Changes in Correlation Coefficients with Spatial Scale and Implications for Water Resources and Vulnerability Data

Shama Perveen
Columbia University

L. Allan James
University of South Carolina

Previous studies of correlation coefficients between paired observations using census, hydrologic, and remote sensing data abound. It is well established that bivariate relationships at coarser spatial resolutions are often stronger than at finer resolutions. No assessment as yet, however, corroborates this tendency with water resources variables. In this study, multiscale correlations between water use or water availability and population are presented in three river basins—the Missouri (United States), Danube (Europe), and Ganges (South Asia). High-resolution gridded data sets were obtained at 0.5° and resampled to fourteen different geographic scales to examine the effects of scale on the strength and trends of correlations. Correlation coefficients between most variable pairs increased at coarser scales. Smoothing fine-scale spatial patterns in the data at coarser scales is posited as a possible explanation. The increase was not often linear, however, nor was there always an increase. The Missouri Basin did not show a significant increase in correlations between water use and population with grid-cell size and nonlinear increases are evident in the Ganges Basin. **Key Words: correlation, geospatial, multiscale, river basin, water resources.**

以往对数据对之间的相关系数的研究，使用普查，水文，和遥感的数据比比皆是。众所周知，在更粗糙空间分辨率中的二元关系往往比在更细的分辨率中要更强。然而，还没有研究使用水资源的变量来评估证实这一趋势。在这项研究中，水的使用或水的供应和人口之间的多尺度相关性，在三大江河流域，即密苏里河（美国），多瑙河（欧洲），和恒河（南亚），被呈现出来。我们获取了0.5度高分辨率的栅格数据集，并把它们重采样为14个不同的地理尺度，以研究尺度对相关性的强度和趋势的影响。大多数变量对之间的相关系数随更粗糙的尺度而增加。数据在较粗尺度中平滑精细的空间格局可作为一种可能的解释。但是，此种增加通常既不是线性的，也不是总有的。密苏里河流域里水的使用和人口之间的相关性，并没有随栅格尺寸变化而显著增加，而在恒河流域，非线性增加很明显。关键词：相关性，地理空间，多尺度，流域，水资源。

Son abundantes los estudios anteriores sobre coeficientes de correlación entre observaciones pareadas que utilizan datos censales, hidrológicos y de percepción remota. Está bien establecido que las relaciones bivariadas a resoluciones espaciales gruesas son a menudo más fuertes que a resoluciones más finas. Sin embargo, hasta ahora ninguna evaluación corrobora esta tendencia con las variables de los recursos hídricos. En este estudio, se presentan las correlaciones de multiescala entre el uso del agua o su disponibilidad y la población, en tres cuencas fluviales—las del Missouri (Estados Unidos), Danubio (Europa) y Ganges (Asia Meridional). Se obtuvieron conjuntos de datos cuadriculados de alta resolución a 0.5° en muestras retomadas en catorce diferentes escalas geográficas para examinar los efectos de la escala sobre la fuerza y tendencias de las correlaciones. Los coeficientes de correlación entre la mayoría de los pares variables aumentaron a escalas más gruesas. Como posible explicación se presenta la suavización de patrones espaciales a escala fina en los datos a escalas más gruesas. No obstante, a menudo el incremento no fue linear, ni siempre se presentó aumento. La Cuenca del Missouri no mostró un incremento significativo en las correlaciones entre el uso del agua y la población con el tamaño de las celdas de la cuadrícula, y los incrementos no lineares son evidentes en la Cuenca del Ganges. **Palabras clave: correlación, geoespacial, multiescala, cuenca fluvial, recursos hídricos.**

The Professional Geographer, 64(X) 2012, pages 1–12 © Copyright 2012 by Association of American Geographers.
Initial submission, February 2010; revised submission, November 2010; final acceptance, February 2011.
Published by Taylor & Francis Group, LLC.

Scale—as an artificial construct to represent reality—is one of the most potent tools available to scientists for understanding geographic interrelationships and processes. Geographers have long been aware of the sensitivity of spatial data to scales of measurement and the utility of multiscale approach to description (Stone 1972). Availability of analytical and visualization tools like geographic information systems (GIS) and enhanced computing power (Atkinson and Tate 2000) has led to a focus on scale issues and concern with the nature of spatial variability. Lam and Quattrochi (1992) and Quattrochi and Goodchild (1997) provided useful overviews of how questions of scale are being addressed in physical geography, GIS, remote sensing, and statistical analysis. Geographers have published extensively on this subject (Arbia 1989), as have landscape ecologists (Turner, Dale, and Gardner 1989; Legendre 1993), geomorphologists (C. D. Clark 1990), hydrologists (Blöschl and Sivapalan 1995), and climatologists (Raupach and Finnigan 1995).

The most significant contributions to the scale problem achieved in these fields have been through the use and improvement of distributed physical models at different spatial and temporal scales. These models enable the testing of hypotheses about the dominance of physical parameters at specific scales and their linkages across scales through various upscaling and downscaling strategies (Marceau 1999), but scale affects the way we collapse and aggregate the data to make it workable and relevant to the problem at hand. Distinctive systems embedded in global change processes operate at different geographic scales. Studies restricted to a local scale can miss global interactions, just as studies at a global scale might miss local relationships (Kates, Wilbanks, and Abler 2003).

Scale affects the very process by which we extract measures of variation and correlation, enabling us to make sense of the phenomena in question and to recover theory from noise that inevitably confounds observation (Atkinson and Tate 2001). Yet, studies using areal data do not distinguish between spatial associations created by the aggregation of data and real associations inherent to the data prior to spatial aggregation (Openshaw 1984). Statistics or models that were derived at a particular scale might be valid at that scale, but attempts to infer these relationships at higher or lower resolution of the data could produce invalid results (Perveen and James 2009, 2010). The statistics and model parameters might differ systematically with the level of resolution, and the present state of knowledge limits predictions about behavior at various scales (Dark and Bram 2007).

