A framework for interdisciplinary watershed research

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Introduction

The purpose of this paper is to propose an approach to scaling problems associated with watershed modeling in the context of the proposed CUASHI Hydrologic Observatories. The Hydrologic Observatory (HO) concept calls for creation of a set of well-instrumented watersheds with a research infrastructure maintained by a specified organization, but used by multiple researchers including but not limited to those associated with the managing organization. These HO's will be much larger than previous experimental catchments, on the order of 10,000 km^2, so only limited portions of the watershed can be intensively instrumented. These intensively instrumented study areas will provide the smaller-scale data that will have to be coupled with larger scale data in the watershed model. Since these HO's represent a considerable investment of resources, it is prudent to consider scale issues before implementation of the program.

Watershed models are inherently multidisciplinary in nature integrating physical, chemical and biological processes. Fundamental physical processes such as rainfall, evaporation, transpiration, infiltration, surface water and ground water flow and connectivity are all linked by complex interactions. These basic processes act on a heterogeneous medium consisting of soil, streambed and aquifer material that have complex associations of flora and fauna that vary with time. Thus, a watershed model must eventually incorporate all of these processes and factors in a time-dependent model. The successful watershed model of the future will have to address relevant societal issues such as surface discharge rates, vulnerability and contaminant transport, and sustainability of water resources both within the watershed and of exports to downstream watersheds over a broad of time scales (Johnes, 1996; Meissner et al. 1998; Karvonenet al. 1999; Kaleris et al. 2001; Koutsoyiannis, 2003; Mueller et al. 2003; Amore et al. 2004; Buck et al. 2004; Canham et al. 2004; Collares-Pereira and Cowx, 2004; Cvetkovic et al. 2004; Hyatt et al. 2004; Kokkonen et al. 2004; Mann et al. 2004; Molinero and Samper. 2004; Ophori, 2004; Parker and Park, 2004; Unger et al. 2004, Yuan and Norton, 2004).

There are two fundamental approaches to modeling watersheds; physically-based models with rigorous mass and energy constraints or conceptual models with empirically-calibrated lumped parameters that enable prediction, but often lack the ability to evaluate fundamental relationships and extend our understanding. The physically-based models require either scaled values for parameters or impossibly complex numerical models to properly represent natural heterogeneity. In conceptual modeling, the selection important factors is not constrained by fundamental considerations and instead may chose formulations that initially incorporate only dominant processes (Blöschl, 2001), and then move to increasing complex models that better represent the actual physical processes, the downward approach to modeling (Jothutyangkoon et al .2001; Sivipalan et al. 2003). These empirical models sometimes incorporate stochastic formulations in order to try and include natural variability of parameters, but all are purpose-driven, and generally narrow in scope (Landman et al. 2001; Bakr et al. 2003, Lingren et al, 2004).

Scaling for the Watershed

Scaling issues in hydrology have been intensively studied for the last twenty or so years, but the central issue is one familiar to all hydrologic researchers since our observations are generally made at spatial and temporal scales much smaller than the watershed and long-term climatic predictions. So the fundamental question, the effect of scale when trying to determine the mathematical formulations for watershed models remains an issue (Wade et al. 1999; Vermulst and de Lange. 1999; Bloschl, 2001; Neuman and Federico, 2003; Hallet et al. 2004; Quinn, 2004; Sivipalan et al. 2004; Tsuyuzaki et al. 2004; Uddameri, 2004). For instance, we know that rainfall and stream flow are linked. However, if the goal is developing a model for seasonal flooding prediction and that model is based on rainfall measurements made at intervals of hours to days at point sources across a watershed, then the scale of prediction (the response of the whole watershed) is very different from the scale of measurements. For very small catchments (<1.0 km^2), the instantaneous unit hydrograph (IUH) can be directly related to the rainfall event magnitude, however if event data is applied to catchments several orders of magnitude larger (10 to 1000 km^2), no systematic relationship is found (Kokkonen et al. 2004). While we may have an intuitive understanding that we do not expect an isolated rainfall event to have an immediate effect on stream hydrographs at the larger scale, we still need to develop conceptual models to relate observations to responses for multiple scales.

