Hydrology in a Dynamic Earth

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A theme of hydrologic change implies that hydrologic processes are changing in their functioning because of changes in external driving conditions, such as land use change, or climate change. In a larger view, however, all change processes can themselves be recognized as expressions of the dynamism of the earth itself. This is the third in a series of short discussion papers written to support the activities of the CUAHSI Science Planning team. In this paper, the theme of hydrology in a dynamic earth is explored in the context of related science plans of neighboring communities in the solid earth sciences.

Community Surface Dynamics Modeling System

In the solid earth sciences, the "critical zone" is the "active soil, rock and sediment layer that forms the earth's surface" according to the Community Surface Dynamics Modeling System Working Group (CSDMS, 2004, p. 4), who state further that "the physical, chemical, and biological systems of the earth's surface are so deeply interwoven that the surface is a kind of 'living skin' of our planet", and "viewed on an appropriate time scale, our planet's surface is dynamic in ways that parallel the more familiar dynamism of the atmosphere and the oceans" (CSDMS, 2004, p. 6). The CSDMS has proposed the development of a modeling system to describe the dynamism of these variously interlinked systems, including atmospheric and climate models, ocean models, earth system models, river models, glacier and ice sheet models, hydrologic models and lithosphere models. They propose to begin with landscape models that simulate evolution in topography and near-surface stratigraphy over time (CSDMS, 2005, p.46).

The science goals of this effort are stated as (CSDMS, 2005, p.4):

1. "What are *the fluxes, reservoirs, and flow paths* associated with the physical, biological, and chemical transport processes in the Critical Zone? How do these depend on substrate properties like morphology, geology, and ecology, and on human activities?
2. What processes lead to *self-organization and pattern formation* in surface systems? How do self-organized patterns mediate surface fluxes and evolution?
3. How do material fluxes and surface evolution vary across *time and space scales*?
4. How are *physical and biological* processes coupled in surface systems?
5. How is the *history of surface evolution* recorded in surface morphology and physical, chemical, and biological stratigraphic records?
6. How do *linked surface environments* communicate with one another across their dynamic boundaries? How do changes in one part of the global surface system affect other parts?

7. How does the Critical Zone couple to the tectosphere, atmosphere, hydrosphere, cryosphere, and biosphere and serve as the *dynamic interface* among them?"

Considering that water flows through all these systems and actively accomplishes some of the processes affecting them, the science goals just stated for the critical zone could be stated without much change for a hydrologic science program. Indeed, the phrases in the above list of seven items have a familiar ring to them when remembering the various science plans and investigative efforts that CUAHSI has engaged in.

Critical Zone Exploratory Network

Another approach to studying the critical zone has been articulated by the Weathering System Science Consortium (WSSC, 2005), whose draft science plan describes the critical zone as the "zone extending from the outer vegetation envelope to the lower limit of groundwater" (WSSC, 2005, p. 2). They propose to examine the question: "how does the Earth's weathering engine break down and solubilize rock to nourish ecosystems, sculpt terrestrial landscapes, and influence global atmospheric processes?" (WSSC, 2005, p. 2).

They consider that the evolution of the critical zone "is driven by a massive disequilibrium resulting from matter and energy fluxes across its boundaries with the external environment", and that the functioning of the critical zone is driven by variability in "climate, substrate age, topographic position, biota, and anthropogenic disturbance" (WSSC, 2005, p. 3), (see also Figure 1). The WSSC has proposed that an observatory network is needed to quantify the effect of the variation of each of these factors.

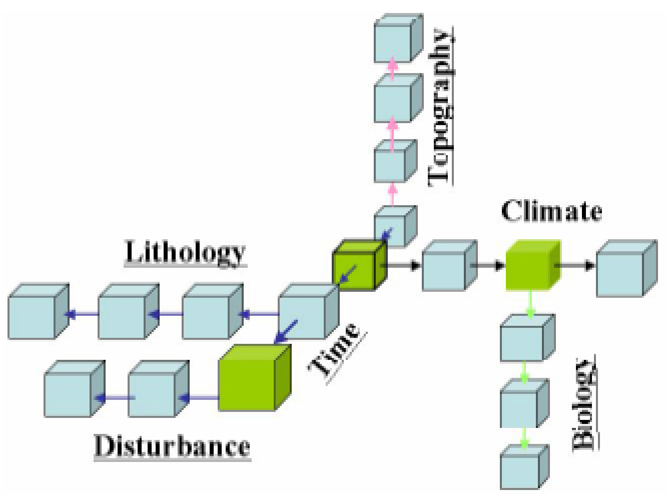

Figure 1. Factors affecting the functioning of the critical zone (from WSSC, 2005)

It is clear that there is a considerable resonance between goals that could be stated for a hydrologic science program, and those articulated by the Weather System Science Consortium.

