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# A Hybrid Dasymetric Mapping for Population Density Surface using Remote Sensing Data

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# 원격탐사자료를 바탕으로 인구밀도 분포 작성을 위한 하이브리드 대시메트릭 지도법

김화환* · 최진무**

**Abstract** : Choropleth mapping of population distribution is based on the assumption that people are uniformly distributed throughout each enumeration unit. Dasymetric mapping technique improves choropleth mapping by refining spatially aggregated data with residential information. Further, pycnophylactic interpolation can upgrade dasymetric mapping by considering population distribution of neighboring areas, while preserving the volumes of original units. This study proposed a combined solution of dasymetric mapping and pycnophylactic interpolation to improve the accuracy of population density distribution. Specifically, the dasymetric method accounts for the spatial distribution of population within each census unit, while pycnophylactic interpolation considers population distribution of neighboring area. This technique is demonstrated with 1990 census data of the Athens, GA. with land use land cover information derived from remotely-sensed imagery for the areal extent of populated areas. The results are evaluated by comparison between original population counts of smaller census units (census block groups) and population counts of the grid map built from larger units (census tracts) aggregated to the same areal units. The estimated populations indicate a satisfactory level of accuracy. Population distribution acquired by the suggested method can be re-aggregated to any type of geographic boundaries such as electoral boundaries, school districts, and even watershed for a variety of applications.

Key Words : Choropleth mapping, Dasymetric mapping, Pycnophylactic interpolation, Population distribution, Residential area, Areal interpolation.

**요약** : 단계구분도는 인구분포를 나타내기 위해 흔히 사용되는 방법으로 인구가 단위지역 내에 균등하게 존재함을 가정한다. 대시메트릭 지도제작법은 주거지역 정보를 통해 단계구분도보다 공간적으로 더 세밀한 인구분포를 작성할 수 있게 한다. 또한 피크노필랙틱 보간법은 단위지역 내 총인구를 유지하면서 주변지역의 인구를 고려하여 인구분포를 보간하는 방법으로 대시메트릭 지도제작법에 의한 인구분포를 연속적이고 부드럽게 하여 좀더 현실적인 인구분포도를 작성할 수 있게 한다. 따라서, 본 연구에서는 대시메트릭 지도제작법과 피크노필랙틱 보간법을 연계하는 방법을 제시하여 인구분포도의 정확도를 향상하고자 하였다. 제시한 방법을 적용하여 인구분포도를 작성하기 위해 1990년도 미국 조지아주 Athens 시의 인구자료와 위성영상으로부터 추출된 주거지역 자료를 활용하였다. 결과를 검증하기 위해 인구분포도 작성에 활용된 공간단위보다 더 세밀한 공간단위의 인구자료를 활용하였으며 하이브리드 방법에 의해 높은 정확도를 확보할 수 있음을 확인하였다. 본 연구에서 제시한 하이브리드 대시메트릭에 의한 인구분포는 선거구, 학군, 분수계 등 각종 경계지역으로 변환이 용이해 다양한 응용분야에서 활용될 수 있을 것이다.

주요어 : 단계구분도, 대시메크릭 지도법, 피크노필랙틱 보간법, 인구분포, 주거지역, 공간적 보간법.

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## 1. Introduction

Decennial census serves as the primary source of spatio-demographic information. However, several problems may arise when using the raw census data for spatial analyses. First, census data are only released as areal aggregates to protect confidentiality. This aggregate nature can result in ecological fallacy or modifiable areal unit problem caused by changing areal units. Second, the census enumeration unit may not be compatible with another areal unit, on which other spatial data are collected, creating problems for spatial data integration. When the spatial unit of interest is 'non-census' area such as grid squares, or circular or irregular areas that might represent the 'catchments' of businesses and services, or areas exposed to environmental hazards, it is common practice to assign the known population of census zones to the expected units. Harvey (2003) distinguished three approaches of 1) choropleth, 2) dasymetric, and 3) pixel regression methodology to disaggregate zonal populations into grid cells. The problem of transferring data from one set of areal units (source zones) to another (target zones) is referred to the areal interpolation or cross-area estimation, and had been well explained by Lam (1983). It is easy to transfer data between different zoning systems if the target set is an aggregation of the source set, but more difficult, if the boundaries of the target set are independent of the source set.

