Position Paper: Scales as additional dimensions in space and time

1. Introduction

The scale of analysis to a large extent determines the insights that can be gained, due to the nature of geospatial information and to its sensitivity to spatial and temporal resolution. The importance of scale has been epitomized in the well-known modifiable areal unit problem (MAUP). Ideally, geospatial data should be analyzed at the level where spatio-temporal processes become evident, are best understood and/or where spatial and temporal dependency is maximized. However, the scale of analysis that is ideally suited to a given problem is not always immediately evident, which raises a compelling justification for exploring data solutions supporting multiple-scale analyses. Analysis and modeling at a pre-defined scale may under-sample the phenomena in the scale dimension and miss critical relationships concealed at other scales.

Multi-scale analysis for spatio-temporal data forms a longstanding challenge for analytic systems in GIScience. Geospatial data are traditionally represented as flat layers at pre-determined resolutions, while spatial analysis tools usually only operate at a single scale or a few selected scales. Dealing with temporal scale is equally important and challenging as dealing with spatial scale. In prevalent GIS, time is conventionally represented as 'stamps' denoting when the data were collected, created and/or published. Geodatabases store temporal information of spatial features as attributes in relational tables to support temporal queries. However, the capacity of temporal analysis in GIS is rather limited compared to the extensive toolbox for spatial data analyses. With only the time stamps, geographical processes that span a time interval can hardly be visualized or analyzed, not mentioning more complex temporal information such as uncertain intervals and time series.

These challenges are largely attributed to the traditional views of linear time and flat space, which become intuitive to humans after the long-time applications of these views in cartography and graphic design. However, these traditional representations of space and time are not efficient for analytical tasks that involve large and complex data over multiple scales. Additionally, from a cognitive perspective, it is uncertain whether these views are truly intuitive or humans are trained to be perceive them that way. Remember the shock we had when first time seeing an upside-down world map. With the development of computer science and visualization techniques, alternative representations that re-arrange the space, time and their scales can help people to better observe and understand patterns and relationships that cannot be easily observed in the traditional models. In the remainder of the paper, I will briefly introduce my work on multi-scale spato-temporal modeling and pose general questions for discussion in the workshop.

2. Integrating Scale and Time

A series of research has been conducted by the author to develop new visual representations and analytical tools for multi-scale spatio-temporal data. This research originated from a two-dimensional representation of time (i.e. the Triangular Model or TM), which transform linear time intervals into points in a two-dimensional space [5-7]. In addition to discrete time intervals, the TM can be created as a continuous field to represent all intervals in a time series [4]. In such a way, temporal data aggregated in all scales (intervals) are represented in a 2D space. Not only a cross-scale visualization of time series, many spatial analysis tools (e.g. overlay, classification and map algebra) can be applied to analyze the temporal data and the results are reflected at multiple scales. The TM and its analytical tools have been applied in various applications such as analyses of archaeological data, mobility data and climate data [1,4].

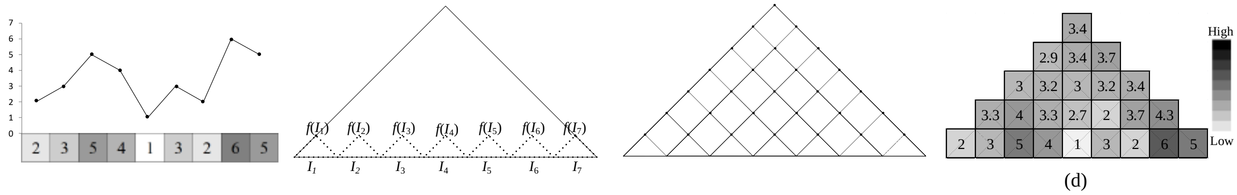

Figure 1: Constructing a simple raster TM from time series. a): a time series. b): mapping intervals at the finest resolution in TM. 3): mapping intervals at different resolutions in TM. 4): A raster TM.

