribution of soil-water interactions in contact with mineral and biological materials in the CZ – is an important contributor to CZ research. This article reviews and discusses the basic ideas and fundamental features of the CZ and hydropedology, and suggests ways for their advances. An "outward" growth model, instead of an "inward" contraction, is suggested for propelling soil science forward. The CZ is the right platform for synergistic collaborations across disciplines. The reconciliation of the geological (or "big") cycle and the biological (or "small") cycle that are orders of magnitude different in space and time is a key to understanding and predicting complex CZ processes. Because of the layered nature of the CZ and the general trend of increasing density with depth, response and feedback to climate change take longer from the above-ground zone down to the soil zone and further to the groundwater zone. Interfaces between layers and cycles are critical controls of the landscape-soil-water-ecosystem dynamics, which present fertile grounds for interdisciplinary research. Ubiquitous heterogeneity in the CZ can be addressed by environmental gradients and landscape patterns, where hierarchical structures control the landscape complex of flow networks embedded in mosaics of matrices. Fundamental issues of hydropedology are linked to the general characteristics of the CZ, including (1) soil structure and horizonation as the foundation of flow and transport characteristics in field soils; (2) soil catena and distribution pattern as a

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first control of water movement over the landscape; (3) soil morphology and pedogenesis as signatures of soil hydrology and soil change; and (4) soil functional classification and mapping as carriers of soil hydrologic properties and soil-landscape heterogeneity. Monitoring changes in the crucible of terrestrial life (soil) is an excellent (albeit complex) environmental assessment, as every soil is a "block of memory" of past and present biosphere-geosphere dynamics. Our capability to predict the behaviour and evolution of the CZ in response to changing environment can be improved significantly if a global alliance for monitoring, mapping, and modeling of the CZ can be fostered.

1 Introduction

"Our own civilization is now being tested in regard to its management of water as well as soil." – Daniel Hillel (1991).

A glimpse of the Blue Marble from space gives us an important perspective of the precious Earth as a system. The US National Research Council (NRC) has recommended the integrated study of the "Critical Zone" (CZ) as one of the most compelling research areas in Earth sciences in the 21st century (NRC, 2001). The CZ refers to that part of the Earth from the top of the vegetation down to the bottom of the aquifer, extending from the near-surface biosphere and atmosphere, through the entire pedosphere, to the surface and near-surface portion of the hydrosphere and lithosphere (Figs. 1 and 2). Interactions at the interfaces between the solid Earth and its fluid envelopes determine the availability of nearly every life-sustaining resource and provide the foundation for all human activities (hence it is called "Critical Zone"). The US National Science Foundation (NSF) also recommended a focus on water as a unifying theme for understanding complex environmental systems (NSF AC-ERE, 2005). Water-related research requires enhanced understanding of processes at environmental interfaces, approaches for integrating across scales, and improved coupling of biological and physical processes. Collectively, such an integrated, multidisciplinary, and multi-scale effort will advance our ability to forecast and plan for changes and to address urgent societal issues such as human safety, human health, economic prosperity, and sustainable development.

Soil is at the central junction of the CZ, representing a geomembrane across which water and solutes, as well as energy, gases, solids, and organisms are actively exchanged with the atmosphere, biosphere, hydrosphere, and lithosphere, thereby creating a life-sustaining environment (Figs. 1 and 2). Water is the circulating force that drives many of these exchanges and is the major transport agent in the cycling of solutes and nutrients in the CZ. Water flux into and through the soil and over the landscape is the essence of life, which resembles the way that blood circulates in a human body (Bouma, 2006). The interactions of soil and water are so intimate and complex that they cannot be studied in a piecemeal manner; rather, they require a systems and multiscale approach. In this spirit, hydropedology has emerged in recent years as an interdisciplinary field that addresses interactive pedologic and hydrologic processes across space and time (Lin, 2003). Hydropedology aims to understand pedologic controls on hydrologic processes and properties, and hydrologic impacts on soil formation, evolution, variability, and functions (Lin et al., 2006).

This article reviews and discusses growing opportunities for advancing soil science, hydrology, and geosciences, given the emerging interest in the CZ, hydropedology, and associated efforts in establishing environmental observatory networks in various parts of the world. Such a discussion is timely because soil science programs worldwide have struggled to survive, the hydrology community is coming together to push for scientific breakthroughs, and the geosciences community has embraced an expanded vision of its role and societal relevance. Specific objectives of this paper include: (1) clarification of basic ideas of the CZ and hydropedology and their relations to classical soil science, hydrology, and geosciences; (2) a proposal of an "outward" growth model, instead of an "inward" contraction, for the future of soil science; (3) a highlight of fundamental characteristics and research needs of the CZ and hydropedology; and (4) a discussion of opportunities to advance CZ science and hydropedology through integrated mapping, monitoring, and modeling. An initiative for fostering a global alliance for integrated studies of the CZ is suggested. Because of space limit and the author's background, this article focuses primarily on the physical and hydrological aspects of CZ processes, with limited discussion on biogeochemical and ecological aspects of the CZ.

2 Critical Zone science

2.1 History of the concept of the Critical Zone and its current meaning and utility

The term "critical zone" first appeared a century ago in a German article by physical chemist Tsakalotos (1909), who used the term ("kritischen Zone" in German) to refer to the zone of a binary mixture of two fluids, where the two liquid phases are no longer separated but mix to give one single phase that is stable under conditions close to a critical temperature and concentration. Subsequently, in 1962, American mineralogist E. N. Cameron called a geological formation (the Bushveld Complex in South Africa) a "critical zone" in his study of the rock structure and sequences. A literature search (through the *Science Citation Index Expanded*, 1900-present) indicated that 314 publications so far have used the term "critical zone" – over half of which (176 papers) were published prior to the 2001 NRC's specific definition of the term. Of these 314 papers, "critical zone" has been used to refer to a wide-range of phenomena: from a geological formation where precious metals (such as platinum and gold) can be mined (Wilhelm et al., 1997) to corrosion of pipe buried in soil within the groundwater fluctuation zone (Decker et al., 2008); from the rhizosphere where soil and roots have close interaction (Ryan et al., 2001) to transitional zones in alluvial coastal plain rivers important for water resources management (Phillips and Slattery, 2008); from body ventricular slow conduction area with electrophysiological limitations (Elsherif et al., 1990) to local regions of ice-structure interaction in cold regions where intense pressures can occur over short time periods leading to ice failure (Johnston et al., 1998). The majority of these 314 papers, however, were in the subject areas of geosciences (46%) and minerals/energy (41%). Only 15 of these papers have used the term in relation to soils, and 15 papers used the term in the context of water related issues.

In addressing basic research opportunities in Earth science, the US NRC specifically defined the "Critical Zone" (note the capitalized letters) as "*a heterogeneous, near surface environment in which complex interactions involving rock, soil, water, air and living organisms regulate the natural habitat and determine availability of life sustaining resources*" (NRC, 2001). Such CZ concept encompasses the soil, deep vadose, and ground water zones, and includes the land surface and its canopy of vegetation, along with rivers, lakes, and shallow seas (Fig. 2). According to the NRC Committee on Basic Research Opportunities in the Earth Sciences, this CZ concept was proposed by a subgroup of the Committee, which consisted of a sedimentologist (Gail Ashley), a pedologist (Larry Wilding), and a hydrologist (Stephen Burges). Prior to the NRC final report, Ashley (1998), on behalf the NRC Committee, presented an earlier version of the CZ concept at the Geological Society of America annual meeting in Toronto, Ontario (in which the CZ was simply referred to the zone from land surface to bedrock). Ashley (1998) stated that "*the upper few meters are crucial for life. It is the home of forests, deserts and agriculture, but potable water and toxic wastes also pass through this zone. A holistic approach is needed to understand the three-dimensional complex linkages involving physical, chemical and biological processes*".

Subsequently, an initiative of the Weathering System Science Consortium (WSSC) proposed to answer the following question: "*How does the Earth weathering engine break down rock to nourish ecosystems, carve terrestrial landscapes, and control carbon dioxide in the global atmosphere?*" (Anderson et al., 2004). This initiative envisioned a concerted effort to predict how weathering rates in the CZ respond to climatic, tectonic, and anthropogenic forcing over all temporal and spatial scales. In the following year, an NSF-sponsored workshop, *Frontiers in Exploration of the Critical Zone*, was held, calling for the development of an international CZ initiative and a systematic approach to the investigation of CZ processes across a broad array of sciences (Brantley et al., 2006). During this workshop, the WSSC solicited proposals to initiate seed sites that would help establish a CZ network. Eight out of more than 20 sites proposed were selected. The WSSC was then renamed the Critical Zone Exploration Network (CZEN). In the same year, the NSF solicited proposals to develop Critical Zone Observatories (CZOs) "*that will operate at the watershed scale and that will significantly advance our understanding of the integration and coupling of Earth surface processes as mediated by the presence and flux of fresh water*". This initiative was a joint effort among the geochemistry, hydrology, and geomorphology communities in the Earth Science Division of the NSF. This competition resulted in three CZOs in the US starting in 2007, which are located in the Sierra Nevada Mountains in California, the Front Range of the Colorado Rockies in the mountain west, and the Appalachian Uplands in the northeast (Anderson et al., 2008).

In 2007, a series of five papers focusing on the CZ were published in *Elements*, an international magazine of mineralogy, geochemistry, and petrology. By way of introduction, Brantley et al. (2007) discussed the geochemical story written in the regolith and the flux of elements at the pedon scale. The subsequent papers discussed how geochemical patterns are influenced by erosion (Anderson et al., 2007), mineral-water interactions (Chorover et al., 2007), biota (Amundson et al., 2007), and dust (Derry and Chadwick, 2007). In 2008, the First International Conference on Hydropedology was held under the theme "*Water and Soil: Key to Sustaining the Earth's Critical Zone*" (Lin et al., 2008). As part of the major geosciences program for the International Year of Planet Earth held at the 33rd International Geological Congress in 2008 in Oslo, Norway, a symposium entitled "*The Earth's Critical Zone and Hydropedology*" was organized. Selected papers presented at these two international meetings are included in this special issue of the HESS.

Enthusiasm as well as skepticism has surfaced in scientific communities since the emergence of the CZ concept promoted by the NRC. This is partly because the concept is new and unclear to many. Thus, an attempt is made here to clarify some of the related issues:

1. Many thought that the CZ is (nearly) the same as the pedosphere. In reality, the CZ is much broader than just soils. It is true that the CZ encompasses the entire pedosphere which is the only sphere in the Earth system that is wholly included in the CZ. However, if we confine the CZ to just soils (this perspective is labeled here as an "inward" contraction, see Fig. 1), then it will lose the unifying power of the CZ concept. Instead, we should promote an "outward" growth (Fig. 1) to advance the study of soils and the entire CZ, thereby implying a broadened perspective and an inclusive vision for soil science. This "outward" growth model is consistent with the soil's "7+1" functions as depicted in Fig. 1 (Lin, 2005) as well as seven soil functions defined by the EU Soil Protection Strategy (Bouma et al., 2008). Soil scientists, while focusing on soil processes, should guide their research not only by what they consider important from a soils point of view but also by what is needed in a broader context. An interesting illustration is the knowledge of soils and their forming processes that can provide a unique contribution to extraterrestrial explorations in search of water and life, and to developing advanced life support systems used in space exploration.

2. Some have used the term CZ as synonymous with the common geological term "regolith", which was propounded by Merrill (1897) and is defined as "*the fragmental and unconsolidated rock material, whether residual or transported, that nearly everywhere forms the surface of the land and overlies the bedrock. It includes rock debris of all kinds – volcanic ash, glacial drift, alluvium, loess, vegetal accumulations, and soil*" (Bates and Jackson, 1987). Regolith is synonymous with mantle or overburden, and is equivalent to the broad definition of soil (i.e., including O-A-E-B-C horizons, with the C horizon often called saprolite; see Fig. 2). The classical definition of soil is narrower (driven by agriculture-centric conception of the soil as a medium for plant growth) that includes only the A-B horizons (referred to as the solum, generally <1–2 m deep; see Fig. 2). The CZ concept

defined by NRC (2001) integrates above-regolith vegetation and below-regolith fresh bedrock or sediments that interact with fluctuating ground water.

3. Some have questioned the utility of the CZ concept because of its imprecise lower boundary and high variability in its thickness. In fact, the CZ concept will force us to better define the variable and dynamic lower boundary of the active water cycle in different ecosystems and geographic regions. Currently we do not know where the active water flow ceases in the subsurface, yet such an understanding is important as this demarcation influences the annual, decadal, and century hydrologic cycles. Hydrological and biogeochemical models are often forced to make assumptions about the lower boundary of the active water cycle (such as impermeable bedrocks or an artificial two meter cut-off for soil depth). However, the diffuse lower boundary of the CZ may extend to a kilometer or more below the surface and the volume of water stored in this zone is an order of magnitude larger than the combined volume of water in all rivers and lakes (NRC, 1991, 2001).

4. Many believe that the CZ is useful because it is inherently process-oriented and is a unifying concept that accommodates the hydrologic cycle, the geochemical cycle, the carbon cycle, erosion and deposition, weathering (chemical and physical), gas exchange (major and trace gases), life processes (macro- and microbial communities, including plants and animals), lithification (diagenesis), and soil formation and evolution (pedogenesis). The timescales included in the CZ concept range from seconds to eons and its spatial scales are enormous (from atomic to global). Integration of disciplinary research is the key to future progress in CZ science. As indicated by the NRC (2001), the rapidly expanding needs for a sustainable society give special urgency to understanding the processes that operate within the complex CZ. Some of the pressing scientific issues identified by the NRC (2001) that involve the CZ include (i) global climate change and terrestrial carbon cycle; (ii) the interactions of life, water, and minerals; (iii) the land-ocean interface; (iv) tectonics, climate, and weathering; and (v) earth history.