The choropleth approach is based on the assumption that the density of a phenomenon (e.g. population density) is uniformly distributed throughout each source zone. The proportion of each source zone that is assigned to each target zone is determined by overlapping area. And then, the total attribute value of each source zone is apportioned to target zones according to the areal proportions. The choropleth approach leads to biased estimates of populations because population is not uniformly distributed in normal case (Langford *et al.*, 1991; Son 2001). Considering this limitation, the use of remotely-sensed data has the potential to enable finer grained studies than are possible with typical social science data (Rindfuss and Stern 1998). An improvement over the uniform distribution assumption is the 'dasymetric' approach (Fisher and Langford 1995; Langford 2006, 2007; Langford *et al.*, 1991; Rase 2001; Yuan *et al.*, 1997). With assistance of ancillary information, it is possible to describe a detailed distribution of the phenomenon. To explain the method in the simplest form for high resolution population estimation, remotely-sensed images are processed to generate a land use land cover data to describe a detailed distribution of residential and non-residential areas (Kim, 2007; Lee and Kim, 2007; Shin, 2004). Then, the population of each census zone is then distributed uniformly, but only among those pixel classified as residential (Langford 2003; Reibel and Agrawal 2007).

In addition to the dasymetric approach which utilizes the remote sensing information as ancillary data, pycnophylactic interpolation - volume preserving areal interpolation - devised by Tobler (1979) can also be used to disaggregate zonal population. Pycnophylactic interpolation divides each zone's total population count equally among the raster cells that fall into each source zone. The rasterized population density grid is smoothed with a certain size of low-pass filtering window so that each pixel value is adjusted by the neighboring pixels. Chang (2003) applied pycnophylatic interpolation to improve population density distribution of Seoul, but the population was assigned into urban areas instead of residential areas because of missing the concept of dasymetric mapping, which may produce inaccurate population distribution.

The main objective of this paper is to improve dasymetirc mapping method by combining pycnophylactic interpolation. The exact processes and principles of a combined solution of dasymetric mapping and pycnophylactic interpolation in which census population data are disaggregated into a population grid map using census data and residential areas extracted from remotely-sensed imagery is presented. More specifically, a population grid surface is built by pycnophylactic interpolation in which the assumption of a uniform distribution throughout the zone is substituted by the dasymetric principle. The dasymetric approach uses land cover information from remote sensing images to classify pixels as residential or non-residential. The results are evaluated by comparison between original zonal population of smaller spatial units (Census block group) and population counts of the grid map built from larger units (census tracts) aggregated to the same areal units.

The next section explains study area and data. Section 3 explains detail methodology including principles and processes of dasymetric mapping, pycnophylactic interpolation, and the combined method. Section 4 compares mapping results and discusses accuracy assessment. Key ideas and findings are summarized in Section 5.

## 2. Study area and data

Our method is tested with the area of Athens-Clarke County in the state of Georgia, USA, a university town with 1990 total population of 87,594. It encompasses 19 census tracts, and more detailed 54 block groups as illustrated in left map of Figure 1. U.S. Census Bureau TIGER 98 Census tracts (UTM) joined with 1990 census data in ESRI coverage format were acquired via Georgia GIS data clearinghouse (http://gis.state.ga.us). The same data in census block group level were also acquired for evaluation purpose. A necessary element for dasymetric mapping is an ancillary dataset. This information is used to assist interpolation of data from the original source zones to new target zones (e.g. regular grid). The 1996 National Land Cover Data of the study area was acquired for this purpose via Georgia GIS data clearinghouse also.