The nature of this problem can also be considered in the context of a fundamental process present in any watershed, the flow of water through porous media. Soils and aquifer material are heterogeneous in nature on scales ranging from microscopic to macroscopic (Vogel and Roth, 2003). Flow and transport of solutes through a porous medium depends in part on hydraulic conductivity, however, values of this fundamental parameter change with the scale of measurement (Gomez-Hernandez and Gorelick, 1989, Desbarats and Bachu, 1994). The same phenomenon is observed for dispersivity where values increase with the scale of measurement (Gelhar, 1986, Neuman, 1990; Nelson et al. 2003). These observations, that fundamental flow and transport parameters vary according to scale, requires that application of the flow equations such as Richard's and Darcy's Laws incorporate such variability in watershed models (Tennekoon et al. 2003).

Methods

If our predictive watershed are limited because of data from different scales, then the obvious solution
is for all the parameters in the model have the same scale, or at least at scales as similar as possible. Approaches to deal with the scale problem have focused on upscaling and downscaling, a.k.a. aggregation and disaggregation, (Schaake and Valencia, 1972; Mejia and Rousselle, 1976; Todini, 1980; Wood et al. 1988; Santos and Salas, 1992; Steward et al 1996; Tarboton et al. 1998; Wood, 1998; Western and Blöeschl, 1999; Bindlish and Barros, 2000; Mueller et al. 2000; Muller-Wohfeil

et al. 2000; Nagesh et al. 2000; Bui and Moran, 2001; Sivikumar et al. 2001; Pellenq et al. 2003; Lock et al. 2004; Luce and Tarboton, 2004; Uhlenbrook et al.2004; Viney and Sivipalan, 2004), or using characteristic scales (Skøien et al, 2003).

Downscaling (disaggregation) techniques have been developed to deal with linking large-scale datasets such as those from remote sensing and atmospheric circulation models (300-500 km scale) to point-scale rainfall events, stream flow and soil properties (Schaake and Valencia, 1972; Venugopal and Foufoula-Georgiou. 1996; Zorita and von Storch, 1997; Tarboton et al. 1998; de Bruinet al. 1999; Sauerborn et al. 1999; Deidda, 2000; Mueller et al. 2000; Yarnal et al. 2000; Koutsoyiannis and Onof, 2001; Reichle et al. 2001; Sivakumar et al. 2001; Stehlik and Bardossy, 2002; Koutsoyiannis et al. 2003; Charles et al. 2004). The process generally involves some form of statistical technique that relates the large-scale parameter such as relative humidity to the point parameter such as rainfall or soil moisture (Ferraris, et al. 2003; Pellenq et al. 2003; Charles et al. 2004). The challenge is to correctly represent the natural variability as large-scale data is scaled downward to smaller time and spatial distributions (Mejia and Rousselle, 1976; Lin, 1990; Gyasi-Agyei, 1999; Wilby et al. 1999; Nagesh et al. 2000; Cannon and Whitfield, 2002; Katz et al. 2002; Andreasson, 2003). This approach cannot substitute for physically-based models, but can resolve variability to smaller scales than present physical models allow (Ferraris et al. 2003).

Upscaling (aggregation) is used when trying to apply small-scale data from experimental or site-scale relationships of fundamental processes such as dispersion or adsorption to the larger scale of a watershed model. One approach is to design the model to incorporate the spatial heterogeneity of the watershed into grid blocks such as Hydrologic Response Units (HRU) or hydrotopes (Becker and Braun, 1999; Viney and Sivipalan, 2004), that have single values for model parameters based on point scale measurements that are scaled up (Zhang et al. 2004). For instance, aggregation is required when point measurements such as rain gage and stream gage data or hydraulic conductivity, typical in hydrology, is distributed over larger areas that represent grid blocks in models (Beven et al. 1996; Kavvas, 1999; Feteke et al. 2001; Wooldridge and Kalma, 2001; Wooldrige et al. 2002; Niedda, 2004). Often the assumption in upscaling is that the projection of values to a larger scale is linear in nature or stochastic methods will correctly approximately natural variability (Njoku et al. 1996; Kabat et al.1997; Öhman and Niemi, 2003; Guadagnini and Winter. 2004; Ungeret al. 2004). This process results in loss of detail, and more critically, may produce erroneous relationships when the process is non-linear, often the case in hydrology (Puente, 1996; Blöschl, 1999; Oldak et al. 2002; Guntner and Bronstert, 2004; Ivanov et al. 2004; Viney and Sivipalan, 2004).