2.2 General characteristics of the Critical Zone

The CZ is perhaps "*the most heterogeneous and complex region of the Earth*" (NRC, 2001). The processes occurring in the CZ are highly dynamic, nonlinear, and interdependent, governed by complex networks, linkages, and feedbacks that involve a vast array of physical, chemical, biological, geological, and anthropogenic systems. The NRC (2001) identified the following four main categories of processes occurring in the CZ (of which at least the first two or three are known to occur on other planets such as Mars). A fifth category is added here, that of human activity, which is increasingly recognized as pervasive (e.g., the Anthropocene has been defined as "*a new geological epoch in which humankind has emerged as a globally significant, and potentially intelligent, force capable of reshaping the face of the planet*", Clark et al., 2004).

1. *Tectonics* driven by energy in the mantle, which modifies the Earth surface by geological processes such as magmatism, faulting, uplift, erosion, and subsidence, leading to the creation of basic landforms over the geological timescale;

2. *Weathering* driven by the dynamics of the atmosphere, hydrosphere, and biosphere, which controls soil formation and evolution from rocks or sediments, water quality, ecological functions, and biogeochemical cycles over generally long timescale;

3. *Fluid transport* driven by energy or mass gradients (e.g., pressure, temperature, and concentration), which shapes the landscape and the distribution of water, soil, vegetation, and microbes, with water being the primary conduit;

4. *Biological activity* driven by the need for life-sustaining resources (water, nutrients, air, and light), which controls the biogeochemical cycling and ecological functioning among soil, rock, air, and water, and which greatly accelerates weathering and spatio-temporal variability in the CZ over much shorter timescale as compared to geological processes;

5. *Human activity* driven by socio-economic, political, and personal interests, which significantly alters natural landscapes, changes global climate, impacts biodiversity, increases the spread of chemicals including toxins in the environment, and further accelerates material and energy cycling on Earth potentially resulting in more risks (such as flooding, landslides, fires, erosion, and extreme weather events).

Despite the extreme complexity and dynamics, some general characteristics of the CZ can be identified. Three of which are highlighted below – cyclical, vertical, and horizontal characteristics – which will be further linked to hydropedology in Sect. 3.2.

2.2.1 Cycles and coupled systems

Formation of the CZ is the consequence of two overarching cycles – the geological (or "big") cycle and the biological (or "small") cycle (Fig. 3a). It is the reconciliation of these two cycles vastly different in space and time scales that is critical for predicting CZ processes. *The geological cycle* refers to the weathering of rocks, the erosion, transport, and deposition of weathered products that eventually end up in oceans as sediments, and then are lithified and uplifted back to the land by tectonic or volcanic activities. This cycle occurs over the geological timescale (e.g., 10^4–10^8 years) and covers a large area (e.g., 10^0–10^5 km). This cycle is fueled by solar energy and the Earth's internal heat and influenced by the leveling force of the Earth's gravity. The endogenic (internal) system is at work building landforms while the exogenic (external) system is wearing them down. This big cycle is composed of three major cycles – tectonic, rock, and hydrologic (Fig. 3a). The tectonic cycle brings heat energy and new materials to the surface and recycles materials, creating movement and deformation of the crust. The rock (or rock-soil) cycle produces three basic rock types found in the crust – igneous, metamorphic, and sedimentary, including related soil cycle as rocks weather into soils and soils return to rocks over the geological timescale. At this geologic timescale, the hydrologic cycle processes materials with the physical and chemical actions of water, ice, and wind.

The biological cycle refers to the production and consumption of food and energy in an ecosystem and the accumulation and decomposition of organic matter in soils. The flow of energy, the cycling of nutrients, and trophic (feeding) relations determine the nature of an ecosystem. As energy cascades through such a system, it is constantly replenished by the Sun. But nutrients and minerals cannot be replenished from an external source, so they constantly cycle within and through each ecosystem and the biosphere in general. Compared to the geological cycle, the biological cycle occurs over a much shorter timescale (e.g., 10^{-5}–10^{5} years) and a much smaller area (e.g., 10^{-6}–10^{0} km). Three principle cycles are involved – ecological, biogeochemical, and hydrologic (Fig. 3a). The ecological (or life) cycle generates biomass through producers such as plants, reaching consumers and eventually detritivores through the food chain. Soils support vast communities of microorganisms that decompose organic matter and re-circulate elements in the biosphere (Fig. 2). Anthropologic impacts can be considered as part of the ecological cycle; alternatively, human activity can be elevated to a separate cycle (maybe called the anthropogenic cycle) because of its increasingly dominant impacts on the biological cycle. The biogeochemical (or elemental) cycle, combining biotic and abiotic processes, redistributes elements and materials (such as carbon, oxygen, hydrogen, and nitrogen) through liquid (e.g., water), solid (e.g., sediments), and gas (e.g., air). At the biologic timescale, the hydrologic cycle transports organic and inorganic materials and energy throughout the CZ.

Fluid transport is involved in both the geological and biological cycles, as water is the key conduit for mass and energy transfer. Life on Earth as we know it would be impossible without the involvement of liquid water. The functioning of the biological cycle implicitly depends on the existence of the mobile hydrosphere and atmosphere, both of which are in intimate contact with the pedosphere and lithosphere and exchange substances with them. The biosphere is ultimately what ties the major systems of the Earth together and drives them far out of thermodynamic equilibrium (Jacobson et al., 2000). On the geological timescale, however, steady-state is often used as an approximation for the big cycle. A steady-state system may demonstrate a gradually changing trend over time (either increasing or decreasing). However, a system may reach a threshold at which it can no longer maintain its structure and character, leading to an abrupt change, after which a new equilibrium may eventually be re-established.

The cyclical approach to describing the CZ allows conceptual simplification of materials movement on Earth and their couplings to the environmental factors. Using the most basic description of the cyclical processes, we can mathematically model the cycles to describe and predict the distribution of important elements of interest, such as water, sediment, carbon, nitrogen, and others. A basic goal of the cyclical approach is to determine how the fluxes into and out of various reservoirs depend on the content of reservoirs and on other external factors (Jacobson et al., 2000). Many computer models, especially those of the global scale, use this approach. In many cases the details of the distribution of an element of interest within each reservoir are disregarded, and for the most simplified calculations, the amounts of material in each reservoir are assumed to remain constant (i.e., steady-state) (see an example in Fig. 4 for global water balance). This allows an element budget to be defined for the entire cycle. Such a steady-state budget-based approach, however, has limitations as it provides little or no insight into what goes on inside the reservoir or into the nature of the fluxes between reservoirs (Jacobson et al., 2000). The average-based analysis also does not consider spatial and temporal variation, and thereby could give a false impression of certainty.

The cyclical approach mimics the coupled nature of the Earth system and of the CZ. Important evidences of such interconnectedness are the chronology provided by chemical and isotopic analysis of ice cores (e.g., Jacobson et al., 2000) and pedogenic analysis of paleosol sequence (e.g., Fang et al., 2003). In the two examples illustrated in Fig. 3b, major variations for the variables shown seem to correlate either positively or negatively with each other, indicating strongly coupled systems.

The intertwining relationships of climate, hydrology, biology, lithology, topography, chronology, and anthropogenic impacts pose challenges to the independence assumption made in Jenny's (1941) soil-forming theory, although in some areas one of the factors may dominate (thus permitting relative study using the gradient of this dominant factor). More often than not, individual soil-forming factor involves continuous and strong interactions with other factors, making parts of the CZ dependent to some degree on other parts. As Schaetzl and Anderson (2005) pointed out, it is the five soil-forming factors that team together in myriad ways that form the diversity of the world soils. However, the lack of adequate understanding of such interactions and feedbacks makes the quantitative relationships among soil-forming factors difficult to be established. It is hoped that CZ science can help advance such an understanding through a more holistic approach (instead of a factorial approach).

Most natural systems are open in terms of energy, for solar energy enters freely and heat energy goes back into space. Because of this continuous energy input to the CZ, such an open system is far from equilibrium, leading to changes in storages and fluxes into and out of different spheres or reservoirs. The biological cycle is particularly impacted in this regard as life evolves and thrives in the CZ.

In terms of physical matter – soil, water, air, and other resources – Earth is essentially a closed system from a global perspective. The only exceptions are the slow escape of lightweight gases (such as hydrogen) from the atmosphere into space and the input of frequent but tiny meteors and cosmic and meteoric dusts. Thus, Earth's physical materials are finite. Therefore, no matter how numerous and daring the technological reorganizations of matter may become, the physical base of the CZ is, for all practical purposes, fixed and limited (Christopherson, 2007). Now more than ever, the interactions of human activity and natural cycles must be addressed in order to sustain the global environment (NSF AC-ERE, 2003, 2005). The CZ is where all humans live, thus population growth, urbanization, and industrialization all have put increasing pressures on the CZ, and will do so even more in the future.

2.2.2 Layers and interfaces

The Earth is a layered system: from outer atmosphere down to inner core, different layers of materials with vastly different thicknesses and other characteristics are evident (Figs. 2 and 4). The CZ consists of layers including the vegetation zone, the soil zone, the deep vadose zone, and the groundwater zone, with each layer having various sub-layers. Because of this layering characteristic and a generally gradual increase in density with depth (with exceptions), there is a general trend of increased response time (i.e., slower response) to external perturbations when moving from the atmosphere, down to the hydrosphere, biosphere, pedosphere, and further down to the lithosphere (Fig. 4). Conversely, the feedback time generally decreases (i.e., faster feedback) when moving up from the deep underground zone to the shallow subsurface zone to the surface zone and to the aboveground zone. Arnold et al. (1990) suggested the following schematic of decreasing temporal changeability and increasing characteristic response time (i.e., time period needed to reach a quasi-equilibrium status with the environment) of the major spheres as follows: atmosphere>hydrosphere>biosphere>pedosphere>lithosphere. Such a rough trend, however, has many exceptions. Based on the global water balance data present by Shiklomanov and Sokolov (1983), average turnover time (defined as storage volume divided by inflow or outflow volume) for major water reservoirs in the terrestrial environment (excluding oceans and glaciers) is: biosphere<atmosphere<pedosphere<hydrosphere<lithosphere (Fig. 4).

The general trends of response and feedback times also exist for sub-layers within each zone, such as soil horizons within a soil profile. Soil profiles nearly always have layers (Figs. 1 and 2), which are either inherited from parent materials (such as sedimentary or bedrock layers) or created, modified, and destroyed by pedogenesis. Processes that involve depletion and accumulation of constituents such as clay, carbonate, or organics can create distinct horizons (such as E, Bt, Bk, Bh, O, and A horizons), while soil fauna (worms, termites, and other burrowing animals) and human activities often mix and loosen layers. Fluctuating ground waters also have a huge influence on the nature and properties of the lower part of soil profiles. Within each of the major soil horizons (i.e., O, A, E, B, and C), sub-horizons are common. Even in a thin O horizon of a forest floor, distinct layers of undecomposed litter (L), partially degraded

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organic matter (F), and humus (H) can frequently be identified. The recognition of soil horizons and the description and identification of soils on the basis of the number, character, arrangement, and composition of horizons have been the most significant early contributions to soil science made by soil surveys (Marbut, 1921).

The fact that natural soils are layered has significant implications for water flow and chemical transport through the unsaturated zone. Interfaces between soil layers often slow downward water movement and promote lateral flow, especially in sloping landscape with an underlying water-restricting layer. Soil horizons of different textures and structures also often alter flow patterns, leading to various types of preferential flow. These factors are important in defining at what depth a soil profile will begin to saturate and the runoff pattern for a catchment.

A fundamental control on the thickness of a soil is the long-term balance (over thousands of years) between the production of new soil (caused by weathering of underlying bedrock or deposition of sediment or dust or through biological accumulation) and the loss associated with erosion or biological removal. Soil formation from weathering of bedrock is a very slow process (the rate depending on rock type, temperature, water availability, biota involved, and thickness of the overlying soil). Many studies indicate an average rate of 1 mm per 1000 years or less (McKenzie et al., 2004). In contrast, the rate of soil erosion is often accelerated because of human activities, reaching an average rate of 10–20 mm per 1000 years in many areas (McKenzie et al., 2004). Alarmingly, humans now move about 10 times or more sediment as all natural processes combined (Brantley et al., 2006).

Interfaces between layers and cycles are critical controls in the landscape-soil-water-ecosystem dynamics. Key interfaces in the CZ – such as the vadose zone-ground water interface, the ground water-surface water interface, the soil-stream interface, the soil-bedrock interface, and the land surface-atmosphere interface – provide fertile ground for interdisciplinary research, where physical, chemical, and biological processes interact to generate possible "hot spots", i.e., localized areas that are critical for understanding how the landscape works. Similarly, various forcing and perturbations can lead to "hot moments" when a major proportion of annual flux occurs. For instance, NRC (2004) highlighted the importance of groundwater fluxes across interfaces when estimating recharge and discharge to aquifers. However, many challenges remain in understanding and measuring the dynamic interchange among the water reservoirs of atmosphere, surface, and subsurface, especially for interchanges with the subsurface (NRC, 2004).