Dynamic Hydrology

Hydrology is dynamic because water conditions change through time in all phases of the hydrologic cycle. We normally think of the hydrologic environment through which the water passes for surface and subsurface hydrology – the critical zone – as being static, and having time-invariant properties. Suppose, in line with the thinking of the solid earth scientists, we consider the critical zone as being a dynamic system which itself is changing through time, although on a much longer time scale than that normally considered for hydrologic processes. If that is so, then "dynamic hydrology" can be thought of as "hydrology in a dynamic earth". In this context, a theme of "hydrologic change" becomes a goal of measuring for a particular location or region, the change in functioning of a particular hydrologic process or the condition of a particular hydrologic environment over an interval of time in response to external changes in driving factors acting singly or in combination.

For example, during the mid-1980's the Great Salt Lake accumulated water for several years until the flooding encroached upon the boundaries of Salt Lake City, then this was followed by a dry period from 1987 to 1994. The sustained year to year variations in wet and dry periods are greater than can be explained by pure random year to year variations in annual precipitation taken alone and point to larger variations in the global climate systems determining weather patterns in the Great Salt Basin. These in turn, imply the existence of multi-year variations in oceanic circulation, solar insolation and other factors.

On another time scale, the occurrence of fires many decades ago in the forests of the Pacific Northwest denuded the landscape of vegetation, released debris into stream valleys, which may take more than a century to be gradually carried away by fluvial transport to the oceans. Considerable controversy exists as to the impact of logging activities on sediment loading to streams but these loading variations may be dominated by the existence of an essentially infinite source of moveable sediment already in the stream valleys that just awaits the next storm to carry some more of it downstream. In other words, the sediment concentration in downstream rivers may be limited only by the transport capacity of the water and not by the sediment supply capacity of the upland watershed, regardless of the nature of the logging practices pursued there.

On a third time scale, the heterogeneity of porous media in soils and geologic strata is known to exert an important influence on fluid flow and chemical process functioning. If this heterogeneity could be simulated through dynamic modeling of the evolution of soils and geologic strata, it may be possible to depict in a much more detailed way the micro-details of lenses and strata formation that lead to preferential flow paths for water.

Hydrologic Science

How do we think about hydrologic science in the context of hydrology in a dynamic earth? First of all, it is necessary to separate the effects of dynamism in the surrounding environment from dynamism in hydrologic processes and conditions. In this sense, a phrase stated in a previous discussion paper on hydrologic environments and processes may be useful: *the description of hydrologic processes by means of equations should be supported by an equal emphasis on the description of hydrologic environments by means of data*. (Maidment, 2005, p.1). In this context, the "hydrologic environment" describes the physical, chemical and biologic character of the critical zone, and "hydrologic processes" describe the principles and equations for flow, transport and transformation mechanisms that drive the changes in water conditions, in both quantity and quality. As shown in Figure 1, the interplay of hydrologic processes and the hydrologic environment is what defines "hydrologic conditions", that is, the fluxes, flows that define water movement, and the chemical and biological parameters that define water quality.

Ultimately, we measure water conditions in the field and seek to infer the behavior of hydrologic processes, but this search for process description can never be completely separated from the characteristics of the hydrologic environment within which a particular set of hydrologic conditions is measured. Put another way, a given set of processes will produce one set of hydrologic conditions in one hydrologic environment, and another set in a different hydrologic environment. The physical laws and principles of gravity and solar energy operate the same in the Great Salt Basin as they do in the Susquehanna Basin, but the hydrologic conditions in those two basins are very different.

We may thus partition hydrologic science into:

- *Hydrologic process science* – the description of water flow, transport and transformation processes by principles and equations, using simulation models for process integration and hydrologic prediction;
- *Hydrologic information science* – the description of hydrologic environments by observations, using data models for information integration and hydrologic visualization.