The aggregative approach requires that we identify the correct values for important parameters and incorporate the type of dependency of parameters on scale (Chappell et al. 1998; Vrugt et al. 2004). Figure 1 shows several possible types of relationships between a property, such as hydraulic conductivity and the scale of observation proposed by Cushman (1990). We can see that depending on the scale of the model grid (cell), we may have to use different mathematical formulations to represent the parameter of interest in the watershed such as macroscopic homogeneity, discrete hierarchy, continuous hierarchy, and fractal depending on the grid scale.

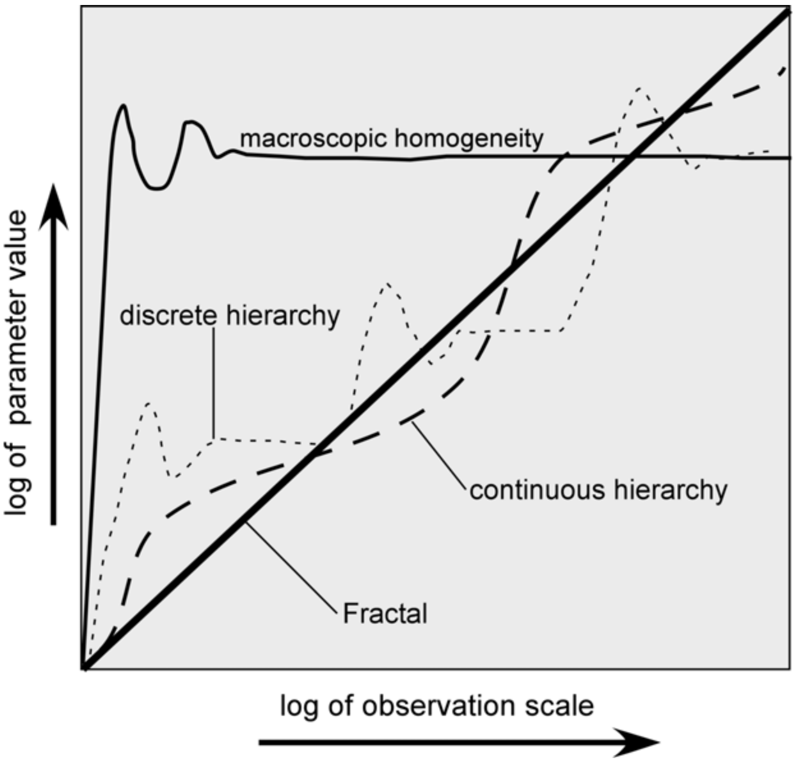

Figure 1. Different relationships between observation scale and parameter values. Modified from Vogel and Roth, 2003.

An alternative or combination is the disaggregation-aggregation approach that tries to downscale catchment-scale variables to point-scale, applies physical models to the downscaled data and upscales the point-scale responses back to catchment scale (Becker and Braun, 1999; Wheater et al.1999; Viney and Sivipalan, 2004). This approach tries to implicitly incorporate point-scale physical processes into the larger-scale conceptual models.