Within a soil profile, important interfaces include the soil horizon interface, the soil-bedrock interface, the soil-water table interface, the soil-root interface, the macropore-matrix interface, the ped interface, the microbe-aggregate interface, the water-air interface, and the soil-atmosphere interface, all of which are places where important actions occur. For instance, nearly all soil chemical reactions occur at some kind of interface, including the equilibrium and kinetic processes of dissolution/precipitation, adsorption/desorption, oxidation/reduction, and polymerization/biodegradation. Illuviation occurs at interfaces leading to various coatings on the surface of soil aggregates (such as clay films, carbonate coatings, or redox features). Many interfaces are also triggers of preferential flow and significantly impact the upscaling or downscaling of flow and transport processes.

2.2.3 Heterogeneity and hierarchical patterns

A third important characteristic of the CZ is ubiquitous heterogeneity across space and time which poses significant challenges for scaling and for knowledge transfer from laboratory to the field. Landscape heterogeneity may be addressed by gradient or by pattern. Various environmental gradients result in different soil sequences when one of the soil-forming factors dominates, resulting in so-called climosequences, biosequences, lithosequences, toposequences, or chronosequences (Jenny, 1941). Some areas in the CZ are composed of gradients that change so gradually that it is difficult to detect a repeated pattern because there are no clear edges. In areas where distinct boundaries are defined with varying degrees of contrast, patterns are useful to describe heterogeneity. These boundaries may be defined by structure or composition of soil, rock, water, topography, vegetation, or anthropogenic impacts. Pattern is the diagram of process (Bell, 1999), which offers rich and comprehensive insights into many phenomena in nature. For example, Grayson and Blöschl (2000) demonstrated that rich information in spatial patterns provided much more stringent tests of hydrological models and much greater insights into hydrological behavior than traditional spatially-aggregated methods.

Patterns in landscapes are not often clear because they comprise many layers of elements, with each element having its own heterogeneity. These elements are often intricately woven together due to the interactions of all the processes at work. Bell (1999) suggested that it is possible to consider landscapes as complexes of networks and mosaics. The networks are patterns of linear-oriented features, such as the meandering and branching systems that run through and between the elements that produce the mosaics. Mosaic patterns can be found over a wide range of spatial scales, from the submicroscopic matrix of the soil to the entire pedosphere. Mosaics arise because of uneven and dynamic energy inputs into the open systems of the CZ, leading to spatial, structural, compositional, and temporal heterogeneity at all scales. The mosaic patterns can be determined by mechanisms characteristic of various underlying processes, which may be grouped into three main ones (Bell, 1999): (1) inherent processes: the substrate heterogeneity beneath the land mosaic, which is dependent on the processes of geology, geomorphology, pedology, and hydrology, interacting with the climate and biota; (2) extrinsic processes: the effect of natural disturbances (such as fires, hurricanes, insect pests, and diseases) to the biota that colonize and grow on the variable substrate; and (3) anthropomorphic processes: human activity ranging from land use/land cover change to modification of landform, urbanization, and interference with the climate.

There is a strong hierarchical structure to most natural and human patterns and processes. Patterns may emerge at the large scale from the complex interactions of a large number of different elements at a smaller scale. The dominant process and controlling factor also change as scale changes in a hierarchical manner. Therefore hierarchical frameworks have been conceptualized by geoscientists including soil scientists and hydrologists as a means for organizing natural systems from the pore scale to the global scale (Fig. 5). However, a quantitative description of such hierarchical systems that could be integrated into models of flow, scaling, and rate processes is still lacking. It is possible that heterogeneity is huge and the numbers of possible patterns may be limitless at a fine level of detail while the possible range of patterns may be remarkably limited as spatial dimensions increase (Stevens, 1974; Bell, 1999).

A conceptual framework has been used to understand the *magnitude* of land surface/subsurface variability as a function of five space-time factors (Lin et al., 2005b): spatial extent or area size, spatial resolution or map scale, spatial location or geographic region, specific property or process, and absolute or relative age. Broadly speaking, it is expected that as spatial extent, spatial resolution, or time scale increase, the magnitude of overall soil variability should increase, reaching a possible maximum and then starting to stabilize or decrease as space or time dimensions continue to increase; however, the mode and magnitude of such changes would depend on the landscape (i.e., spatial location) and which soil type or specific soil property/process is of concern. Numerous publications have provided evidence that supports such a general conceptualization (e.g., Wilding and Drees, 1983; Burrough, 1993; Heuvelink and Webster, 2001). A significant need, however, still exists for explicit quantification of the complexity, diversity, and interactions related to such a conceptual framework.

While spatial variance is often attributed to spatial autocorrelation in geostatistics, the *causes or mechanisms* of heterogeneity are important for understanding why field variation exists and how that changes with scale. Systematic (ordered) variation is controlled by the environmental gradients (such as landforms, geomorphic elements, soil-forming factors, and land management) which can be identified; while random (disordered) variation is stochastic (because of differential processes, biological factors, sampling or analytical errors, or simply unidentified or non-visible variation) which is unpredictable. Hence, predicting much of the nonlinear system behavior is possible, but not the fine local details which tend to be produced by random processes. Differentiation of systematic vs. random variation allows us to focus on the proportion of soil variability that can be related to known causes versus that which is yet to be discerned. Critical to this differentiation is the scale of investigation and the sampling scheme used to collect data. As an example, when a soil system is investigated in greater detail, a part of the variation originally considered random may be recognized as systematic. On the other hand, if the spacing of observations is too far apart, then even systematic variability may appear random.

The challenge of bridging scales from microscopic to megascopic levels underlies nearly all of the CZ studies (Fig. 5). For example, the question of how landscape architecture affects the upscaling of soil processes to a regional level remains unresolved. It is highly desirable to investigate how dominant processes change with spatial and temporal scales, and to explore quantitative transfer from microscopic (e.g., molecular and pores), to mesoscopic (e.g., pedons and catenas), to macroscopic (e.g., watersheds and regional), and to megascopic levels (e.g., continental and global) (Figs. 5 and 6). As remote sensing techniques for estimating large-area soil, hydrologic, and ecosystem properties, and in situ measurements for local areas continue to be developed, bridging multiple scales becomes even more essential. It appears that, while advanced imaging, spectroscopic, and other technologies become widely used at the pore or molecular level, and remote sensing, computer modeling, and other tools are increasingly employed at the global and regional level, what is urgently needed is enhanced techniques and tools for the intermediate scale of the landscape which is often most critical (i.e., from the pedon to hillslope and catchment scales). At present, no single theory emerges that is ideal for spatial aggregation (or upscaling), disaggregation (or downscaling), and temporal inference (or prediction) of diverse hydropedological, biogeochemical, and ecological processes. Further exploration in this area is widely recognized as critical to advancing CZ science.

3 Hydropedology

3.1 Characteristics of hydropedology and its link to CZ science

Hydrogeosciences have encountered a new intellectual paradigm that emphasizes connections between the hydrosphere and other components of the Earth system. While hydrometeorology, hydrogeology, and ecohydrology are well recognized, an important hidden piece of the puzzle is the interface between the hydrosphere and the pedosphere. Hydropedology addresses this interface (Fig. 6), and seeks to answer the following two basic questions:

1. How do soil architecture and the distribution of soils over the landscape exert a first-order control on hydrologic processes (and associated biogeochemical and ecological dynamics) across spatio-temporal scales?

2. How does landscape water (and the associated transport of energy, sediment, chemicals, and biomaterials by flowing water) influence soil genesis, evolution, variability, and functions?

The first question calls for connection between the complex soil architecture and diverse soil functions in the landscape. Three important features are highlighted here: (a) hydropedology pursues the opening of the "black box" of the soil system by closely examining soil structural heterogeneity and soil distribution pattern in the landscape, rather than treating the soil as a simple homogeneous thin layer on the Earth surface; (b) hydropedology views the soil as a "living" entity in nature, not as a "dead" material manipulated artificially; and (c) hydropedology links the forms and functions of the soil system across scales (Fig. 5), rather than mapping soils without considering soil functions or modeling soils without incorporating soil architecture and soil-landscape distribution patterns. As Jenny (1941) pointed out, "*the goal of soil geographer is the assemblage of soil knowledge in the form of a map. In contrast, the goal of the 'functionalist' is the assemblage of soil knowledge in the form of a curve or an equation*[...]

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Clearly, it is the union of the geographic and the functional method that provides the most effective means of pedological research". Such a union of soil maps and soil functions is emphasized in hydropedology.

The second question relates to the understanding of how the soil has been shaped in the landscape by water and how the characterization of diverse soil functions can be enhanced by hydrologic understanding. Three key aspects are worth mentioning here: (a) hydrology may be considered as an integrating factor of soil formation and a major driving force of soil change, potentially offering an integrated means of quantifying soil functions and soil changes; (b) new ways of characterizing and mapping soils information are needed (i.e., to go beyond the classical soil taxonomy). One of which may be the delineation of *hydropedologic functional units* in the landscape, which can be defined as soil-landscape units having similar pedologic and hydrologic functions; and (c) soils are historical records of environmental changes, which can be better interpreted and quantified if historic hydrology is considered simultaneously.

The connection between hydropedology and CZ science centers on the key roles that soil and water play in the CZ. Specifically, this includes: (1) the interrelationships between hydropedology and ecohydrology, and how they influence soil moisture, ground water recharge, ecological health and diversity, and environmental quality (Young et al., 2007; Li et al., 2009); (2) the integration of hydropedology and hydrogeology, including holistic modeling and prediction of subsurface flow and transport from the ground surface all the way down to the groundwater (Lin, 2003); (3) the linkage between hydropedology and hydrometeorology, concerning issues related to soil moisture and global climate change, soil carbon sequestration, greenhouse gas emission from soils, and remote sensing of soil climate (Lam et al., 2007); (4) the coupling of hydropedology and biogeochemistry, including the identification of hot spots and hot moments of biogeochemical cycles in different landscapes (McClain et al., 2003); (5) the study of palesols and palehydrology that provides historical records of past environment and ancient landscape-soil-water relationships (Ashley and Driese, 2000); and (6) the connection between hydropedology and land use planning, because how natural soils "throb" upon

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precipitation inputs under various climatic regimes offers clues as to "what" can best be done and "where" with the lowest risks and the greatest opportunities for land use and management (Bouma, 2006).

3.2 Fundamentals of hydropedology

Fundamental scientific issues of hydropedology can be summarized into the following four interrelated areas (Fig. 6):

1. Soil structure and horizonation as the foundation of flow and transport characteristics in field soils, emphasizing quantitative soil architecture and its impact on preferential flow across scales;

2. Soil catena and distribution pattern as a first control of water movement over the landscape, with an emphasis on quantitative soil-landscape relationships and its impact on landscape hydrological processes;

3. Soil morphology and pedogenesis as signature of soil hydrology and soil change, emphasizing quantitative soil hydromorphology and soil evolution and their values as environmental records;

4. Soil functional classification and mapping as carriers of soil hydrologic properties and soil-landscape heterogeneity, with an emphasis on quantitative functional soil maps and cataloging of soil hydrologic functions in the landscape.

The first fundamental issue is linked to the CZ's feature of layers and interfaces; the second one is related to the heterogeneity and hierarchical patterns of the CZ; the third one is connected to the cycles and coupled systems of the CZ; and the last one integrates the above three. In the following, these fundamental issues are further discussed in greater detail.

3.2.1 Foundation of flow and transport in field soils: soil structure and horizonation

"*Ped*" (a naturally-formed soil aggregate such as a block, granule, plate, or prism) is a unique term, and "*pedology*" (a branch of soil science that integrates and quantifies the morphology, formation, distribution, and classification of soils as natural or anthropogenically-modified landscape entities) reflects that uniqueness. Natural soil architecture and how it changes horizontally, vertically, and temporally are of essence to understanding soil physical, chemical, and biological processes. That natural soils are structured to various degrees at different scales is the rule; whereas the existence of a macroscopic homogeneity is the exception (Bouma and Dekker, 1978; Hoogmoed and Bouma, 1980; Vogel and Roth, 2003). It has been said that a crushed or pulverized sample of the soil is related to the soil formed by nature like a pile of debris is to a demolished building (Kubiena, 1938). Lin (2007) also suggested that a crushed soil sample is as akin to a natural soil profile as a package of ground beef is to a living cow. The fundamental difference between in situ soils in the landscape and disturbed soil materials in the laboratory lies in "soil architecture". The soil is a living entity, with many dynamic forces acting upon it so its internal architecture forms and evolves over time to serve multiple functions. A new era of soils research should rely on soil architecture – built upon the past "texture-centered" efforts – to improve the modeling and prediction of flow pathways, patterns, and residence times. Research needs along this line include the development of (1) innovative techniques and devices for quantifying soil architecture *directly*, especially in situ and non-invasively; (2) quantitative relationships between in situ soil architecture and field-measured soil hydraulic properties; (3) effective means of representing field soil architecture in a manner that can be coupled into models of flow, transport, and rate processes; (4) a means of quantifying anthropogenic influences on soils as land use and management impacts are often reflected in soil structural changes; and (5) a theory of soil architecture formation, evolution, and quantification that can bridge orders of magnitude in scale and integrate physical, chemical, biological, and anthropogenic impacts.