The land cover dataset was produced as part of

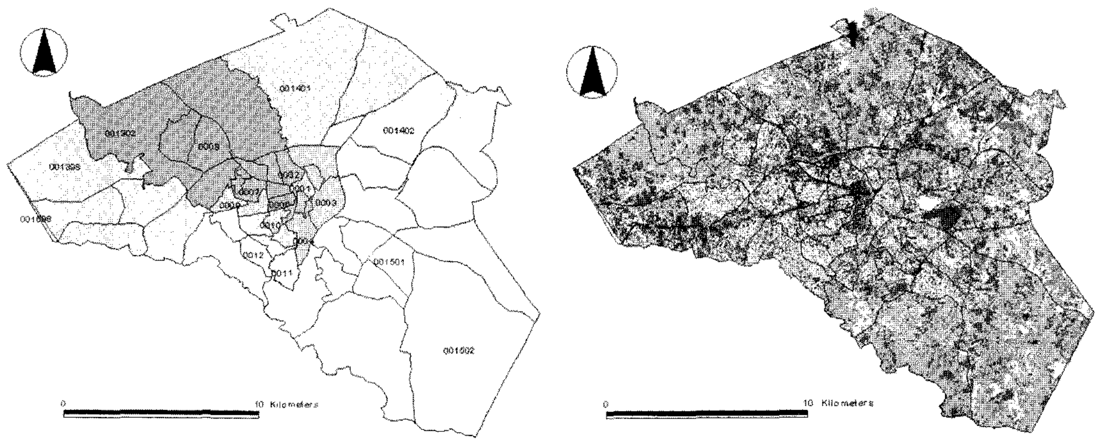



Figure 1. Study area and Data (Left: Athens-Clarke County, Georgia presented in Census block group level, Right: National Land Cover Data Georgia, Athens area from Landsat TM image)

a cooperative project between the U.S. Geological Survey (USGS) and the U.S. Environmental Protection Agency (U.S. EPA) to produce a consistent, land cover data layer for the conterminous U.S. based on 30-meter Landsat Thematic Mapper (TM) data. The base data set for this project was leaf-on Landsat TM data, nominal-1992 acquisitions. The total 23-Class National Land Cover Data Keys were used for supervised classification.

## 3. Methodology

The workflow of this study is illustrated in Figure 2. The first step is to reconstruct the census geographic entity and retrieve population data. The census boundary data downloaded from Georgia GIS data clearinghouse is in ESRI coverage format associated with census tabular data. So, the first step could be skipped. The second is to process the remotely sensed image so that it can be used as ancillary data in dasymetric mapping. The original National Land Cover Data (NLCD) is in 23-class classification scheme. It has to be converted to a binary mask of residential pixels by a reclassification process. The third is the most important part in this study to generate population density grid map using three different methods (dasymetric method, pycnophylactic interpolation, combined method). The census tract population map of the first step and the binary map are used as basic data for these methods. The final step is to aggregate three population density grid maps into census block group level - it is merely a sample target zone for evaluation purpose, and to compare and evaluate the performance of each method.