In most areas of the social sciences, properties of areas are scaled up from data on individuals or smaller subareas (including point locations) by the arithmetic operation of averaging—implicitly assuming additivity. So with aggregations from one scale to another, an implicit assumption can be made that the spatial process, as captured by two different scales, is comparable (Amrhein and Reynolds 1996). This seems to be the consequence of the nature of area-level concepts in social sciences that allow analysts to adopt any reasonable operational convention. In environmental sciences, a similar change of scale problem arises in change of data format problems where data measured from one format (e.g., point samples) are converted to another (e.g., small area or block) through weighted averaging. Not all change of scale problems in social or environmental sciences are linear and can be handled in this way (Haining 2003).

Although problems of aggregation error and inference across scales have been recognized for decades, little is known of the details and no attention has been paid to the issue of aggregation and scaling in water resources research. Existing global river basin data sets, for instance, are relatively coarse grained, which has limited the ability to move between the different scales of analysis. In recent decades, the development of gridded macroscale hydrologic models has made it possible to estimate the spatial variability in resources over large areas—at a spatial resolution finer than can be provided by observed data alone. This study quantitatively examines scaling effects and trends, especially the trends in correlation between population and water resources (availability and demands) with scale. Multiscale analyses using ArcGIS 9.3 and statistical tools are presented for three river basins globally—Danube (Europe), Missouri (United States), and Ganges (South Asia). The impact of scale on correlations between common water resource variables and population within large river basins is demonstrated.

Many studies on scale effects exist, most of which are based on changing the scale of model parameters and examining the effects on model output, so the effects of scale are integrated with a complex series of processes within the model. In this study, a single data set is resampled at varying scales to account for the effect of scale as the sole factor governing the changes observed. As is evident from the results, this study shows that the correlation between two variables depends on the scale at which the variables are studied. In particular, as fine grid cells are resampled to coarser cell sizes, a stronger correlation between variables results. This implies that if gridded data are aggregated from finer to coarser scales, the larger grid cells might not be as sensitive to clusters of population, topographic features, or other regularly spaced phenomena as the finer scaled grid cells. Thus, the behavior of correlation coefficients with scale might be diagnostic of intrinsic spatial patterns and should be considered in analyses.

Conventionally, population has grown around available water sources. Consequently, consumption of water (demand) is higher at population centers. The nature of these relationships, however, might vary with the socioeconomic condition, topography, and climate of the region. The variability in these factors could vary from country to country or even from one part of a large river basin to another (Zeid and Biswas 1992). Regions with high population growth, for instance, might be under severe water stress due to high consumption. Conversely, some regions with low population growth might also be under high stress due to no ready availability of water. These local spatial patterns could get lost as data sets are aggregated at the scale of river basins and might obscure local areas with conditions of extreme shortage. Because demand or supply measures to ameliorate water stress or scarcity in a region depend on the underlying reasons for stress (Perveen and James 2009), the calculations at a broad scale might not represent the true risk of water shortages at a more local scale. This lack of representation has tremendous bearing in studies of water resources vulnerability. Within a river basin, a fine-scale assessment as described in this article can enable one to assess the patterns of water consumption; that is, where demands for water meet or exceed the supply. One can then assess how much that relationship changes with changing scale and the scale (thresholds) at which scaling relations change. In other words, how much does data aggregation (to coarser scales) filter out the spatial patterns existing at fine scales of analysis? These assessments can consequently be useful for formulating water management and ameliorative policy measures targeted locally rather than for the basin as a whole.

In addition to the considerations of scale discussed here, this study is timely for several reasons. First, multiscale correlations between water resources and population variables within a river basin have not been previously examined in a systematic, controlled manner. Second, and perhaps most important, the water resources variables examined here are key metrics of vulnerability to water stress and scarcity. These variables are commonly reported at a variety of scales to explore the potential effects of global change and climate change on society, including downscaling global-scale changes to local systems. Yet, failure to critically evaluate the behavior of these metrics at various scales leaves open the strong possibility that such comparisons across scales are misleading. Third, new geospatial analytical methods now facilitate the simulation of data sets at multiple scales and examination of scaling trends. Questions of scaling phenomena that have been raised for decades can now be simulated and tested in a small fraction of the time previously required. Finally, the availability of new high-resolution geospatial data sets provides an empirical basis for study—allowing for visualization of differences, generation and comparison of statistics, and estimation of models across multiple scales of interest. Together, these factors should permit the development of new theoretical understandings and mathematical procedures to compensate for scale effects in water resources.

Complexity of Natural Systems Requires Multiscale Assessments

Almost four decades ago, Stone (1972) signaled the importance of multiscale analyses for studies on integrated environmental assessments by suggesting that a geographic study cannot be complete without a multiple-scale approach. Subsequent studies have highlighted the fact that, given the complexity of natural systems, multiscale evaluations are imperative (Hay et al. 2001). For instance, the advantages of scaling are immeasurable in addressing a wide range of ecological and environmental problems concerning biodiversity loss and global change. The incentives were reiterated recently through the landmark Millennium Ecosystems Assessment (MEA 2005) conducted globally from 2001 to 2005. Represented by more than 1,360 natural scientists and experts, the MEA consisted of a subglobal appraisal group dedicated especially to multiscale assessments of the environment.

The variability in statistical results originating from the use of different scales or aggregation levels was first demonstrated by Gehlke and Biehl (1934). Using census data, they found that the correlation between two variables tended to increase as districts formed from census tracts increased in size. Later, correlation coefficients were shown to vary greatly according to the number and size of areal units used to describe the phenomenon under investigation (Yule and Kendall 1950; McCarthy, Hook, and Knos 1956; Marceau 1999). All of these earlier studies concluded that correlation coefficients only measure the relationship between variables for specified units (scale) chosen for study and that they have no validity independent of these units.