In the US *Soil Taxonomy*, various diagnostic surface and subsurface horizons have been identified (Soil Survey Staff, 2006). The presence or absence of these horizons plays the major role in determining in which class a soil falls in *Soil Taxonomy*. Numerous water-restricting subsurface soil horizons (such as fragipan, duripan, glacic, ortstein, permafrost, petrocalcic, petrogypsic, and placic horizons) and features (including aquic conditions, cryoturbation, densic contact, fragic soil properties, gelic materials, lamellae, lithic contact, lithologic discontinuities, petroferric contact, and plinthite) are important to hydrdologic and biogeochemical cycles (Soil Survey Staff, 2006). Other subsoil horizons may also act as an aquitard or aquiclude to downward moving water (Fig. 7), ultimately resulting in a seasonal perched water table and water moving laterally within the soil as subsurface throughflow (e.g., Kemp et al., 1998; Gburek et al., 2006). Such subsoil horizons include agric, argillic, glossic, kandic, nitric, oxic, and spodic horizons. In addition, stratified or dense geological materials (C or R horizons) also often develop a hydrologically-restrictive layer that leads to a perched water table, biogeochemically enriched zone, and lateral water movement. The soil-bedrock interface and bedrock topography have been recognized as important to subsurface stormflow in hillslopes (e.g., Freer et al., 2002).

Numerous studies over the past decades have demonstrated that preferential flow (vertical and/or horizontal) can occur in practically all natural soils and hillslopes. Although the degree and pattern of preferential flow vary considerably (depending on initial and boundary conditions as well as soil types and landscape settings), non-uniform flow has been recognized as the rule rather than the exception (e.g., Kirby, 1978; Beven and Germann, 1982; Flühler et al., 1996; Uhlenbrook, 2006; Clothier et al, 2008). Preferential flow in soils has been related to soil structural differences (e.g., macropore flow), textural contrasts (e.g., fingering flow and funnel flow), and interfaces between soil layers or soil-bedrock interfaces (e.g., subsurface stormflow). Because of continuous energy or force inputs to the open system of natural soils and landscapes, plus the ubiquitous heterogeneity of the land, water always follows the least resistant paths, forming multiscale preferential pathways. Many studies have demonstrated that preferential flow severely limits the applicability of standard models for flow and transport that are based on the homogeneous domain theory. As Beven (2006) noted, "*Nearly all hydrologic, water quality, and sediment transport models use the same small-scale laboratory homogeneous domain theory to represent integrated fluxes at the much larger scales of hillslope and catchment [. . .] This is the root of many discrepancies between model predictions and the reality*".

3.2.2 First control of water movement over the landscape: soil catena and distribution pattern

A catena (also called toposequence) is a chain of related soil profiles along a hillslope, which have about the same age, similar parent material and climatic condition, but differ primarily in relief that leads to differences in drainage and soil thickness (Fig. 8). Catenary soil development often occurs in response to the way water runs down the hillslope and reflects the interrelationship between soil and geomorphic processes. Catenas are thus also often called hydrosequences, especially in depositional landscapes. Drainage condition, water table depth, and fluxes of water, solutes, and sediments typically differ in soils along a catena (Fig. 8). However, contrasting hydrology and soil morphology shown in Fig. 8b vs. Fig. 8a cannot be explained by simple catenary model where surface topography controls hydrological regimes; instead, the topography of the underlying weathered rock substrates with low-permeability causes subsurface distribution patterns of soil and hydrology (Coventry, 1982).

The catena concept provides a useful paradigm to decipher soil pattern and related trends in soil properties at the hillslope scale. Based on matter distribution related to mobilization processes and hydrological regimes, Sommer and Schlichting (1997) grouped four types of catenas: (1) *transformation catenas* showing no gains or losses of element/soil component, (2) *leaching catenas* with losses in at least part of the catena and no accompanying elemental gains in other parts, (3) *accumulation catenas* showing gains in at least part of the catena but no losses elsewhere in the catena, and

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(4) *translocation catenas* having element losses combined with gains in different parts of a catena. The spatial arrangement and extension of depletion/accumulation areas and flow directions of translocated elements/soil components could further subdivide the catena types (Sommer and Schlichting, 1997). Catenas as a whole, however, are subject to changes in time, i.e., in different development stages following a possible sequence of transformation, translocation, leaching, and accumulation (Fridland, 1976). Sommer and Schlichting (1997) suggested that an integration of three different approaches to study soil distribution – geomorphic/stratigraphic, hydrologic, and pedologic approaches – is the most promising way forward toward a four-dimensional (4-D) understanding of soil-landscape relationships.

Catenas in different climatic and physiographic regions may exhibit markedly different relationships between soil and hydrologic properties. For example, in many low-relief landscapes of humid regions, proximity of a water table to the soil surface increases with distance away from stream or drainage way. An example of this can be seen on the broad, flat, low-relief Atlantic coastal plain in the Southeastern US. The most poorly drained soils are found toward the centers of the broad inter-stream divides, while the most well-drained soils are restricted to the edges of the flats and slopes closest to the streams and estuaries (Daniels et al., 1971, 1984). The opposite trend is seen in the higher-relief landscapes associated with the nearby Piedmont region. Water table proximity to the soil surface decreases with increasing distance away from the streams or drainage ways. As a result, the well-drained soils occupy the uplands and the more poorly drained soils occupy the lower slope positions near the streams (Daniels et al., 1984). Similarly, fluxes associated with overland flow, subsurface lateral flow, percolation, capillary rise, and return flow can also vary along a catena in different climatic and physiographic regions (Schaetzl and Anderson, 2005). For instance, in a humid forested catchment developed from shale on the ridge of central Pennsylvania, soil thickness and wetness generally increase in concave hillslopes from hilltop to valley floor, while that of the convex and planar hillslopes remains similar from the hilltop to the bottom (Lin et al., 2006a). In contrast, in the rugged Hill Country of central Texas with stair-step topography developed from limestone, soil thickness and infiltration capacity decrease from the hilltop (upper riser with steeper slopes) to the hill bottom (tread with flatter slope), with the upper riser subsoils saturated or very wet for extended periods (Wilcox et al., 2007).

Two types of soil distribution patterns can be differentiated in terms of their controls and scales. At the hillslope and landscape scales, soil patterns are heterogeneous due to factors that vary over short distances such as topography and parent materials (i.e., the site factors of soil formation). This soil pattern is often referred to as a "soilscape," i.e., the pedologic portion of the landscape (Hole, 1976; Buol et al., 2003), which includes catenas and other more localized distribution patterns. At the regional and global scales, however, zonal soil patterns are expressed by a gradual change in soil over large areas, resulting from climatic and vegetative gradients (i.e., the flux factors of soil formation). These physiographic-oriented soil patterns are recognized in the US Major Land Resources Areas (MLRAs), which are defined as geographically associated land resource units that are geographic areas (usually several thousand acres in extent) characterized by a particular pattern of soils, water, climate, and land use (USDA-NRCS, 2006). The MLRA approach to modern soils inventory may contribute to the classification of watersheds currently pursued in the hydrology community.

3.2.3 Signatures of soil hydrology and soil change: soil morphology and pedogenesis

Among various pedogenic features observable in the field are soil morphological properties that can be seen, felt, and sometimes smelt or tasted. Soil morphology is the basis for field soil characterization, pedogenesis interpretation, soil mapping, and soil classification, because it can be determined in the field using relatively simple methods. Soil morphology reflects the history of long-term flow and transport processes that drive the formation of soil structure and result in visible pedological features (such as clay films, infillings, tonguing, lamellae, and plinthites). Soil macro- and micromorphology thus have long been used to infer soil moisture regimes, hydraulic and biogeochemical properties, and landscape processes (e.g., Lilly and Lin, 2004; Rabenhorst et al., 1998). In particular, water-dominated pedogenesis leads to so-called soil hydromorphology – a result of permanent or temporary state of water saturation in the soil associated with conditions of reduction. Soil hydromorphic features are formed predominantly by the accumulation or loss of Fe, Mn, S, or C compounds by the processes of alternating reduction and oxidation due to saturation and desaturation and the subsequent translocation or precipitation of chemical compounds in the soil (USDA-NRCS, 1998). Repeated periods of saturation and/or inundation of more than a few days occur in nearly all hydric soils (though a total saturation is not absolutely needed for the formation of redox features). The presence of organic matter and a suitable temperature and pH are also generally required for hydromorphism to occur. Such biochemical processes might have implications for finding clues to life on Mars – if Martian soil hydromorphism or paleo-hydromorphism (formed in ancient hydromorphic condition) is observed. This is because biological activity is often involved (although not absolutely required) in soil hydromorphism on Earth, while diagenetic hydromorphism is also considerably accelerated by microorganisms.

A subset of soil morphological features, called "*hydric soil indicators*" (including redox concentrations, depletions, and reduced matrices), are directly related to a specific set of hydrologic conditions (USDA-NRCS, 1998). Hydric soils are soils that formed under conditions of saturation, flooding, or ponding that last long enough during the growing season (repeated periods of more than a few days) to develop anaerobic conditions in the upper part (usually 0.15–0.3 m) of soil profiles (USDA-NRCS, 1998). Hydric soils are one of the three requirements (along with hydrophytic vegetation and wetland hydrology) for identifying jurisdictional wetlands in the US Certain redox patterns occur as a function of the patterns in which the ion-carrying water moves through the soil and as a function of the location of aerated zones in the soil (Fig. 8). Characteristic color patterns are thus created by the reduced Fe and Mn ions removed from a soil if vertical or lateral water flow occurs, or the oxidized Fe and Mn precipitated in a soil if there is a lack of sufficient water flux. Consequently, the spatial relationships of redox depletions

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and redox concentrations may be used to interpret water and air movement in soils (Vepraskas, 1992). Even without the formation of visible morphological features, soil chemistry and biology may provide clues regarding field-scale water movement. For example, difference in mobility between redox-sensitive Mn and Fe in acid soil systems allows secondary Mn/Fe ratios to be used as pedochemical indicators of field-scale throughflow (McDaniel et al., 1992).

Hydrology has been suggested as an integrating factor of soil formation and a main driving force of soil dynamics (Lin et al., 2005b). This is because all of the five natural soil-forming factors affect and are affected by hydrology. The flux factors of soil formation (climate and vegetation) and the site factors (topography and parent materials) can be linked to landscape hydrology, which is further modified by the soil internal hydrologic environment. For example, 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. In addition, all four generalized soil-forming processes (additions, deletions, transformations, and translocations) (Simonson, 1959) involve water in significant ways. Without the action of water, a soil profile would not have been formed. Figure 7 illustrates a general sequence of soil development from a young Entisol to a highly-weathered Ultisol. Water from precipitation is a primary requisite for parent material weathering and soil development. To reach a highly developed stage, sufficient amount of water must not only enter the profile and participate in weathering reactions, but also percolate through the profile and translocate weathering products (such as solutes and clays). Therefore, the characteristics of a soil profile would reflect total amount of water that has passed through over time, which is determined by the interaction of precipitation, temperature and evaporation, site topography, and soil permeability (Brady and Weil, 2004).

An alternative view of integrated soil evolution may be expressed as a function of hydrology (Fig. 6c), i.e., $S=f(Sn, h, a)$, where Sn is a soil naturally-formed in the past, h is the hydrologic condition, and a is anthropogenic impact. Both h and a have all-encompassing influences by alternating the original soil-forming factors, including possible resetting of pedogenic time through creating new soils or redeposition of sediments. This perspective could facilitate the use of hydrologic condition as an integrating factor for quantifying soil evolution, and allows the incorporation of human impacts into soil characterization. For human impacts, the concepts of "*genoform*" (for genetically defined soil series) and "*phenoform*" (for soil types resulting from a particular form of management in a given genoform) (Droogers and Bouma, 1997) offers a possible means to incorporate management effects into pedologic and hydrologic characterizations, which can enhance pedotransfer functions that involve soil series and land use as carriers of soil hydraulic information.

Pedogenesis is essentially an integrated weathering phenomenon that results from a series of physical, chemical, and biological processes via combined geological and biological cycles, hence it provides an integrated view and historical record of the processes occurred in the CZ. Pedogenic regimes are distinguished primarily on the basis of climate as reflected in temperature and moisture availability and secondarily on the basis of vegetation cover. However, local geology and topography can also significantly influence pedogenic processes, leading to possibly multiple soil orders within the same landscape or hillslope. For example, gleization and Histosol can occur just about anywhere where there is a waterlogged area, as they are more dependent on local topography than on macroclimate.

3.2.4 Carriers of soil hydraulic properties and soil heterogeneity: soil functional classification and mapping

Soil horizons, pedons, and taxonomic classes can be used as "carriers" of soil functional properties. Soil taxonomic units are abstract concepts that group soils according to specific ranges of soil properties for the purposes of scientific categorization. Within each taxon (individual taxonomic class), be it a soil order or a soil series, all included pedons are not exactly alike (much like individual trees of the same species may differ in size and shape). A polypedon (an individual soil) is a recognizably distinct cluster of pedons that are dominated by the characteristics defined by a taxonomic unit and are separable from adjacent polypedons by boundaries that are loci of relatively abrupt changes in soil properties (Hole and Campbell, 1985). However, traditional soil classification has focused on a "generic" system that is based on field soil morphological features, often linked to interpretive soil genesis, and sometimes supplemented by limited laboratory measurements of soil physiochemical properties. Such a generic system (called a morphogenetic system) does not target any particular use or function of the soil. While such a system has its own merit (such as the understanding of natural soil formation and evolution), it does not work well with quantitative modeling of soil functions and their responses to changing environment. Thus, functional classification or grouping of soils are needed for diverse applications, such as estimating the magnitude of expected soil hydraulic properties, determining a priori how important preferential flow is in a given soil, and providing a first approximation to model input parameters.

The development of soil hydrologic functional classification or grouping is still in its infancy. Quisenberry et al. (1993) devised a preliminary and descriptive system of classifying selected soils in South Carolina based on water flow pathways and patterns using subsoil structure, surface soil texture, and clay mineralogy. A general soil hydrological classification (termed Hydrology of Soil Types or HOST) has been developed in the UK based on soil morphological attributes to predict water movement through

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soils and substrates (Boorman et al., 1995). While this classification has been applied to predict river levels in ungauged catchments, design spillways, apportion flow in transport models, and estimate mean residence time in watershed hydrology (e.g., Lilly et al., 1998; Soulsby and Tetzlaf, 2008), a more quantitative system to functionally classify soils is still lacking.