The method can be developed in any GIS

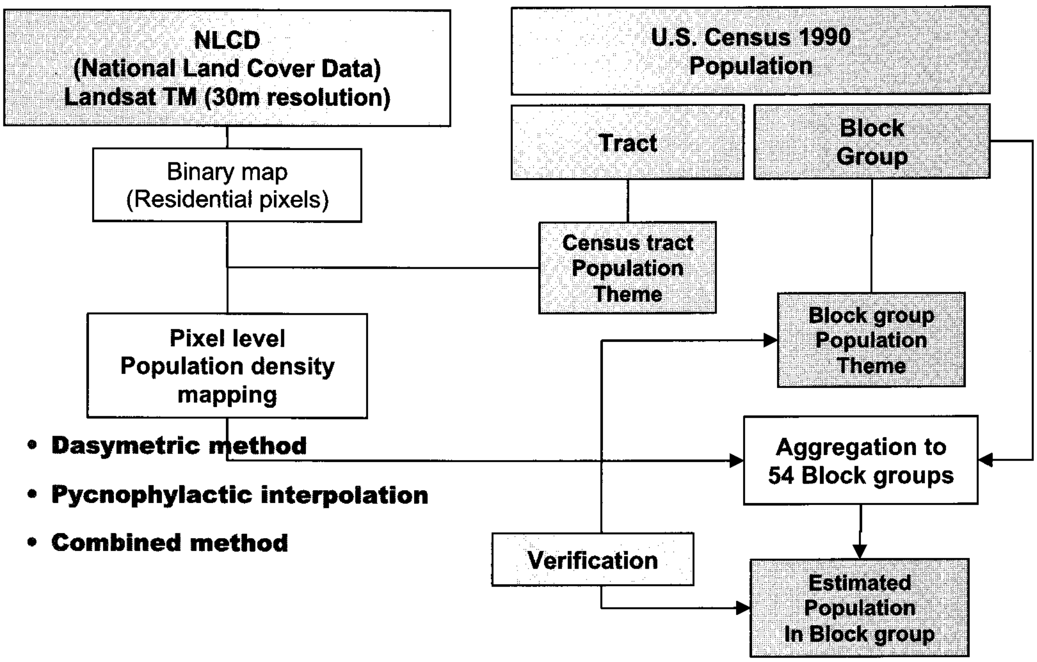



Figure 2. Research flowchart

environment. In this study, *ERDAS Imagine®* 8.5 version is used to make binary image from Land cover data, and *ESRI ArcView®* 3.2 is used for converting vector population map to GRID format and other processes which involve the work associated with tabular data. Especially, the pycnophylactic interpolation and combined method developed in this study are implemented by *ESRI Avenue®* script which was originally developed by Riedl (1998) and modified for this research.

### 1) Dasymetric method

Population statistics are invariably collected and published according to some spatial aggregation. In the United States, the smallest unit is census block and the units are hierarchically arranged into spatial units of progressively coarser spatial resolution, block group, tract, etc. All census data are published only for these spatial aggregations. However, analysts commonly want to integrate the census data with data collected in some other spatial division of the study area, but the boundaries of the census area are rarely coincident with the other units. The transformation of attribute data from one zonation to another is known as areal interpolation (Langford *et al.*, 1991), with the areal units of the initial zonation (source zones), and those of the subsequent zonation (target zones). Many different methods of areal interpolation have been suggested (Lam 1983).

The areal weighting method is the simplest and most easily implemented approach. It simply allocates population to target zones according to the relative area of source zone overlapped with it. This method is based on the assumption that people are evenly distributed within each source polygon. This assumption is acceptable only if nothing else is known about the population distribution, but even then it is generally inaccurate. People live in collections of houses, which are commonly interspersed with non-residential land (Fisher and Langford, 1996).

Various methods have been suggested to overcome the fundamental flaw in the areal weighting method. Of those, Fisher and Langford (1995) show that the dasymetric method provides the best results because it takes a local subset of the source zones into account in interpolation to each target zone. Wright (1936) used the basic concepts of dasymetric mapping which means "density measuring" of Russian origin from a concern that choropleth maps do not give even a remotely valid representation of the distribution of population within enumeration areas. The basic principle of dasymetric mapping is to subdivide source zones into smaller spatial units that possess greater internal consistency in the density of the variable being mapped (Langford 2003).