To describe the error resulting from statistical inferences about individual relationships made from aggregated data, Robinson (1950) introduced the term *ecological fallacy*. He examined the correlation between the percentage of native-born population and percentage of illiteracy and found a positive correlation at the individual level (0.118) but a negative correlation at the census division level (–0.619). Later, Openshaw and Taylor (1979) coined a related term—the *Modifiable Areal Unit Problem* (MAUP)—emphasizing the effects of scale and data aggregation as well as zoning or grouping of basic units. They constructed all possible groupings of the ninety-nine counties in Iowa into larger districts and noted that a large number of correlation coefficients were possible between the percentage of elderly and percentage of Republican voters.

Previous literature suggests that statistical correlations between variables collected geographically increase at coarser spatial scales (Robinson 1950; Blalock 1964; W. A. V. Clark and Avery 1976). One plausible explanation for the observed increases in correlation coefficients with scale could be the reduced variability that results from smoothing or filtering associated with the aggregation of spatial data (Jelinski and Wu 1996). For example, heterogeneity is reduced as spatial aggregation drives mean grid-cell values toward a modal value. The effects of such changes on traditional statistical analyses (e.g., correlation analysis or linear regression) are relatively well understood (Fotheringham and Wong 1991). In fact, the observed increase in correlation at coarser scales led to the formulation of the second law of geography (Arbia, Benedetti, and Espa 1996, 124): "Everything is related to everything else but things observed at a coarser spatial resolution are more related than things observed at a finer resolution." As it follows, with each subsequent aggregation of data sets, a generalization is introduced and values within the data set tend to become more strongly correlated due to smoothing and averaging.

Insufficient details exist, however, as to how correlations can increase with scale, especially using the variables in water resources and vulnerability analyses. Premised on the assumptions of increasing correlations at coarser scales from these earlier studies, this study conducted a hypothesis test using common water resources and vulnerability variables. Hypothesis testing was conducted by setting up null hypotheses that no significant differences exist in correlation coefficients (in the two variable pairs—population with water availability and population with water use) with scale (Table 1). Hypothesis testing was based on the slopes (ß) of two univariate regressions with population with water availability (PWA) and population with water use (PWU) as dependent variables and scale as the independent variable, where PWA is the correlation coefficient between population and water availability and PWU is the correlation coefficient between population and water use at multiple scales. The tests were conducted at $\alpha = 0.05$ as one-tailed t tests, as the test assumes that ß increases as grid-cell size becomes coarser.

As discussed earlier, how populations evolve around water sources (i.e., availability) and consequently affect the supply through their demands (i.e., water use) have important bearings

Table 1 *Two hypotheses (H_1 and H_2) for increasing correlations with grid-cell size (scale)*

Hypotheses	**Correlation between water resources variables increases with scale in all three basins**	
H_1	H_1: $ß_{PWA} > 0$	H_{o1}: $ß_{PWA} \leq 0$
H_2	H_2: $ß_{PWU} > 0$	H_{o2}: $ß_{PWU} \leq 0$

on water vulnerability calculations. Therefore, an understanding of how these variable pairs are correlated at various scales (i.e., trend) within a given region has important implications. Based on the results of the hypothesis testing, the geographic characteristics of basins with trends are compared to those without trends to explore potential explanations for anomalous behavior in covariance with scale. Linear increases are often assumed with little empirical validation of such trends. Whereas in spatially homogeneous systems, scale problems might not exist because process measurements can be summed directly, scaling complexities tend to arise in heterogeneous landscapes or aquatic systems, where averaging of process measurements obtained at fine scales might not produce accurate regional estimates. Weighted averages in such cases do not always produce reasonable measures (King, DeAngelis, and Post 1988) because heterogeneity might influence processes in a nonlinear manner. This suggests that increasing the level of spatial heterogeneity might also increase the difficulty of extrapolating information across scales (Turner, Dale, and Gardner 1989). In this context, a consensus now exists among scientists that multiscale experiments, in which spatial or temporal scale is an independent variable, are crucial for understanding the nature of scaling (Turner, Dale, and Gardner 1989).

Objectives and Methods

The overall objective of this study is to empirically document the effects of data aggregation (scale) on statistical correlations between water resources variables and population and to explore explanations and implications of the results. The specific objectives of this study are threefold:

1. Calculate bivariate correlation coefficients between the two variable pairs—PWA and PWU—at multiple scales within three selected river basins.
2. Test for trends (hypothesis tests) in correlation coefficients between the two variable pairs for the entire range of scales.
3. Compare the geographic characteristics of basins with trends to those without trends to explore potential explanations for anomalous behavior in covariance with scale.

Two high-resolution modeled outputs for water resources and population were used: WaterGAP 2.1f (Döll, Kaspar, and Alcamo 1999; Alcamo et al. 2003) and Landscan (ORNL LandScan 2005). Gridded water resources and population data were used to calculate correlations among variables with subsequent aggregations. Because gridded data have similar areal units, much less information is lost during the aggregation procedure (Crawford and Young 2004). In the context of this study, *scale* is analogous to the spatial resolution or grid-cell size of the observations, and these terms will be used synonymously in this study. Similarly, *fine* and *coarse* will be used in conjunction with scale to represent the spatial extent of individual data elements; for example, the size of grid cells or other structural elements.