Another way of portraying soil heterogeneity and providing soil input parameters to models is through soil maps. A soil map unit is composed of delineations on a map devised to represent spatially-associated soil individuals or soilscapes, as map scales may allow (Buol et al., 2003). There are five orders of soil maps in the US, ranging from the Order I for the most detailed mapping (minimum delineation size≤1 hectare, 1:15 840 or larger cartographic scale, mapping units mostly consociations) to the Order V for very general mapping (minimum delineation size 252-4 000 hectare, 1:250 000 or smaller cartographic scale, mapping units largely associations) (Soil Survey Division Staff, 1993). Consociations are cartographic map units represented dominantly by a single soil taxon (usually soil series), and associations (or complexes) consist of two or more dissimilar components occurring in a regularly repeating pattern (Soil Survey Division Staff, 1993). However, virtually every delineation of a soil map unit includes other soil components or miscellaneous areas that are not identified in the name of the map unit. Many of these components are either too small to be delineated separately at a given soil map scale or deliberately included in delineations of another map unit to avoid excessive detail in the map or the legend (Soil Survey Division Staff, 1993). These inclusions reduce the homogeneity or purity of map units and thus require appropriate quantification for use in modeling. While many studies have suggested the need for a reliable estimate of the proportionate extent of map unit components within a soil map unit for probabilistic assessment of soil properties (e.g., Nordt et al., 1991; Foussereau et al., 1993; Lin et al., 2005a), such information is still largely lacking in modern soil survey databases. This is because traditional soil surveys have overlooked spatial variability within map units for a variety of reasons, including scale limitations, lack of appropriate sampling design, and inadequate quantitative data (Lin et al., 2005a). Hence, quantification of map unit purity for different scales of soil maps is a needed area of improvement in modern soil surveys (Arnold and Wilding, 1991).

Modern soil maps also need to be improved for functional applications beyond the traditional purpose for general land use planning – which has accepted the following soil map limitations: (1) inhomogeneities within soil bodies arising from both inclusions and variations; (2) a certain imprecision of the delineated boundaries; (3) variable significance of the boundaries; and (4) paucity of below-ground information (Campbell, 1977). Therefore, several advances in soil mapping need to be happening to make it more relevant to quantitative modeling: first, precision soil mapping (together with quantification of within map unit variability) is of great demand for site-specific applications (such as precision agriculture and landscape hydrology). As the utility of any map depends upon the precision of statements that can be made about delineated units vs. the area as a whole, hillslope and catchment scale studies will require a more precise soil map than currently available Order II soil maps (called SURRGO). Second, soil map units are better considered as *landscape units* rather than individual soil types (Wysocki et al., 2000) because of often encountered short-range soil variability over the landscape. Thus, developing soil-landscape units that have similar pedologic and hydrologic functions (such as *hydropedologic functional units*) is attractive. Third, soil maps can no longer be static documents; rather, derivative and dynamic maps, tailored for a specific function or purpose, must be generated and updated on a regular basis. Up to now, however, there is a lack of appropriate means to produce derivative and dynamic maps such as soil hydraulic properties through space and time.

Two hierarchical frameworks have been suggested to bridge the forms and functions in hydropedology (Lin and Rathbun, 2003) (Fig. 5): one is a soil mapping hierarchy that deals with soil spatial heterogeneity, and the other is a soil modeling hierarchy that addresses temporal dynamics. The soil mapping hierarchy relates to the "forms" of soils that portrait the spatial pattern of soil types or specific soil properties over the landscape of varying sizes, while the soil modeling hierarchy relates to the "functions" of soils that describe physical, chemical, and/or biological processes at different scales.

An explicit link between these two hierarchies, however, has not yet been established. This is in part due to the mismatch of scales used in mapping and modeling. In a spatial sense, “aggregation” and “disaggregation” are used for mapping soil distribution, which are defined irrespective of a process-based model. In contrast, “upscaling” and “downscaling” are used in modeling soil processes and/or quantifying model inputs/outputs, and thus are defined in the context of a specific model. The meaning of “scale” carries different meanings between mapping and modeling: in cartography, map scale refers to a ratio of map to reality, and the scale becomes smaller as spatial information is aggregated for a larger area; whereas in the modeling arena, scale is often used in a colloquial sense (without a specific quantifier), so large scale loosely refers to a large area extent. Improved connection between the mapping and modeling hierarchies is a needed research area for hydropedology.

4 Opportunities for advancing Critical Zone science and hydropedology

Integration of Mapping, Monitoring, and Modeling (3 M) is suggested here as a strategy for advancing the study of the CZ and hydropedology (Fig. 9). An iterative loop of this 3 M allows the development of adaptive strategy as our knowledge and database expand. Mapping addresses spatial heterogeneity in the CZ, provides a sense of location in monitoring, and facilitates spatially-distributed modeling. Monitoring records the temporal dynamics and cycles in the CZ, provides ground truthing for mapping and spatial interpolation or extrapolation, and supplies model inputs or validates model outputs. Modeling integrates the form and the function of the CZ to enable prediction, guides site selection for (additional) monitoring and ground truthing, and permits dynamic and functional mapping.

We normally monitor pedons to collect point-based data and model landscapes attempting to understand areal-wide patterns. A key connecting these two is the mapping of various soils and landscape features, because the fabric of soils over the landscape provides valuable clues to appropriate selection of monitoring/sampling sites and the design of modeling experiments. Relatively static properties such as topography and soil texture may be mapped to assist in monitoring and modeling, while dynamic properties such as hydrology and soil moisture should be monitored to refine model predictions and to provide ground truthing for mapping and remote sensing. Mapping also provides a means of diagnosing and stratifying the landscape before designing experiments and selecting optimal number of monitoring sites. Thus, the value of mapping in the study of the CZ and hydropedology should not be overlooked.

The 3 M strategy has been employed in the hydropedology study in the Shale Hills Catchment, one of the first US National Critical Zone Observatories (Lin et al., 2006; Lin, 2006; Lin and Zhou, 2008). Based on comprehensive surveys and various maps developed for this catchment, an extensive soil moisture monitoring network has been developed (Fig. 10). Example data shown in Fig. 10b demonstrates the importance of location, depth, and flow pathways in soil monitoring. Valuable experience from our initial hydropedology studies in the Shale Hills CZO includes:

1. *Map first, then design*: because of the ubiquitous heterogeneity in the CZ, a sense of *location* is needed when deciding where to monitor. Mapping soils and landscape features provides a foundation for selecting optimal monitoring sites;

2. *Look first, then measure*: because of the layered nature of the CZ, a sense of *depth* is also needed when installing monitoring devices. Drastically different outcomes would result if depth function of the soil is ignored or simply treated in equal depth interval. Soil horizons and landscape features provide hints regarding how best to measure based on site conditions;

3. *Direction first, then speed*: because of various cycles going on in the CZ, a sense of *flow direction and its temporal shifting* (in addition to the rate of flow) is important to understand hydrological and biogeochemical processes. Flow pathways and patterns are essential in modeling CZ processes if we are to get the right answer for the right reason, particularly in view of the ubiquitous nature of preferential flow in natural soils and landscapes.

4.1 Mapping

Soil pattern in the landscape is a necessary prerequisite for extrapolation and upscaling of point results to greater areas. Place-to-place variability reflects the geographic qualities of natural soils. While geostatistics provides powerful *interpolative* tools after an extensive dataset has been gathered on a particular area, geostatistics is not a very powerful *extrapolative* tool, especially from one tested area to a new area where the database has not been collected. This makes geostatistics a costly and inefficient method to extrapolate knowledge from one area to the next. Furthermore, geostatistical functions should be derived from landscape stratified units such as soil type, geology, land use, parent material, and not indiscriminately across a broad landscape without prior partitioning of the *sources* of variability. In this regard, soil mapping and geospatial data such as DEM can assist the appropriate application of geostatistics to landscape analysis.

Quantifying soil heterogeneity in the field at high spatial and temporal resolutions demands technological advancements. While landforms and vegetation can now been mapped with high resolution (e.g., using Light Detection and Ranging or LiDAR for DEM, and the earth observation satellite IKONOS for land use/land cover), there is a "bottleneck" for in situ high-resolution (e.g., submeter to centimeter) and spatially-temporally continuous and non-invasive mapping of subsurface architecture. This "bottleneck" has constrained our predictive capacity of many soil and hydrologic functions in the subsurface. Thus, there is a great need to develop enhanced tools and techniques for precision and noninvasive mapping/imaging of the subsurface in situ, so that subsurface processes can be better understood and predicted.

We also need new ways of mapping soils beyond the classical approaches where soil taxonomic units, rather than soil functional units, are used in mapping. The concept of *Hydropedologic Functional Unit (HFU)* could be defined as a soil-landscape unit having similar pedologic and hydrologic functions to provide a means of cartographically representing important landscape-soil-hydrology functions (Lin et al., 2009). The goal of such HFUs is to subdivide the landscape into similarly functioning hydropedologic units by grouping various geomorphic units that have similar storage, flux, pathway, and/or residence time of water in various soil-landscape units. These units can be identified and delineated using traditional survey methods and data in conjunction with new digital data sources, geophysical surveys, and in situ real-time monitoring. A map of HFUs can then serve as a cartographic building-block to increase the effectiveness of knowledge transfer and the extrapolation of point-based observations. This is consistent with the flexible box models suggested by McDonnell (2003) and can facilitate the prediction of ungauged basins (Sivapalan, 2003).

4.2 Monitoring

Long-term monitoring of the health of our land – through monitoring its "blood pressure" (soil water potential), temperature, respiration, and other signs of global change – is fundamental to CZ studies. The famous "Keeling Curve" of long-term CO_2 data demonstrated the value of continuous recording of a seemingly *routine* atmospheric measurement, which turned out to be a vital sign of the Earth's climate and led to the first alert to the world about the anthropogenic contribution to the "greenhouse effect" and global warming. The long-term study at the Hubbard Brook Experimental Forest is another example that demonstrated undiminishing scientific returns and led to the discovery of "acid rain" in North America. In this time of accelerating global change, continuous Earth observations are essential as they have the potential to open our eyes for unexpected but relevant developments and processes.

It is important to connect mapping with long-term monitoring of the CZ. A major challenge in understanding the CZ is the inherent heterogeneity of three-dimensional spatial structures across scales. All processes within the subsurface are bound to this structural framework, which is typically unknown or hard to quantify with currently available technologies. This is a fundamental difference compared to atmospheric monitoring where the heterogeneity of the system can be explored at one sensor location. However, the signals of two sensors at nearby locations in many soils may be completely uncorrelated. This is why we need the mapping of the subsurface heterogeneity. Then, and only then, can the point-based monitoring provide the required observations to develop and improve predictive potential of process-based models. Unlike atmosphere and ocean, the land is not a continuous fluid; rather, it poses hierarchical heterogeneities with controlling structures that dictate discrete flow networks and reaction pathways embedded in land surface and subsurface mosaics. This implies that a completely new foundation for subsurface flow and transport modeling is needed.

Another fundamental difference between soil monitoring and atmospheric monitoring is the varying timeframes needed to detect soil changes. Considering the multi-phase nature of the soil system (gaseous, liquid, solid, and biotic phases), it is inadequate to determine soil change or temporal variability by only one characteristic. Each soil phase and property has its own characteristic response time. Very labile soil properties have characteristic response time almost coinciding with that of the atmosphere (such as soil air, soil moisture, and soil temperature), while very stable soil properties have long characteristic response time close to that of the lithosphere (such as soil mineralogy and particle density), but many soil properties have characteristic response time falling in between the above two ends of the spectrum (such as soil carbon and soil microbial biomass).

While numerous soil properties and processes in the CZ could be monitored, the following are some of the key signs of our land's health: (1) soil matric potential (similar to the blood pressure of a living organism – too high or too low are not good to the functioning of soil system), (2) soil temperature (reflecting land surface energy and perhaps even global warming), (3) soil gaseous concentration (particularly CO_2, O_2, and trace gases), (4) soil carbon content (related to carbon sequestration), (5) soil redox potential (critical to many biochemical processes), (6) soil pH (a foundation for many chemical and biological reactions), and (7) soil microbial biomass (representing organic matter decomposition and other biological reaction capability). Long-term, ideally in (near) real-time, monitoring of these basic elements of soil systems would permit fundamental assessments of the health and productivity of our soil, and allow important recording of active exchanges among the atmosphere, biosphere, hydrosphere, lithosphere, and pedosphere.

Changes in many other soil properties are inherently long-term, undetectable in a short period of time, but irreversible and threshold-like in the long-term. This evolutionary process presents significant challenges to designing and implementing scientific research and land management programs dealing with the CZ. However, ecosystem functions and watershed processes depend on the evolution of the soil. Therefore, long-term monitoring of soils is critical.

4.3 Modeling

Models are necessary tools for quantitative assessment and prediction of complex systems such as the CZ. When integrated with real-time monitoring and spatially-distributed maps, models can provide temporal trends and spatial patterns of CZ processes. Models can also be used to provide guidelines for sampling and monitoring. For example, Weiler and McDonnell (2004) developed numerical experiments with a model driven by collective field intelligence, called "virtual experiments", as a new approach for improving process conceptualization in hillslope hydrology. Phillips (2008) promoted the use of models to generate field-testable hypotheses unrelated to the model itself – propositions derived from model outputs or implications, the testing of which provides pedologic insight independent of the model and its underlying assumptions.