Fractal (scale-invariant) relationships have been evaluated for some hydrologic processes, but other important processes do not show factual scaling (Gupta and Waymire, 1989; Agnese 1996; Gupta et al. 1996; Moussa and Bocquillon, 1996; Muller, 1996; Olsson and Niemczynowicz, 1996; Roth et al. 1996; Tarboton, 1996; Olsson and Nieczynowicz, 1996; Veltri et al. 1996; Venugopal and Foufoula-Georgiou, 1996; Millan and et. 2003; Neuman and Federico. 2003; Pardini, 2003; Castle et al. 2004; Zhang and Schilling, 2004). While the fractal approach is attractive, it is unlikely that all the processes involved in a watershed are fractal in nature (Alder, 1996; Claps et al. 1996; Kirchner et al. 2001; Lingren et al. 2004). The HO facilities could help accumulate the temporal and spatial data to test the fractal nature of many watershed processes.

These efforts have produced progress in resolving specific problems, but as yet no single method has been successful for the variety of processes that act on the watershed scale. Recently, Blöschl (2001) noted the trend toward fragmentation in hydrological subdisciplines as each group focuses on scale problems within their field. He suggests that a change in this paradigm may be more productive. In this spirit, we suggest considering a framework for integrated multidisciplinary analysis (FIMA) in HO's based on:

1 – use of an earth system approach that facilitates integration of multidisciplinary data in a single model (e.g. hydrologic, biological, ecological and geomorphologic),
2 - GIS will be a fundamental tool for constructing future watershed models,
3 – the assumption that investigators will be provided core data for any HO (the actual core data has yet to be defined),
4 – hydrologists typically make and will continue to make point to small catchment scale measurements that must be up-scaled to model grids,
5 – the scale of measurements in watersheds is limited to existing or emerging technologies,
6 - model grids will remain coarser than measurement scales,
7 – the likelihood that both empirical and fundamental approaches will continue to be used to formulate models,
8 – the methodology must be able to relate the present smaller research sites to the much larger HO's, essentially the distributed approach,
9 – the methodology should try and minimize the degree of scaling (up or down).

Methods

We begin with the assumption that GIS is clearly the best available tool for organizing and processing data for watershed models (McNulty et al. 1997;Thieken et al. 1999; Vermulst and De Lange, 1999; Lachassagne et al. 2001; Schreier and Brown, 2001; Renschler, 2003; Vanderpoorten et al. 2005). A GIS stores spatial data, determines model parameters, provides scale-independent visualizations, and allows analysis and combination of maps from various scales (Thieken et al. 1999). GIS-based approaches also facilitate evaluations of the effects of data aggregation. GIS coverages of core data should be provided to investigators that will conduct research in the HO's to maximize productivity.

The first step was to consider what common data will be required for our hypothetical watershed model and to evaluate how much of the required data is actually available at the similar scales. We confine ourselves to the spatial data to simplify the evaluation, but note that the link between temporal and spatial dimensions may not be separable (Kandel et al. 2004). This approach produces the hydrologic framework for the watershed model where the spatial "core data" scale becomes the fundamental unit to which other spatial data or observations are scaled using approaches such as 'the scaleway' proposed by Vogel and Roth (2003). Using such an approach also provides a guide for researchers from other disciplines to ensure their observations can either be made at a similar scale, or the available methodologies for scaling can be evaluated prior to observation to facilitate integration (Schreier and Brown, 2001).

We considered the question of which factors are required to formulate our watershed model. For our hypothetical model, we wish to describe the discharge rate and water quality of surface water from a watershed. In our case, we began with the assumption that the geomorphology has a fundamental relationship with on a variety of watershed properties including surface water discharge, groundwater gradient, microclimate, and water quality (Wade et al. 1999; Cammeraat, 2002; Hennrich and Crozier, 2004; White et al. 2004; Xu et al. 2004; Yair and Raz-Yassif, 2004). Geomorphologic data is available at a variety of scales, but the most widely available dataset is probably the Digital Elevation Model (DEM), with spatial resolutions of 30 meters allowing fairly detailed resolution in the model. We acknowledge that there are studies that show there is an effect of the spatial resolution of base data such as topography or soil type on measured watershed response such as surface discharge (Thieken et al. 1999; Zhu and Mackay, 2001; Ibbitt and Woods, 2004; Niedda, 2004), but note no ideal scale has been identified as yet.