3. Integrating scale and space

Following the same modeling principle of TM, 2D spatial data can be extended into a 3D by adding spatial scale as the 3rd dimension, which leads to a Pyramid Model (PM) with progressive aggregation of spatial units. For computing and visualization purposes, the PM can be implemented as 3D raster, where each voxel is associated with a function $f(x, y, z)$ of the area it represents [2]. The vertical dimension (z) indicates the scale of analysis or aggregation. The function can be focal statistics (e.g. ratio, mean, standard deviation) or local spatial indices (e.g. kernel density, spatial autocorrelation or fitness of local models). In addition to raster spatial data, the configuration of PM can also be modified to represent irregular tessellations and vector features. 3D visualization techniques can be applied to analyze the variance and patterns in the PM. For instance, the isosurfaces can help to identify areas and scales where a spatial index is high [1] or a model has best fit.

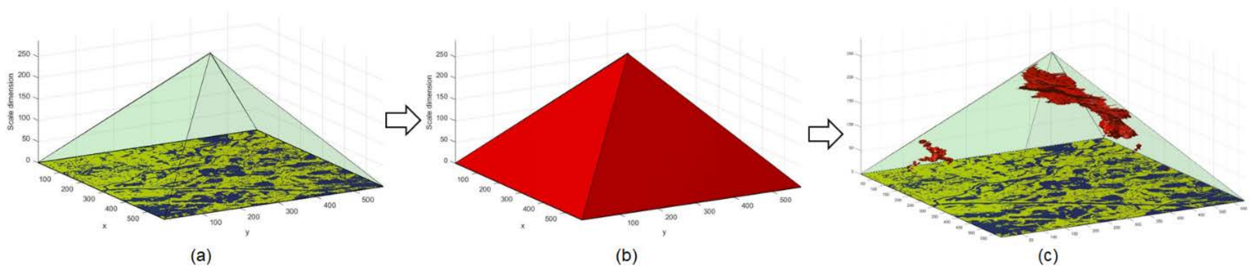

Figure 2: Visualizing fractal dimensions at multiple scales in PM.

4. Multi-scale spatio-temporal analysis`

The TM and PM deal model time-scale and space-scale respectively. Given the increasing amount of spatio-temporal data, dealing with scales in both space and time becomes a pressing need for future analytical tools. Combining spatial location (s), spatial scale (s'), temporal location (t), and temporal scale (t') leads to a 5D conceptual framework, where any type of analysis is varying in one or more of the dimensions. Due to the high-dimensionality, the framework cannot be completely displayed in a simple visualization like the TM and the PM. Figure 19 provides a conceptual illustration of how time series of spatial data are represented in the framework [1,4].

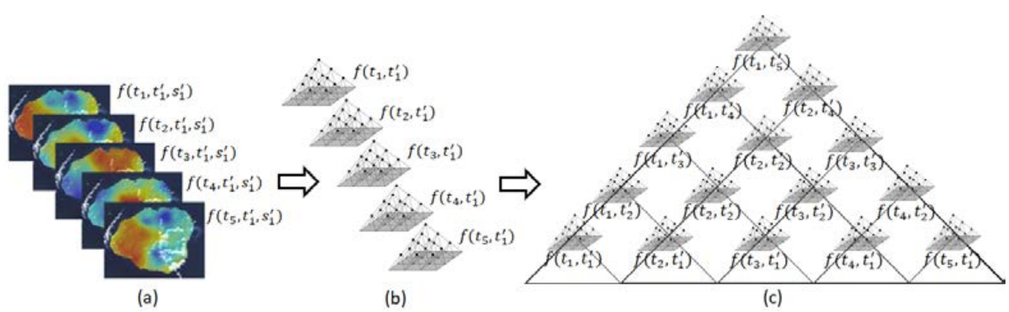

Figure 3: The representation of multi-scale spatio-temporal data in the CSTM framework.

5. Questions for discussion

Empowered by cutting-edge computing techniques, research of integrated modeling framework of space, time and scales will create profound influence on the design of next-generation GIS and analytical systems. In this symposium, I would like to share my thoughts and discuss with other participants the research agenda in GIScience to solve the following questions:

1. Can we gain additional knowledge by analyzing variations and patterns in the dimensions of scale?
2. What representations and analytical tools can be developed to better handle scales with the support of cutting-edge computing techniques?
3. How can we develop an integrated framework to model the complex interactions between environmental and societal processes?

References

Reference (numbers) cited in this paper can be found in the submitted 2-page C.V.