Current models in watershed hydrology are based on well-known small-scale physics such as the Darcy-Buckingham's law and the Richards' equation built into coupled mass balance equations (Beven, 2006; McDonnell et al., 2007; Kirchner, 2006). However, heterogeneities in land surface, hierarchical structures of soils, channel geometries, and preferential flow networks all make the land surface and subsurface different from the continuous field assumption (CUAHSI, 2007). It is becoming increasingly recognized that the solid Earth is not a continuous fluid; rather, it poses hierarchical heterogeneities with discrete flow networks embedded in both the surface and subsurface.

It has been observed, for example, that the dominant process governing unsaturated flow in soils may change from matrix flow to preferential flow under different conditions when moving from the pore scale to the pedon scale (Blöschl and Sivapalan, 1995; Hendrickx and Flury, 2001). When moving from the pedon scale to the landscape/watershed scale, our knowledge for extrapolating the Darcy-Buckingham's law and the Richards' equation is further constrained (Lin et al., 2006b). This is a "*conceptual bottleneck*" that needs to be resolved in order to develop a new generation of hydrologic models. "Network-based" approach to hillslope and watershed hydrology is emerging (e.g., Rinaldo et al., 2006; Uhlenbrook, 2006; Sidle et al., 2001; McDonnell et al., 2007), where internal network structures in the subsurface govern vertical and lateral preferential flow dynamics and the threshold-like hydrologic response under varying precipitation, soil, and antecedent moisture conditions (e.g., Tromp Van Meerveld and McDonnell, 2006; Lehmann et al., 2007; Lin and Zhou, 2008).

The concept of subsurface preferential flow networks provides a strong scientific advance in our understanding of seemingly complex hydrologic and biogeochemical phenomena across the landscape. For instance, Sidle et al. (2001), Gish et al. (2005), Lin (2006), and many others have reported evidence of preferential flow self-organization in forested hillslopes and agricultural landscapes, where individual short preferential flow pathways are linked via a series of "nodes" in a network, which may be switched on or off, or expand or shrink depending on local soil moisture conditions and landscape locations. Different levels of nodes may be used in a network to approximate preferential flow dynamics. This conceptual breakthrough, however, is hinged on how we can measure the network characteristics to provide inputs to a new class of models.

4.4 Fostering a global alliance

With growing interest in international scientific communities to establish various environmental observatory networks to monitor the ever-changing environment, and as large-scale monitoring networks are increasingly called for by funding agencies and scientific communities to address "big" science questions, a synergistic effort to foster a global alliance for monitoring, mapping, and modeling of the CZ is desirable. Long-term monitoring, along with precision spatial mapping, and process-based modeling, of the CZ across scales and geographic regions (Fig. 9) can serve many purposes of societal importance. Optimization of whole systems for multiple benefits rather than one benefit permit synergistic outcomes and would be more cost-effective in the long-run. Since nature does not recognize man-made disciplinary divides, it is imperative that a systems approach be taken to achieve comprehensive understanding of the complex CZ. An integrated network for observing, modeling, and sustaining the Earth's CZ *as a whole* is in the early stages of development, but it is clear that it will require inputs from many basic and applied disciplines. However, no one team or organization can do that alone, and a diversity of funding sources supporting a heterogeneous mixture of overlapping programs is probably the best formula for long-term stability of observatory networks (Keeling, 2008). Therefore, a global alliance is suggested here.

With advances in various sensor technologies, data handling and transmission facilities, now is the right time to go for a global monitoring program of the CZ that should be realized in a coordinated way to maximize the benefit for global environmental research. In particular, "hot spots" based on the projected global change should be selected to monitor the impacts of global climate and land use change on future landscape-soil-water-ecosystem relationships. Critical Zone Observatories, as initiated in the US, are excellent platforms for addressing such grand challenges, where terrestrial processes and ecosystem dynamics are studied through detailed multidisciplinary field observations and in situ monitoring, in combination with systematic modeling and detailed mapping.

To proceed with such a global alliance, we should develop international monitoring protocols and standards. Once the agreed protocols and standards are developed, then the selection of sites for major soils of the world along heterogeneity gradients would be an important next step. Mapping and modeling should be used in assisting the selection of major monitoring sites. Once monitoring sites are chosen, real-time monitoring datasets should be continuously utilized, in combination with precision mapping and process-based modeling, to provide spatial extrapolations and temporal inferences about the trends and feedbacks in the CZ.

Together, our capability to predict the behavior and evolution of the CZ (including the productivity and health of soil and the quantity and quality of water) in response to changing environment will improve significantly – if a global alliance for monitoring, mapping, and modeling of the CZ can be fostered.

5 Summary and conclusion

The CZ concept provides a synergistic framework for holistic studies of terrestrial ecosystems and their foundation – soil and water. While soil is central to the CZ, the entire CZ requires integration with above-ground vegetation and below-soil aquifer. The growing interest in the CZ is an excellent opportunity to advance the studies of the most complex and heterogeneous region of the Earth – the land and its soil. This brings a new hope of revealing the secrets underfoot, tapping into the treasures underground, embracing a focus on water as a unifying theme for understanding complex soil and environmental systems, and providing a stimulating framework for integrated studies of water with soil, rock, air, and biotic resources. The CZ is the right platform for breakthrough collaborations across scientific disciplines, including soil science, hydrology, geosciences, and others.

The crucial juncture of all the interacting spheres on the Earth surface is the product of five soil-forming factors plus human impacts. The pedosphere is a unique, relatively immobile, and highly heterogeneous and dynamic sphere. In contrast to the other spheres of the Earth system, the pedosphere can neither quickly intermix (as the atmosphere does), nor rapidly move laterally along the landscape (as water does), nor clearly be separated into individual units and avoid undesirable environmental changes (as the biota can be and does), nor escape rapid human and biological perturbations (as is characteristic of the lithosphere). Therefore, each soil, as a relatively immovable

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and formed in situ natural body, is fated to react, endure, and record environmental changes at each location by being transformed according to the interactions of climatic, biotic, and anthropogenic forcing, as conditioned by geologic and topographic setting, over geological and biological time scales. This makes the monitoring of soil change an excellent (albeit complex) environmental assessment, since every block of soil is a timed "memory" of past and present biosphere-geosphere dynamics (Arnold et al., 1990). This memory takes multiple forms, including soil micromorphology, soil profile features, and soil physical, chemical, and biological properties. Learning to "decode" soil features and their changes into environmental information is as valuable as reading the records of ice cores for atmospheric conditions and interpreting tree rings for eco-climatic dynamics.

Hydropedology, as an intertwined branch of soil science and hydrology, deals with the variably-unsaturated zone that includes the root zone, deep vadose zone, capillary fringes, wetlands, and subaqueous soils (i.e., soils that form in sediment found in shallow permanently flooded environments such as in an estuary). The spatial scale considered in hydropedology ranges from microscopy to the entire pedosphere and its temporal scale ranges from infinitesimal to the geological time. Four fundamental issues of hydropedology are linked to the three general characteristics of the CZ. Hydropedology addresses how the subsurface heterogeneity develops and evolves, how soil architecture influences preferential flow, how soil distribution patterns influence hillslope/watershed hydrology, and how the hydrologic cycle feedbacks to pedogenesis and controls soil functions. Hydrologic cycle and human activities have become prominent driving forces in understanding soil changes and CZ dynamics, thus deserving elevated attention in the understanding and modeling of soil evolution and soil functions.

This article has attempted to stimulate discussions on integrated approaches to understand the Earth's CZ and how hydropedology can contribute uniquely to that endeavor. To propel soil science and CZ science forward, an "outward" growth model needs to be embraced by the community. Historically, soil science has followed a circuitous path in its evolution from a discipline with roots in geology, to an applied agricultural and environmental discipline, and now to a bio- and geo-science focused on the CZ investigations (Wilding and Lin, 2006). This closes the loop or spiral, but along the way soil science has become more extensive, comprehensive, and quantitative. It is time to embrace soil science as a science in the broadest sense and to advance its basic and applied research through multiscale and interdisciplinary efforts using the unifying concept of the CZ. An initiative to foster a global alliance for monitoring, mapping, and modeling of the CZ, as recommended in this paper, can contribute significantly to such an advancement.

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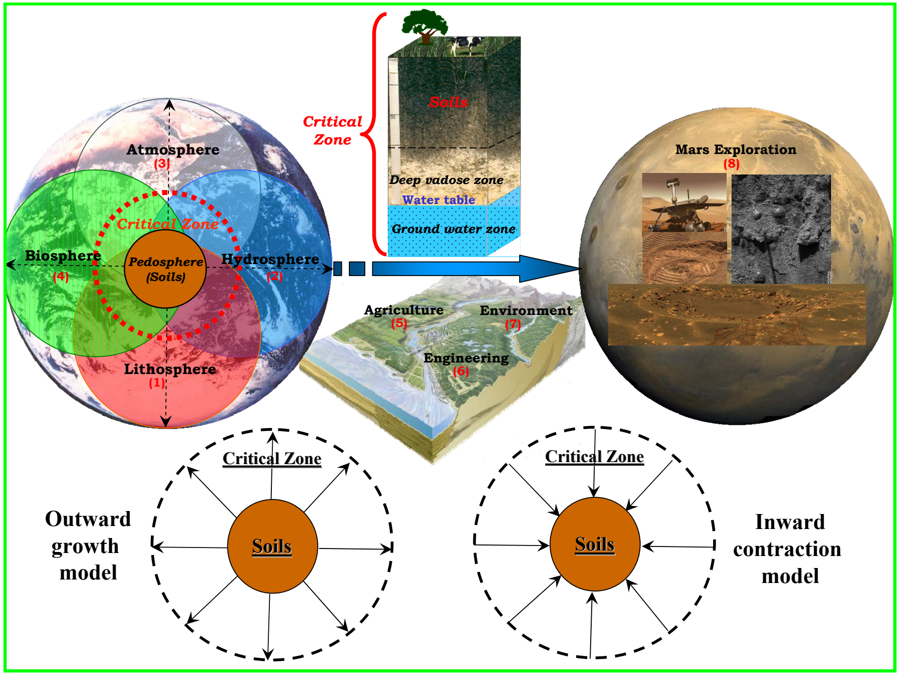

Fig. 1. An inclusive vision for future soil science: 7+1 roles of the soil from the Earth's Critical Zone (CZ) to Mars exploration. The numbered roles of soils are: (1) soil is an Earth history recorder as soil is a natural body formed under the influence of climate, organisms, parent material, relief, and time (i.e., the five soil-forming factors) in the Earth's system; (2) soil is a fresh water storage and transmitting mantle in the Earth's CZ; (3) soil is a gas and energy regulating geoderma in the land-atmosphere interface; (4) soil is the foundation of diverse ecosystems; (5) soil is a living porous substrate essential for plant growth, animal production, and food supply; (6) soil is a popular material for a variety of engineering and construction applications; (7) soil is a great natural remediation and buffering medium in the environment; and (8) soil is a frontier in extraterrestrial explorations to explore signs of liquid water and life. This diagram also depicts the cyclical, vertical, and horizontal heterogeneity involved in the CZ. In the lower portion of the graph, two models for future soil science are illustrated: an "outward" growth vs. an "inward" contraction. The outward growth model suggests a broadened perspective of the soil and its synergistic integration with other disciplines within the framework of the CZ. The inward contraction model, on the other hand, implies a classical and narrow view of the soil and a confined perspective of the CZ (by equating the CZ to the soil alone).

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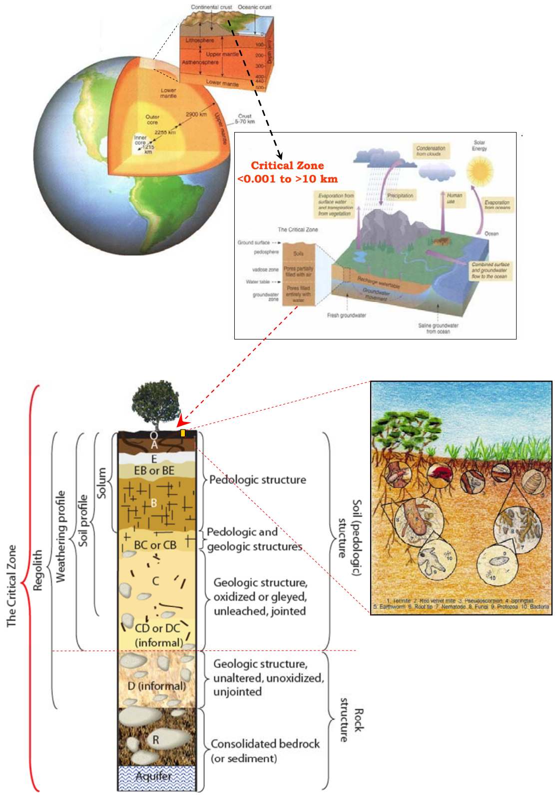

Fig. 2. Earth in cross section, showing the Earth's inner core to outer crust (from Christopherson, 2007) and the Critical Zone in the upper crust (from NRC, 2001). Comparison of the concepts of the Critical Zone, regolith, weathering profile, soil profile, and solum: solum is the classical narrow conception of the soil (from O to B horizons, with O horizon only exists in forest floors). The C horizon (also often called saprolite) is the part of the regolith that underlies the solum, but may be slowly changing into soil in its upper parts. The unmodified/unweathered portion of the C horizon is here labelled as D horizon (after Tandarich et al., 1994). Soil profile is a vertical section of the soil through all its horizons and extends into the weathered C horizon. All materials above fresh, unweathered bedrock are called regolith, which is equivalent to the broad definition of the soil. Sometimes the regolith is so thin that it has been changed entirely to soil; in such a case, soil rests directly on the bedrock. The Critical Zone is the broadest holistic concept, going from the top of the tree to the bottom of the aquifer. Also shown in the surface soil is the abundance of microbes and insects, where one heaping tablespoon of fertile soil may contain up to 9 billion microorganisms. Amidst this vast number and variety are a host of microbes now valued for their potential to help solve environmental problems. But soil is also home to many disease bacteria (such as botulism and anthrax), and organisms in the soil may supply the cure as well as the disease.