The WaterGAP model provides fine-scale (0.5°) gridded global water availability and water use data. Developed by the Centre for Environmental Systems Research at the University of Kassel in Germany, the model consists of two main components: a global hydrology and a global water use model. The global hydrology model computes runoff and discharge at each grid cell by calculating the daily water balance of the cell. A vertical water balance is determined for both the land and open water fraction (wetlands, lakes, and reservoirs) of the cell. Total runoff is partitioned into fast surface and subsurface runoff, and groundwater recharge and then transported laterally within the cell and to the downstream cell (after subtracting consumptive use). For routing, the influence of wetlands, reservoirs, and lakes is taken into account. Transport between cells is assumed to occur only as surface water flow and groundwater is assumed to return to the surface before it leaves the cell. The hydrology model is based on the best global data sets available and calibrated against measured discharge for about 50 percent of the global land area (Döll, Kaspar, and Lehner 2003).

The Global Water Use Model includes submodels for each of the water use sectors: irrigation (Döll and Siebert 2002), livestock, households, and industry (Döll, Kaspar, and Lehner 2001). Irrigation water requirements are modeled as a function of cell-specific irrigated area, crop, and climate, and livestock water use is calculated by multiplying livestock numbers by livestock-specific water use. Household and industrial water use in grid cells is computed by downscaling published country values based on population density, urban population, and access to safe drinking water (Döll, Kaspar, and Lehner 2003).

Another fine-scale (30″ × 30″) geospatial data set for population count was derived from the LandScan Global Population Project (ORNL LandScan 2005) at Oak Ridge National Laboratory, Tennessee. The LandScan population distribution model utilized the best available census counts (usually at subprovince level) for each county and four primary geospatial input data sets as key indicators of population distribution: land cover, roads, slope, and night-time lights (Dobson et al. 2000).

The two geospatial global data sets, each in a different format (raster and vector), were processed using ArcGIS geo-processing tools, clipped to basin boundaries and projected for the three regions under study. Following this procedure, the 0.5° × 0.5° grid data (or simply 0.5° data) for water availability and water use were aggregated at 1°, 1.5°, 2°, 2.5°, and so on, up to 7° × 7° using ArcGIS 9.3. The aggregation procedure involved simple sums of multiple cells, so that subcell sampling that could complicate interpretations was avoided. Statistical correlations (Pearson) were then computed for the two variable pairs: population with water availability and population with water use. In the next step, ordinary least squares regressions were conducted to establish empirically how correlation coefficients between each pair of variables changes with scale. In the final regressions reported here, scale is always the independent variable and the correlation coefficients between PWA and PWU are the dependent variables.

Results

In most cases, the strength of bivariate correlations shows a statistically significant increase with data aggregation to coarser resolutions. This increase generally corroborates conclusions recorded in the ecological and geographic literature. Correlation coefficients calculated for regressions of population and water availability and population and water use are plotted at multiple scales for the three river basins under study (Figures 1 and 2). Five of the six curves display some form of statistically significant positive increase in correlation coefficients with scale. Pearson correlation coefficients (r) calculated between PWA decline from coarser to finer scales in each of the three river basins under study (Figure 1). Although the tendency for increasing r between variables at coarser scales conforms to convention, the trends varied substantially between basins. In the Ganges Basin, for instance, the relationship is nonlinear, with very weak correlations between population and water availability at the finest scales that increase rapidly to intermediate scales and then flatten out at coarser scales.

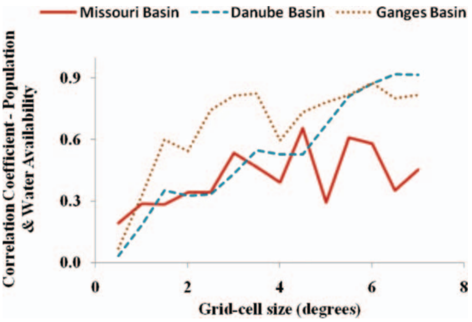

Figure 1 *Pearson correlation coefficients between population and water availability (PWA) increase with grid-cell size in all three basins. (Color figure available online.)*

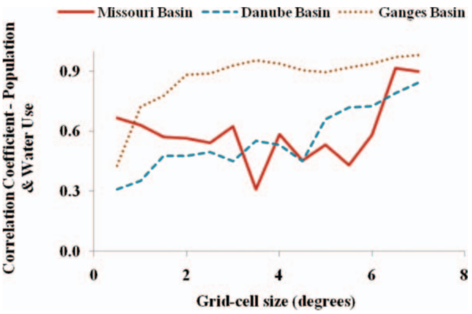

Figure 2 *Pearson correlation coefficients between population and water use (PWU) increase in the Danube and Ganges basins but not in the Missouri Basin. (Color figure available online.)*

Table 2 *T statistic and* p *values (linear model) for Pearson correlation coefficients (r) at multiple scales ($\alpha = 0.05$)*

	Danube			**Missouri**			**Ganges**		
Variables	***r***	***t***	***p***	***r***	***t***	***p***	***r***	***t***	***p***
Population and water availability (PWA)	0.979	16.5	.000	0.572	2.42	.016	0.769	4.17	.001
Population and water use (PWU)	0.929	8.71	.000	0.283	1.02	.164	0.738	3.80	.002

Correlation coefficients computed for PWU show an increase overall from fine to coarse scales for all of the study basins (Figure 2), but the rate of change in correlation coefficients with cell size in the fine-scale range is more gradual with PWU than with PWA. As with the PWA results, the trends for correlation between PWU in each basin vary. In the Ganges Basin, for instance, correlations between PWU are nonlinear, with rapid increases in the fine range, after which correlations cease to increase and the curve flattens out. Increases in correlation with scale in the Ganges Basin, for both PWA and PWU, therefore appear to be nonlinear. Correlation coefficients in the Danube Basin for PWU, on the other hand, show a gradual increase with scale overall that is approximately linear. In the Missouri Basin, high correlations between PWU at coarse grid-cell sizes decline rapidly toward intermediate sizes before rising gradually at small cell sizes. Overall, for both the variable pairs, PWA and PWU, the trends in correlation coefficients with scale are much weaker in the Missouri Basin than for the other two basins.