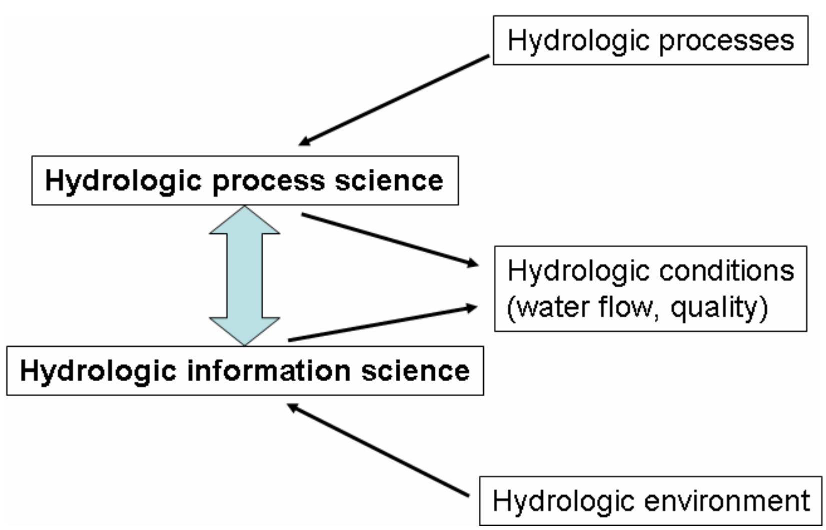

Figure 1. Hydrologic process and information sciences

It is inherent in the concept of a dynamic earth that simulation models will describe the dynamism of external driving forces, such as the climate or geologic systems. It is the output of such simulation models that is then used to establish the boundary and interior state conditions for simulation of the hydrologic system. For example, the North American Regional Reanalysis of climate presents a 3 hour time step, 32 km spatial grid of surface climate conditions simulated from 1972 onwards using the National Centers for Environmental Prediction's numerical weather forecasting model applied in a reanalysis mode (using past weather observations with a current climate model). http://wwwt.emc.ncep.noaa.gov/mmb/rreanl/ The surface evaporation field computed in this reanalysis is probably the most extensive dynamic map of evaporation over North America that presently exists. It can be used as a boundary condition for groundwater recharge estimates for aquifers and other purposes. In this context, shared data models between hydrology and the atmospheric science are needed to integrate the continuous fluid domain type of representation typical in the atmospheric sciences with the discrete space objects (watersheds, aquifer boundaries) more typical of hydrology.

Space and Time Coordinate Systems

When considering hydrology in a dynamic earth, the combination of many scales of space and time is involved. This involves some obvious things, such as that geology evolves over geologic time scales that are very different than current time measurement, and some subtle factors about the shape of the earth that are sometimes overlooked but can become important. A geotemporal reference frame is a combination of a geospatial coordinate system for describing the locations of things on earth, and a time coordinate system for indexing change through time. At least four geotemporal reference frames are involved, as shown in Table 1: atmospheric, hydrologic, anthropogenic, and geologic. Indeed the circle closes back on itself, because geologic change is associated with long term climate change, and thus changes in the atmosphere can be measured in geologic time as well as current time coordinates. In this context, anthropogenic change is change in land use and land cover, urbanization, and other impacts of human activity on the land surface.

	Geospatial Coordinates	**Time Coordinates**
Atmospheric	Latitude, Longitude, Elevation (ϕ, λ, z)	Universal time (UTC): hours, days
Hydrologic	Easting, Northing, Elevation (x, y, z)	Local time (e.g. Eastern Time): hours, days, years
Anthropogenic	Easting, Northing, Elevation (x, y, z)	Years, decades
Geologic	Latitude, Longitude, Elevation (ϕ, λ, z)	Geologic time (millions of years before present)

Table 1. Space and time coordinate systems for measuring various forms of change.

Two kinds of geospatial coordinates are shown in Table 1, "Geographic" coordinates are defined by latitude, longitude and elevation, typically symbolized as (ϕ, λ, z), where latitude (ϕ) and longitude (λ) are measured in degrees, minutes and seconds, or decimal degrees, and elevation (z) is measured in meters or feet above mean sea level. "Projected" or Cartesian coordinates are defined by Easting (x), Northing (y), and elevation (z), where elevation has the same meaning as in the geographic coordinate system, while Easting and Northing refer to the distances in meters or feet to the east and north of a coordinate origin point. Cartesian coordinates are needed to apply physical laws appropriately, such as the relationship between water velocity and water surface slope. It makes no sense to be defining slope if the horizontal coordinates are in degrees and the vertical coordinates are in meters.

Although not often recognized there is a distinction between geographic coordinates defined on a *spherical* earth and a *spheroidal* earth. The earth is truly spheroidal but in climate modeling it is usually assumed to be spherical because the equations of motion that are solved in atmospheric models are described in a spherical coordinate system. Correct placement of the locations of cells of an atmospheric model (or a Nexrad rainfall grid) on the earth's surface requires careful consideration of these distinctions, which affect latitude but not longitude.

Time coordinate systems are also important. Atmospheric modeling and also remote sensing is done in Coordinated Universal Time (UTC) which is essentially equivalent to Greenwich Mean Time. Hydrologic modeling and observation is done in local time coordinates, such as Eastern Time or Central Time. Local time can itself change as daylight saving is invoked or not during the year. Hydrologic models may exist in their own geotemporal reference frame, such as Modflow cells (layer, row, column) and Modflow time (measured in stress periods), and to make their results meaningful in a larger context these data have to be georeferenced against a standard geotemporal reference frame.

Conclusion

It is interesting to consider a theme of hydrologic change in the context of hydrology in a dynamic earth, where change is taking place on many time scales, and even long-term processes like geological evolution and soil weathering may themselves be simulated through geologic time as are hydrologic processes on a shorter time scale. This approach requires separating the changes external to hydrology (e.g. geologic, anthropogenic, climatic) from the changes internal to hydrology (changes in flow paths, runoff patterns, water chemistry). Hydrologic information science establishes the context of description of the hydrologic environment and hydrologic conditions, to support hydrologic process science, which is illuminating the changes in hydrologic processes occurring in that environment.

References

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