This aggregative approach can produce models with large numbers of elements that may be computationally challenging, but 30-meter gridding produces approximately 11 million cells for a typical HO, which is tractable given probable increases in microprocessor speeds. The 30-meter grid spacing is also tractable for data from other disciplines that should be included in the model. For instance, pump tests from wells used to characterize the hydraulic conductivity could be formulated to test a 30 m radius of influence. Multiple sample sites for chemical contaminants and tracers in ground and surface water (Xiahong et al. 2004) and soil samples are common at environmental sites at this scale, as is often the case for ecological and biological studies.

Next the spatial resolutions of other "core" data were evaluated and are listed in Table 1 (the choice of what data is "fundamental" to the watershed model may vary for different investigators) to see if the scales were similar. The data we considered to be essential includes soil type, precipitation, vegetation, land use, surface water locations, geology and temperature. Many of these data are available at the same or very similar scales. This approach would then dictate that the model have a 30-meter grid of the core elements consisting of topography/elevation, vegetation, surface water location, stream temperature, precipitation (NEXRAD), surface temperature, geology, land use, and soil properties (STATSCO/SSURGO). Note that data such as precipitation may have more than one source (rain gages versus NEXRAD) and we chose the source with a scale closest to the other core data. This allows the difference in scales between various parameters to be minimized, which reduces potential scaling issues .

Then we begin to evaluate additional desired parameters that we consider to be important or even "core" for our model (see Table 2). Some of this data could be derived from local, State and Federal agencies that have permitting and monitoring data related to environmental compliance for numerous types of industrial and public facilities (landfills, military bases, petroleum production facility, chemical facilities, etc.). In addition, there may be EPA superfund sites or private sector studies of contaminated sites in the watershed that would provide useful data.

Discussion

1) Scientific questions or examples our paradigm (uniquely?) addresses
    a) integrating biota – ecohydrology approach
        i) groundwater/surface water interactions
            (1) can you characterize the watershed, e.g., GW/SW interactions by knowing vegetation type, density, etc.
        ii) can we monitor stability of the ecosystem due to anthropogenic perturbations of hydrology?
    b) modeling of pollutant transport
        i) Nutrient transport (e.g., nitrogen or nitrate, phosphorus)
        ii) Pharmaceuticals or emerging contaminants
        iii) Pathogens
        iv) Natural attenuation
    c) Sustainability
        i) imbalance between supply and demand
        ii) climate change
        iii) increasing urbanization
    d) example from Kathleen

2) Implementation using examples
    a) Currently available data
    b) Needed data

3) Future

The HO facilities could help accumulate the temporal and spatial data to test the various types of watershed models. It would be especially productive to adopt a modular architecture to facilitate collaboration (Leavesley et al. 2002).

- i) If data not readily available at core data scale, this could serve as impetus to develop new methods or approaches
- ii) New theories and/or approaches may be necessary
    - (1) Prior examples such as ET

Table 1 – Available Core Data

	Data Source	Resolution
Precipitation	**Nexrad**	
Elevation	**DEM**	**10-30 m**
Soil	**STATSGO/SSURGO**	**30 m30 m**
Vegetation	**Landsat**	**30 m**
Land use	**NLCD (?)**	
Surface water locations	**NWIS**	**10-30 m**
Surface temperature	**RS radiometer at 30 m (?)**	
Geology	**Geological surveys**	**1:24,000**

Table 2 – Measured/Interpolated/Estimated Core Data

	Data Source	
Streamflow		
Groundwater level		
Water quality		
ET		
Imports and diversions		
Point source discharge	**EPA database**	
Soil moisture		
Wind		
Solar radiation		
Humidity		
Hydraulic conductivity		
Porosity		

Table 3 – Hydrology Data

Table 4 – Example (Pharmaceutical Transport)

Processes	**Available Data at 30m**	**Needed Data**		
Sorption				
Biodegradation				
Phys. degradation				
Source strength				

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