Another set of six linear regressions was run on correlation coefficients versus scale (Table 2). These regressions were run for the entire range of scales (the hypothesis tests) and the correlation coefficients from these regressions are different from the individual correlation coefficients run at each scale. The t and p values in Table 2 refer to the overall regressions against scale. Results of hypothesis testing for correlation coefficients, including the t statistic and corresponding p values, are based on a one-tailed test with $\alpha = 0.05$. The t statistics and corresponding p values indicate that the regressions of correlation coefficients against scale are significant except for PWU in the Missouri Basin. Corresponding results for the null and research hypotheses are given in Table 3. Comparing the p values of the t statistic with $\alpha = 0.05$, the null hypothesis H_o is rejected for both pairs of variables (PWA and PWU) for both the Ganges and Danube basins but only for the PWA in the Missouri Basin. For population and water use in the Missouri Basin (PWU), the null hypothesis, H_o, was not rejected; that is, no significant linear relationship between r_{WU} values and scale was demonstrated. The common assumption of linear increases in correlation (r) was best met with the Danube data, where correlation coefficients for both PWA and PWU increased in a linear manner.

Previous studies have shown that conclusions derived at one scale are specific to that scale and might not be valid at another scale. In the Danube Basin, for example, no apparent relationship exists between population and water availability at a grid-cell scale of 0.5° (Figure 3A). At a coarser scale of analysis (1.5°), however, grouping and averaging of grid cells results in a smaller sample size and a weak linear relationship between the variables begins to appear (Figure 3B). The correlation is much stronger at 3.0° (Figure 3C).

Table 3 *Summary of hypothesis test results (one-tailed test of linear model)*

H	**Correlation between variables increases with scale in all three basins**	**Accept/reject null hypothesis (H_o) at $\alpha = 0.05$ (one-tailed test)**
H_1	H_1: ß$_{PWA} > 0$; H_{o1}: ß$_{PWA} \leq 0$	Missouri: Reject H_{o1} Danube: Reject H_{o1} Ganges: Reject H_{o1}
H_2	H_2: ß$_{PWU} > 0$; H_{o2}: ß$_{PWU} \leq 0$	Missouri: Fail to reject H_{o2} Danube: Reject H_{o2} Ganges: Reject H_{o2}

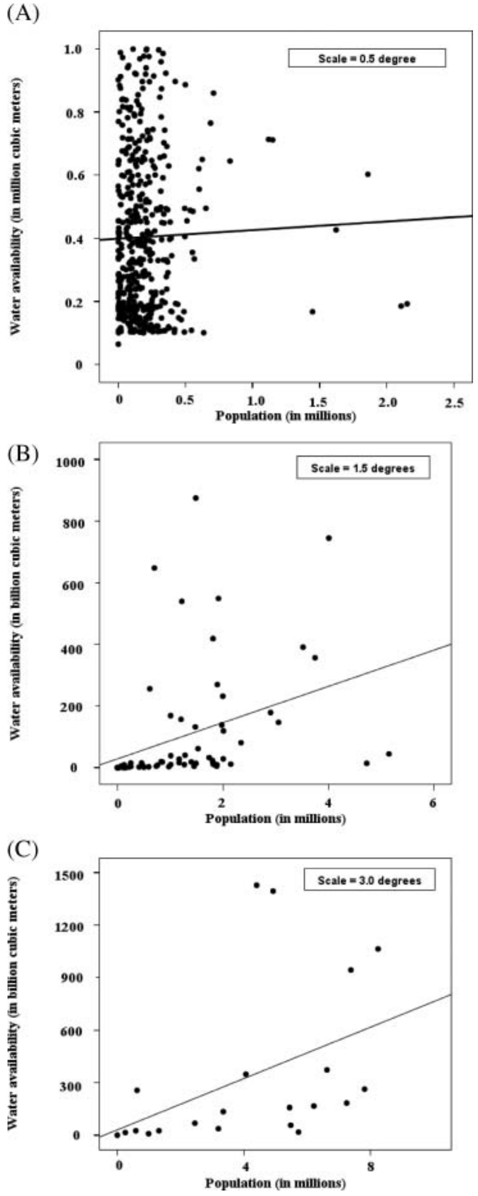

Figure 3 *Plots of population and water availability (PWA) per grid cell in the Danube Basin using three different scales of data. Clockwise from upper left: (A) at 0.5° no relationship is apparent (r = 0.026). (B) At 1.5° a potential weak positive trend becomes apparent (r = 0.35). (C) At 3° a weak linear trend emerges (r = 0.43; data from WaterGAP).*

Discussion and Implications

The increased Pearson correlation coefficients with grid-cell size for linear models of population and water availability are presumably a consequence of spatial lumping and averaging during scaling. Clearly, because the same data were used to generate the grids at various scales in this controlled experiment, the increase in correlation coefficients was not due to changes in the underlying data but is simply the effect of scale. This reiterates the findings of Yule and Kendall (1950), McCarthy, Hook, and Knos (1956), and Marceau (1999) discussed earlier, that correlations are not a meaningful or reproducible measure of the strength of relationships between the two variables unless scale (i.e., unit of analysis) is specified.

The observed changes in correlation coefficients with scale might represent differing spacing and clustering patterns for variables that are averaged with data aggregation. High-frequency repetitive patterns tend to get filtered out when data are aggregated into coarser units (Casetti 1966). Hence, as gridded data are aggregated from fine to coarse scales, higher correlations might result between two variables that are geographically associated but not exactly coincidental in space. For example, water use on an irrigated plain could be dominated by many irrigators evenly spaced across the landscape, whereas population on the plain is primarily clustered in small towns near transportation routes. Such a situation would produce low correlations between water use and population at spatial resolutions fine enough to resolve irrigation water use into separate grid cells from populations in towns. Data aggregation groups the irrigated and town areas together, however, and the correlation strengthens as the settled agricultural plain is distinguished from sparsely populated regions. In some regions, further data aggregation could result in the combining and averaging across regions with different water uses. For example, at coarser grid sizes, averaging across irrigated and urbanized areas dominated by municipal and industrial water use could result in an increase in correlation coefficients between water use and scale as these regions contrasted with sparsely populated regions with little water use, such as arid or mountainous areas.