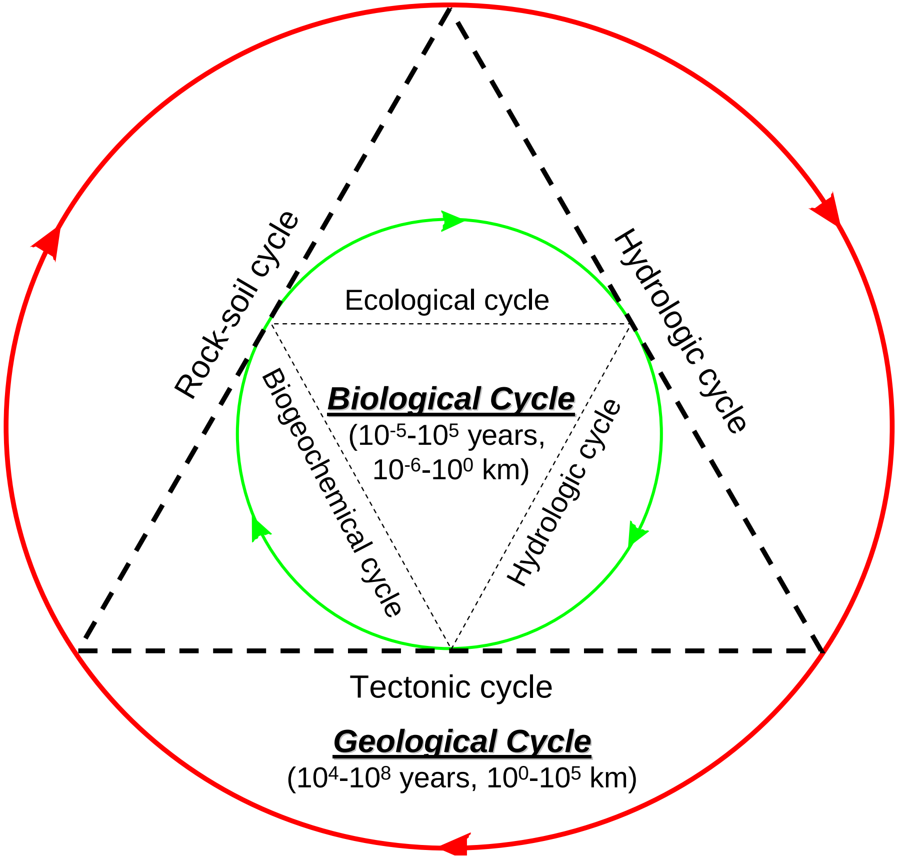

Fig. 3a. Principle sub-cycles within the geological cycle and the biological cycle. General ranges of time scale and spatial extent of the big and small cycles are indicated in parenthesis.

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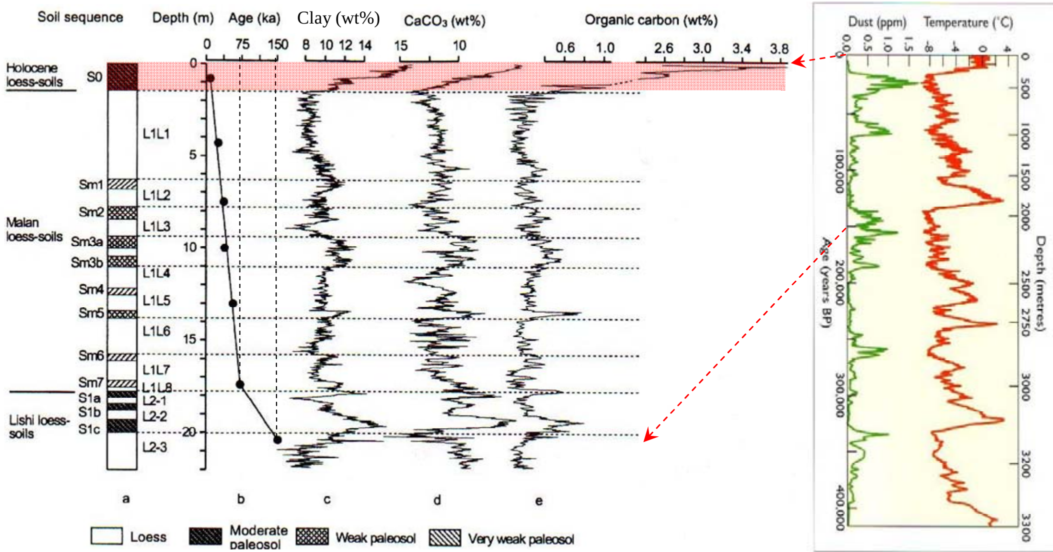

Fig. 3b. Two illustrations of coupled Earth System – left: >20 m deep loess-paleosol sequence on the Tibetan Plateau and the depth function of age vs. pedogenic (clay, carbonate, and organic carbon contents) response to millennial summer monsoon (after Fang et al., 2003); right: history of Antarctic temperature and dust deposition for the last 420 000 years derived from the Vostok ice core, showing the oscillation in temperature and its effect on windiness and aridity that caused major phases of dune building and an increase in dust deposition around the globe (after McKenzie et al., 2004).

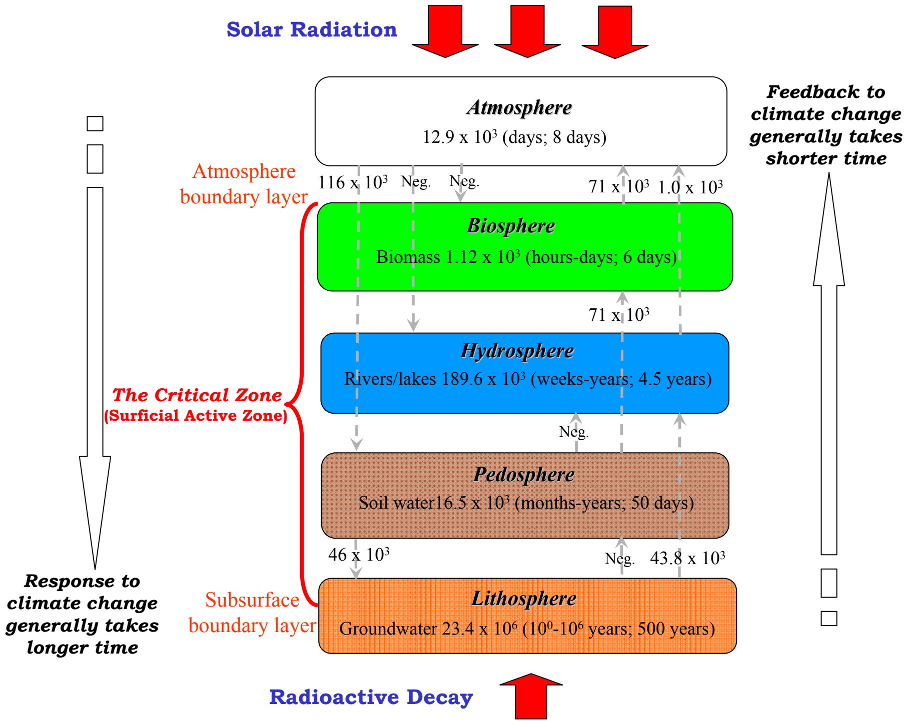

Fig. 4. A conceptual layer model of the Earth's Critical Zone from the upper atmosphere boundary layer to the lower subsurface boundary layer, with a general trend of increasing response time to climate change and decreasing feedback to external perturbations. Global water balance for the terrestrial environment (excluding oceans and glaciers) is indicated for major storages (in km^3), fluxes (in km^3/year), and turnover time (in parenthesis, with a range and a global average) which is calculated as storage divided by total annual inflow assuming steady state (data from Shiklomanov and Sokolov, 1983).

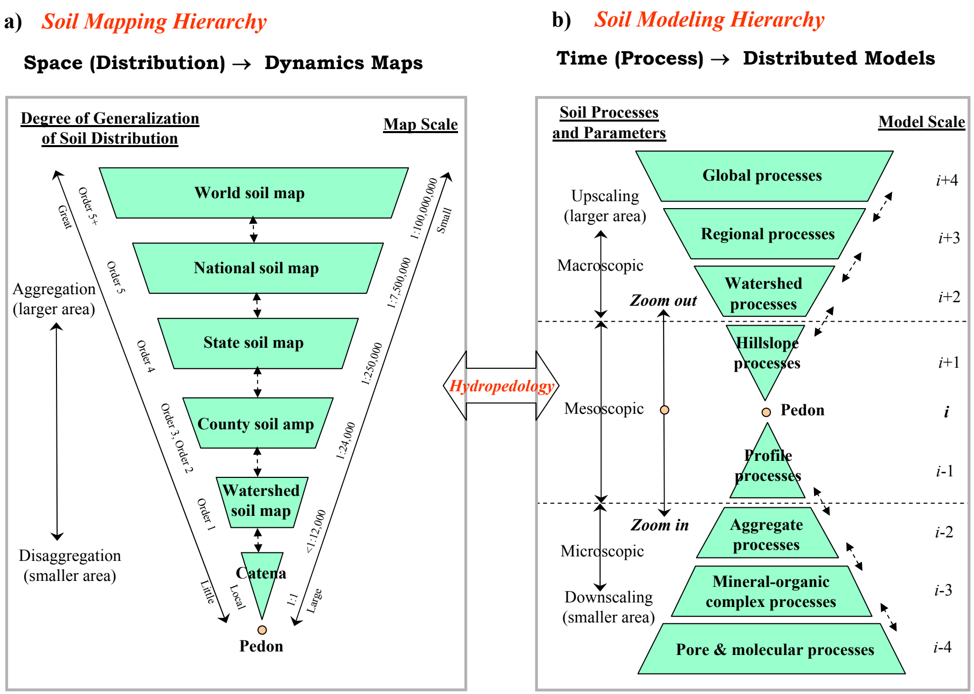

Fig. 5. Hierarchical frameworks for bridging forms (soil distribution) and functions (soil processes) via hydropedology: **(a)** soil mapping hierarchy for depicting soil spatial distributions at different cartographic scales, and **(b)** soil modeling hierarchy for understanding dynamic processes from molecular to global scales. On the left side, different orders of soil survey operations generate different scales of soil maps, with increasing degree of generalization or aggregation of soils information from local to global levels. Traditional soil surveys produce static maps that do not address soil evolution, thus dynamic soil maps are increasingly needed. On the right side, classical modeling approaches have been generally lumped, ignoring spatial heterogeneity. Hence, distributed modeling that couple temporal dynamics with spatial variability are becoming more in demand, and also require appropriate upscaling or downscaling of the processes being modeled and/or model input parameters. Notice gaps exist between different scales in both mapping and modeling hierarchies. Pedon in a local point is considered as the basic scale (i) of observation or monitoring, and $i\pm1\ldots4$ indicate arbitrary labels of larger or smaller scales. Note that the intermediate scale is often the most critical and challenging.

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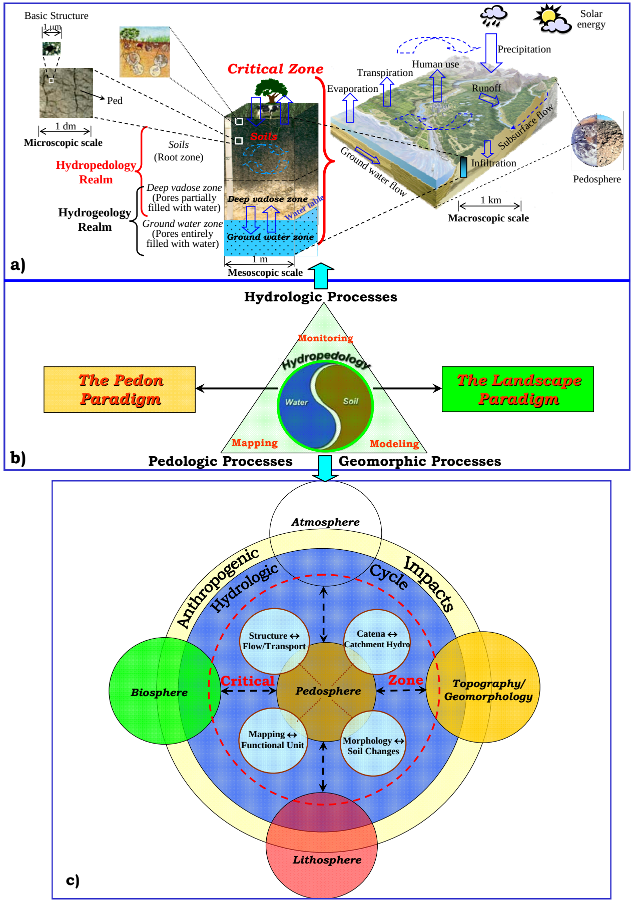
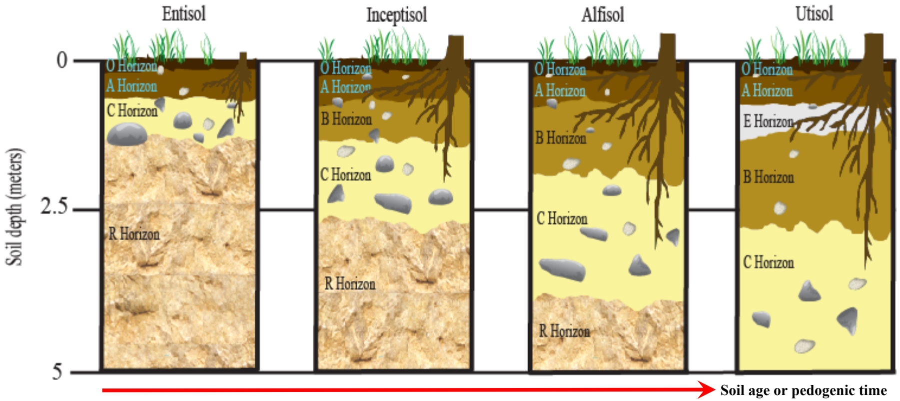


Fig. 6. **(a)** Hydropedology investigates and quantifies interactive hydrologic and pedologic processes across spatial and temporal scales. **(b)** Hydropedology connects the pedon and landscape paradigms through integrated mapping, monitoring, and modeling. **(c)** Schematic showing the classical view of pedogenesis (*Sn=f (c, o, p, r, t, . . .)*, where *Sn* is a given soil type or soil property, *c* is climate, *o* is organism, *p* is parent material, *r* is topography, and *t* is time) versus an alternative view of integrated soil evolution (*S=f (Sn, h, a)*, where *Sn* is a soil naturally-formed in the past, *h* is hydrologic condition, and *a* is anthropogenic impacts). Four fundamental issues of hydropedology within the Critical Zone are also illustrated.