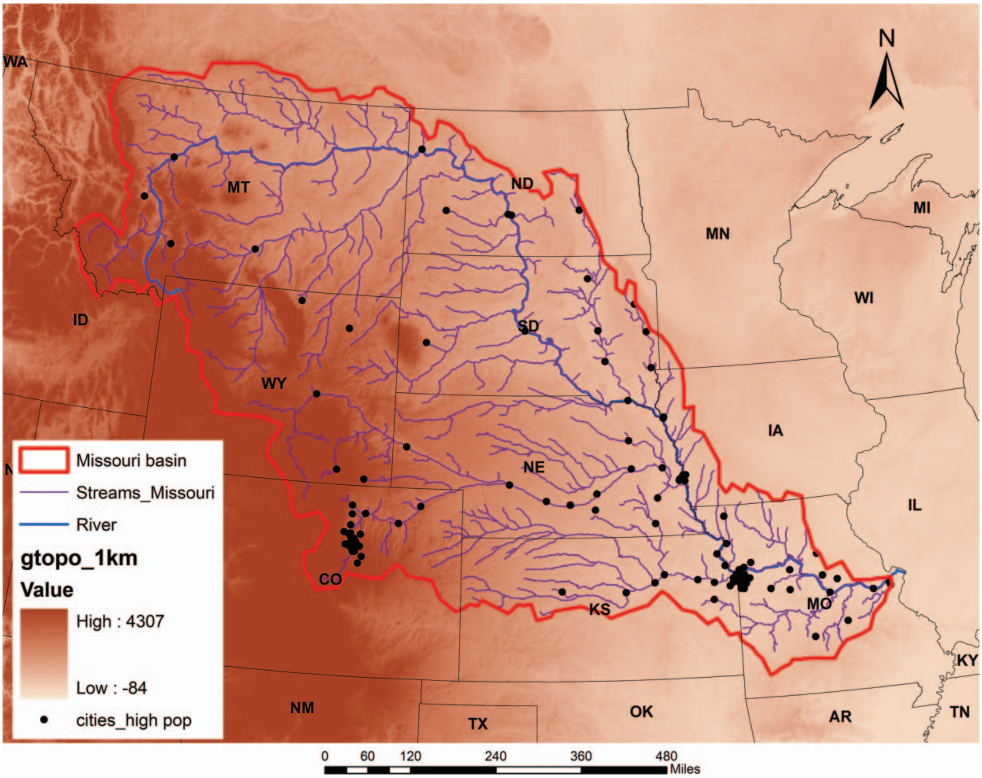

Figure 4 *Missouri River Basin overlaying a 1 × 1 km GTOP030 DEM (USGS-EROS 2006) and showing the concentration of highly populated cities toward the southeast of the basin (black dots). Topographic relief decreases west to east through the basin. (Color figure available online.)*

Thus, the behavior of correlation coefficients with scale might be diagnostic of intrinsic spatial patterns.

In the Missouri Basin, correlations between PWU are relatively constant from 0.5° to around 6° and then rise rapidly. Although sample sizes are small at the coarse scales, this pattern might reflect the broad gradient of climatic conditions, geologic complexity, and topographic relief across the three physiographic divisions that constitute the Missouri Basin—the Rocky Mountains, Interior Plains, and Interior Highlands (U.S. Geological Survey 2008). Three trends from northwest to southeast are strongly expressed in the Missouri Basin: decreasing topographic relief, increasing population (Figure 4), and increasing moisture with proximity to humid air masses from the Gulf of Mexico. Increasing correlations for PWU at very large grid-cell sizes might be explained by an increasing dominance of these gradients. In other words, both population and water use are relatively low in the northwest and high in the southeast at all grid scales. This control on correlations between water use and population only becomes statistically important at cell sizes greater than 6° that average out the effects of local variables governed by finer patterns of settlement and physiography. With greater data aggregation, correlations for PWU begin to respond to these large-scale gradients in association with as well as differences between major population clusters and desolate mountainous areas. The Danube and Ganges basins, on the other hand, do not have such broad regional climatic or population gradients, so they display a stronger scale dependency in the lower range of scales. Although this hypothesis is subject to further analysis, it might help explain some of the variations in responses to scaling within river basins.

Spatial data are often acquired at different resolutions and then resampled or combined, so scaling issues are important to most studies. Under the present limited knowledge of scaling behavior, no uniform method can be specified to compensate for scaling effects. Statistics and model parameters often differ between resolutions, and insufficient information exists to predict how they will behave as data resolutions change. To the extent that correlation coefficients (*r*) behave consistently (e.g., the Danube and Ganges basins), the ability to predict changes in values of *r* with scale appears to be promising. The same cannot be stated, however, for the Missouri Basin. It follows, therefore, that scaling relationships in each basin should be characterized empirically. This could identify the range of scales within which relationships would be valid and thresholds at which finer or coarser scales would result in substantial changes in the strength of relationships. Such scale-dependent trends could also be indicative of processes and patterns that would otherwise go undetected and could have great bearing on water resources vulnerability.

In a study done recently on scale effects in water resources, Perveen and James (2009) demonstrated two distinctly different cases for what were defined as "unscaled" and "scaled" variables. For unscaled variables that increase with area, like freshwater supply, water use, and population, variability increases systematically at coarser scales. This is contrary to the common assumption of decreasing variability as grid-cell size increases. On the other hand, decreasing trends in variability were observed with variables scaled to area or population (e.g., population density, water availability per capita, etc.). Moreover, linear increase models provide reasonable first-order approximations of variability increases in unscaled variables at coarse resolutions (e.g., water availability data at scales greater than $0.5^\circ \times 0.5^\circ$). Nonlinearity of the trends, however, became obvious at grid-cell resolutions less than 0.5°, and power functions provided a superior model of changes in variability in those cases. Knowledge of ranges or thresholds in scale for relationships between water resources and population data is essential for three reasons. First, it can help water resources data managers determine whether or not the expenses of data development or acquisition at finer resolutions beyond what is currently available are justified. Second, knowledge of relationships between variables at different scales could pave the way for informed decision making in water resources and applied vulnerability studies. Finally, a theoretical basis for predicting scale behavior might emerge from this knowledge.

Conclusions

This article presents a multiscale analysis of water resources data focused on correlations between water resources and population variables that are commonly used in water resources vulnerability studies. Correlation coefficients (*p*) were computed for univariate regressions of PWA and PWU at fourteen different spatial scales. In a second phase of the analyses, the resulting correlation coefficients were regressed on scale. Null hypotheses that slopes of linear regression lines for the correlation coefficients on scale are not greater than zero were rejected ($\alpha = 0.05$) in five out of the six cases for the two variable pairs—PWA and PWU in the Danube and Ganges basins but only for PWA in the Missouri Basin. Positive increases in correlations with scale can be expressed as simple linear functions for the Danube and Ganges basins, although linearity is unequivocal only in the Danube Basin. In the Ganges Basin, increases in correlations appear to be nonlinear; that is, they increase rapidly at fine scales and reach a peak at around 3.5°, after which they become approximately uniform with scale. Trends in correlation coefficients in the Missouri Basin were much weaker, which might reflect the importance of broad regional climatic, physiographic, and demographic gradients.

Correlation coefficients have often been shown to increase at coarser scales, but no such assessment has corroborated this tendency with water resources data. This study is timely in that new data and technology allow changes in correlation to be performed at different scales, and such results are needed to parameterize, interpret, and apply the results of global and climate change studies. Results of this multiscale water resources study largely corroborate and expand on the general findings found in other fields about the scale dependency of relationships. They indicate, however, that important exceptions exist to assumptions of both linear and overall increasing trends. The scientific literature suggests that correlation coefficients for paired observations drawn from spatial data should increase at coarser scales. Most variables in the study basins behaved in this manner except for the Missouri Basin, which did not show any significant trend. Possible explanations for varying correlations with scale include smoothing effects and underlying spatial patterns in the data. The importance of smoothing or averaging was exemplified by increasingly strong correlations between population and water availability in the Danube Basin as scale coarsened with data aggregation.

The scale dependency of correlation coefficients shown by this study indicates the need for an increased vigilance with respect to scale. As global science becomes more data dependent, model driven, and multidisciplinary, it is increasingly important that spatial tools and techniques are developed to operate at multiple scales. Data are often used at different scales than the scale at which they were derived, and results often need to be aggregated or disaggregated in ways that suit the decision-making process. Specifically, further study is needed to enhance current understandings of scale effects in water resources and how these apply to assessments of water vulnerability (e.g., water stress and scarcity) and to allow synthesis of these understandings into a set of principles. This capability is essential in formulating targeted and cost-effective water management and adaptive measures within a basin. As regional water shortages intensify with population growth and climate, water planning and management will require detailed assessments of vulnerability. ■

Literature Cited

Alcamo, J., P. Döll, T. Henrichs, F. Kaspar, B. Lehner, T. Rösch, and S. Siebert. 2003. Development and testing of the WaterGAP 2 global model of water use and availability. *Hydrological Science* 48 (3): 317–37.

Amrhein, C., and H. Reynolds. 1996. Using spatial statistics to assess aggregation effects. *Geographical Systems* 3:143–58.

Arbia, G. 1989. *Spatial data configuration in statistical analysis of regional economic and related problems.* Boston: Kluwer Academic.

Arbia, G., R. Benedetti, and G. Espa. 1996. Effects of the MAUP on image classification. *Geographical Systems* 3:123–41.

ArcGIS, Version 9.3. Redlands, CA: ESRI.

Atkinson, P., and N. J. Tate. 2000. Spatial scale problems and geostatistical solutions: A review. *The Professional Geographer* 52 (4): 607–23.

———, eds. 2001. *Modeling scale in geographical information science.* New York: Wiley.

Blalock, H. 1964. *Causal inferences in nonexperimental research.* Chapel Hill: University of North Carolina Press.

Blöschl, G., and M. Sivapalan. 1995. Scale issues in hydrological modeling: A review. *Hydrological Processes* 9:251–90.

Casetti, E. 1966. Analysis of spatial association by trigonometric polynomials. *Canadian Geographer* 10:199–204.

Clark, C. D. 1990. Remote sensing scales related to the frequency of natural variation: An example from paleo-ice-flow in Canada. *IEEE Transactions on Geoscience and Remote Sensing* 28 (4): 503–08.

Clark, W. A. V., and K. L. Avery. 1976. The effects of data aggregation in statistical analysis. *Geographical Analysis* 8:428–38.

Crawford, C. G., and L. Young. 2004. Combining incompatible spatial data: An introductory overview of statistical issues and methods. Paper presented at the Workshop for the SAMSI Program on Multiscale Model Development and Control Design, Research Triangle Park, NC.

Dark, S. J., and D. Bram. 2007. The modifiable areal unit problem (MAUP) in physical geography. *Progress in Physical Geography* 31:471–79.

Dobson, J. E., E. A. Bright, P. R. Coleman, R. C. Durfee, and B. A. Worley. 2000. A global population database for estimating population at risk. *Photogrammetric Engineering and Remote Sensing* 66 (7): 849–57.