Soil order	*Entisol*	*Inceptisol*	*Alfisol*	*Ultisol*
Pedogenic age (year)	10^0 — 10^2	10^2 — 10^4	10^3 — 10^5	10^4 — $>10^6$
Soil profile diagnostic feature	No B hor.	Weekly developed B hor.	Clay-enriched B, with base saturation > 35%	Kaolin and oxide-dominated B, with base saturation < 35%
Soil thickness (m)	0.01 — 0.5	0.1 — 2	1 — 5	5 — >10
Hydrologic feature	Water-restricting within <0.5 m	Moderate water storage and percolation	High water storage, deep percolation	B hor. hydraulic conductivity reduced, turning into an aquitard
Common land use	Forest	Forest, pasture, urban	Forest, pasture, crop, urban	Forest, pasture, crop, urban

Fig. 7. A general sequence of soil development from a young Entisol (left) to a highly-weathered Ultisol (right) under well-drained conditions. The graduate formation of various soil horizons and the deepening of soil profile through time depend on the weathering rate of the underlying bedrock (R horizon), the accumulation rate of organic matter (O and A horizons), and the percolation rate of water through the soil profile. Water from precipitation is a primary requisite for parent material weathering and soil development. To reach a highly developed soil (such as an Alfisol and Ultisol), sufficient amount of water must not only enter the profile and participate in weathering reactions, but also percolate through the profile and translocate weathering products (such as solutes and clays). Further development from Alfisol to Ultisol leads to distinct eluviation of clay, iron, and aluminium oxides, leaving behind a light color and coarse texture E horizon and forming a high clay accumulation Bt horizon that often becomes an aquitard.

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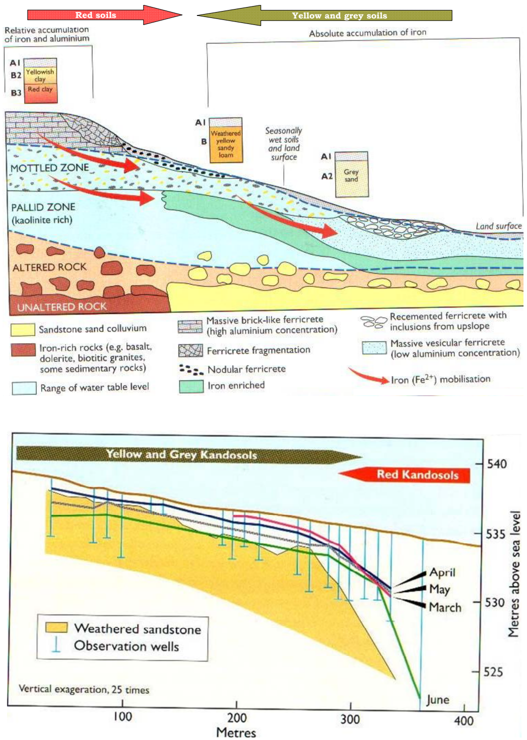

Fig. 8. **(a)** A common soil catena along an eroding hillslope in Australia, showing iron transformations and the formation of ferricrete in relation to iron mobilization and water flow pathways. **(b)** Free-water levels at the end of a wet season (from March to June) along a toposequence near Torrens Creek, Queensland, Australia. The Yellow and Grey Kandosols (highly-weathered soils) are saturated, with shallow depth to free water (0–2 m), whereas the downslope deep Red Kandosols have much greater depth to free water (4–11+m). Different colors, mottle patterns, and ironstone contents of the soils are consistent with their distinctive soil hydrological regimes. Such contrasting hydrology and soil morphology cannot be explained by simple catenary models where surface topography controls hydrological regimes; instead, the topography of the underlying weathered rock substrates with low-permeability causes such distribution patterns of soil and hydrology (Coventry, 1982) (after McKenzie et al., 2004).

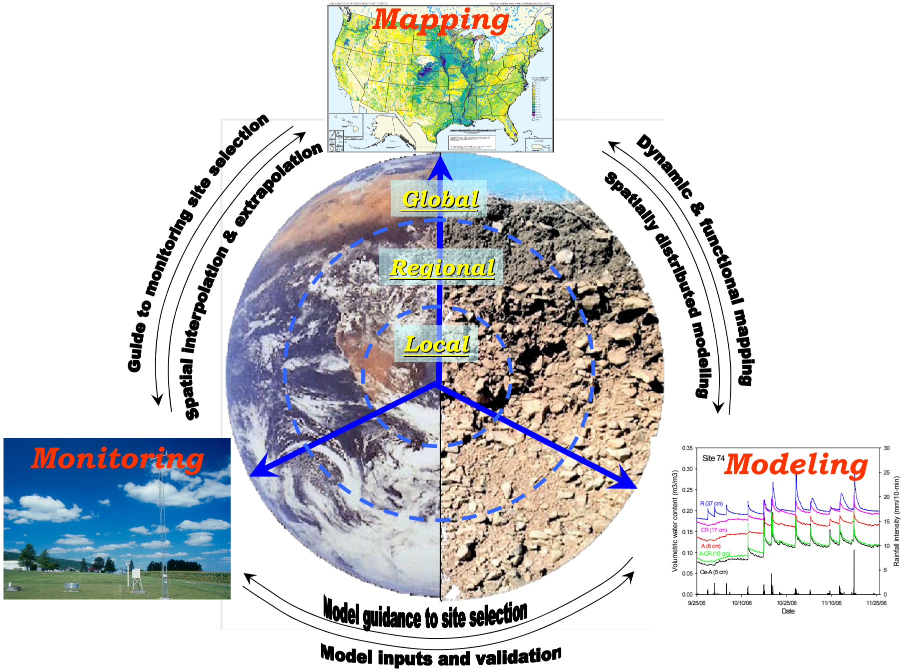

Fig. 9. Integrated mapping (spatial distribution and pattern), monitoring (near real-time and long-term change), and modeling (coupled processes and prediction) for the Critical Zone across scales and geographic regions. The 3 M's (mapping, monitoring, and modeling) are interlinked and feedback to each other, thus providing a 4-D (3-D+time) understanding of the crucible of terrestrial life. Such a 3 M strategy also addresses the three fundamental characteristics of the Critical Zone, i.e., cycles (through appropriate monitoring and modeling), layers (through depth-based monitoring and modeling), and heterogeneity (via mapping and spatial modeling).

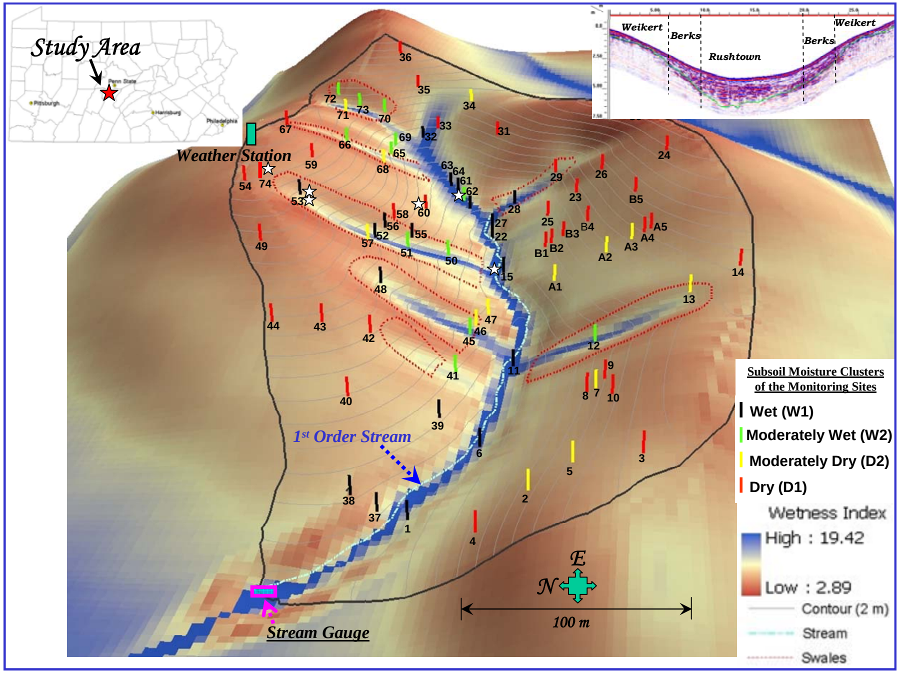

Fig. 10a. **(a)** The 7.9-ha forested Shale Hills Catchment (rendered in 3-D with topographic wetness index as background) in central Pennsylvania, showing a soil moisture monitoring network developed using the 3 M strategy. The subsoil wetness clusters are based on a combined consideration of soil thickness (depth to bedrock), topographic wetness index, and local slope. The red dashed polygons are topographic depressions (swales). Stars are the locations of automatic monitoring stations with example data shown in **(b)**. The upper right corner shows a ground penetrating radar (GPR) image of a subsurface across a swale (from site #51 to 55), with green curve indicating an interpreted depth to bedrock. Dash lines separate 3 soil series along the swale. (b) Soil moisture response to a large storm event (36.83 mm over 7.5 h) occurred on 16 November, 2006 at different depths in selected automatic monitoring stations, illustrating the importance of landscape location and soil depth in understanding soil moisture in the subsurface. This example data also demonstrate short-lived transient water table at hillslope sites (sites #74, 60, and 53) and relatively longer-lived water table at the valley floor (sites #15 and 61) (indicated by blue arrows). The plateaus in the soil moisture curves indicate the attainment of field saturation.

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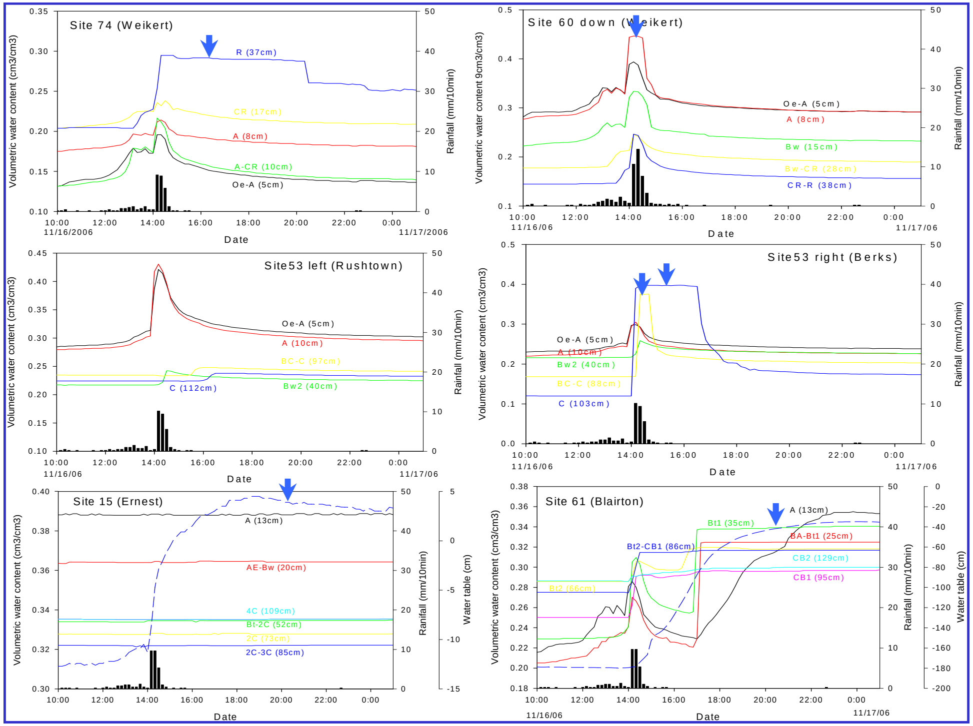

Fig. 10b. Continued.

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