Döll, P., F. Kaspar, and J. Alcamo. 1999. Computation of global water availability and water use at the scale of large drainage basins. *Mathematische Geologie* 4:111–18.

Döll, P., F. Kaspar, and B. Lehner. 2001. The global integrated water model WaterGAP 2.1. In *Kassel world water series 5*, ed. B. Lehner, T. Henrichs, P. Döll, and J. Alcamo, 2-1–2-18. Kassel, Germany: Center for Environmental Systems Research, University of Kassel.

———. 2003. A global hydrological model for deriving water availability indicators: Model tuning and validation. *Journal of Hydrology* 270:105–34.

Döll, P., and S. Siebert. 2002. Global modeling of irrigation water requirements. *Water Resources Research* 38 (4): 8.1–8.10.

Fotheringham, A. S., and D. W. S. Wong. 1991. The modifiable areal unit problem in multivariate statistical analysis. *Environment and Planning A* 23:1025–44.

Gehlke, C. E., and H. Biehl. 1934. Certain effects of grouping upon the size of the correlation coefficient in census tract material. *Journal of the American Statistical Association* 29 (Suppl.): 169–70.

Haining, R. 2003. *Spatial data analysis: Theory and practice*. Cambridge, UK: Cambridge University Press.

Hay, G. J., D. J. Marceau, P. Dubél, and A. Bouchard. 2001. A multi-scale framework for landscape analysis: Object-specific analysis and upscaling. *Landscape Ecology* 16:471–90.

Jelinski, D. E., and J. Wu. 1996. The modifiable areal unit problem and implications for landscape ecology. *Landscape Ecology* 11 (3): 129–40.

Kates, R. W., T. J. Wilbanks, and R. Abler, eds. 2003. *Global change in local places: Estimating, understanding and reducing greenhouse gases*. Cambridge, UK: Cambridge University Press.

King, A. W., D. L. DeAngelis, and W. M. Post. 1988. The seasonal exchange of carbon dioxide between the atmosphere and the terrestrial biosphere: Extrapolation from site-specific models to regional models. Tech. Memo TM-10570, ORNL Lab, Oak Ridge, TN.

Lam, N., and D. A. Quattrochi. 1992. On the issues of scale, resolution and fractal analysis in the mapping sciences. *The Professional Geographer* 44:88–98.

Legendre, P. 1993. Spatial autocorrelation: Trouble or new paradigm? *Ecology* 74:1659–73.

Marceau, D. J. 1999. The scale issue in social and natural sciences. *Canadian Journal of Remote Sensing* 25 (4): 347–56.

McCarthy, H. H., J. C. Hook, and D. S. Knos. 1956. *The measurement of association in industrial geography*. Iowa City: Department of Geography, State University of Iowa.

Millennium Ecosystem Assessment (MEA). 2005. Chapter 4: The multi-scale approach. In *Ecosystems and human well-being: Multi-scale assessments*, Vol. 4, 61–83. Washington, DC: Island Press.

Openshaw, S. 1984. *The modifiable areal unit problem*. Norwich, UK: Geo Books.

Openshaw, S., and P. J. Taylor. 1979. A million or so correlation coefficients: Three experiments on the modifiable areal unit problem. In *Statistical applications in the spatial sciences*, ed. N. Wrigley, 127–44. London: Pion.

ORNL LandScan. 2005. *High resolution global population dataset*. Oak Ridge, TN: UT-Battelle, LLC, Oak Ridge National Laboratory under contract with the U.S. Department of Energy.

Perveen, S., and L. A. James. 2009. Multi-scale effects on spatial variability metrics in global water resources data. *Water Resources Management* 24:1903–24.

———. 2010. Scale invariance of water stress and scarcity indicators: Facilitating cross-scale comparisons of water resources vulnerability. *Applied Geography* 24 (9): 1903–24.

Quattrochi, D. A., and M. F. Goodchild. 1997. *Scale in remote sensing and GIS*. Boca Raton, FL: CRC Press.

Raupach, M. R., and J. J. Finnigan. 1995. Scale issues in boundary-layer meteorology: Surface energy balances in heterogeneous terrain. *Hydrological Processes* 9:589–612.

Robinson, W. S. 1950. Ecological correlations and the behavior of individuals. *American Sociological Review* 15:351–57.

Stone, K. H. 1972. A geographer's strength: The multiple scale approach. *Journal of Geography* 72:354–61.

Turner, M. G., V. H. Dale, and R. H. Gardner. 1989. Predicting across scales: Theory, development and testing. *Landscape Ecology* 3:245–52.

U.S. Geological Survey. 2008. Missouri River infolink. http://infolink.cr.usgs.gov/The_River/ (last accessed 1 October 2008).

USGS-EROS. 2006. GTOPO30. http://eros.usgs.gov/products/elevation/gtopo30.html (last accessed 21 June 2008).

Yule, G. U., and M. G. Kendall. 1950. *An introduction to the theory of statistics*. New York: Griffin.

Zeid, M. A., and A. K. Biswas. 1992. *Climate fluctuations and water management*. Oxford, UK: Butterworth-Heinemann.

SHAMA PERVEEN is a Research Scientist at the Earth Institute's Water Center at Columbia University, Columbia Water Center, Earth Institute, Columbia University, 500 West 120th Street, 842 SW Mudd, MC—4711, New York, NY 10027. E-mail: sp2972@columbia.edu. Her research interests include water resources management and policy, global change, impacts and vulnerability, corporate water risks, and modeling and assessments of these at multiple scales using GIScience.

L. ALLAN JAMES is a Professor in the Department of Geography at the University of South Carolina, 709 Bull Street, Callcott Building, Columbia, SC 29208. E-mail: AJames@sc.edu. His research interests include water resources, river science, fluvial geomorphology, flood hydrology, and applications of geospatial analysis in those fields.