The dasymetric principle is illustrated in figure 3, where the additional source of spatial information takes the form of a set of polygons that depict the location of residential areas within

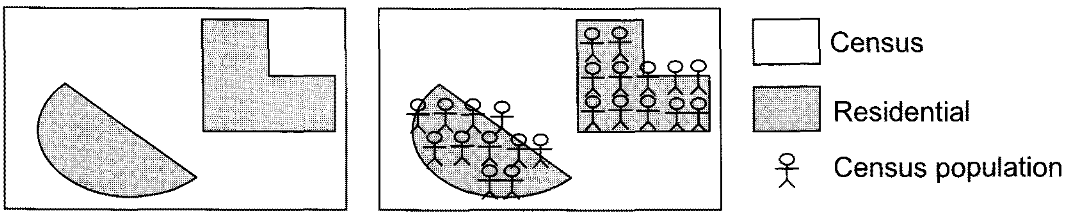



Figure 3. Dasymetric principle for population distribution modeling (Langford, 2003)

the study area. For implementation of dasymetric method, a land use land cover information or other form of ancillary information describing population distribution pattern is essential. Moreover, the accuracy and precision of the information such as residential areas are critical factors in accuracy of the population estimation.

The simplest scheme for implementing dasymetric population mapping is to utilize an ancillary data source that creates a binary mask. This has been referred to as the 'binary dasymetric method' (Eicher and Brewer 2001; Fisher and Langford 1995). That is, a map is employed that has just two classes that identify the locations of 'occupied' and 'unoccupied' areas. Within the boundaries of each source zone (i.e. census unit) population is evenly distributed into just those internal parts that carry the "occupied" label, as is demonstrated in figure 3.

Within a GIS, the dasymetric method is most easily implemented where areas of several different population densities are identified. Here the necessary land use information is simply the binary divide between residential and non-residential use, which is relatively easy to distinguish from classified satellite images. For the purpose, the 23-class National Land Cover Data Keys were reclassified into only 2 categories of 'occupied' and 'unoccupied' as figure 4. And, the whole dasymetric mapping process used in this study is illustrated in Figure 6.

In Figure 5, it can be clearly identified that the pixel level population densities change radically around the zone boundaries by which source zone the pixel was originated. Logically, it doesn't make sense that two adjacent residential pixels have totally different population densities only because they are in the other side of census boundary that is artificially drawn for administrative purpose. It is caused by the calculation of pixel population density in mapping process. The population density of each pixel is calculated by the following equation.

$$P_i = \frac{p_a}{n_a}$$

Where the population density of each pixel ($P_i$) is the total population of the source zone the pixel falls into ($p_a$) divided by the number of residential pixels within the zone ($n_a$), and is exactly same with the other pixels in the same source zone. In the result, any two pixels will have quite different population density values if

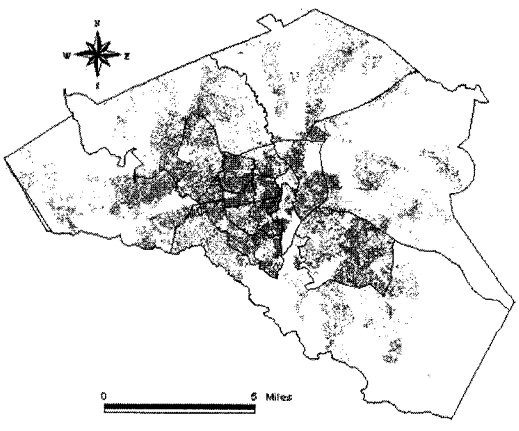



Figure 4. Binary map of residential pixels

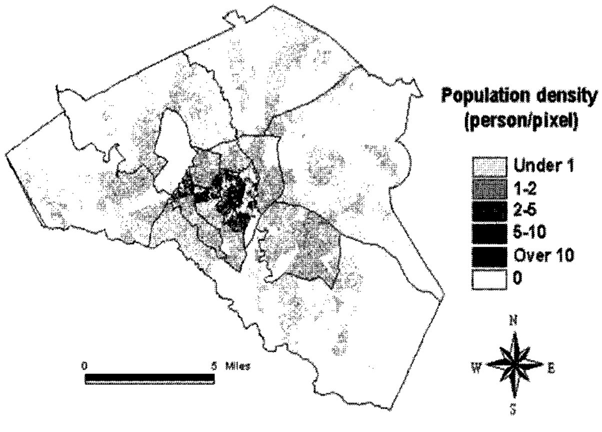



Figure 5. Result of dasymetric mapping

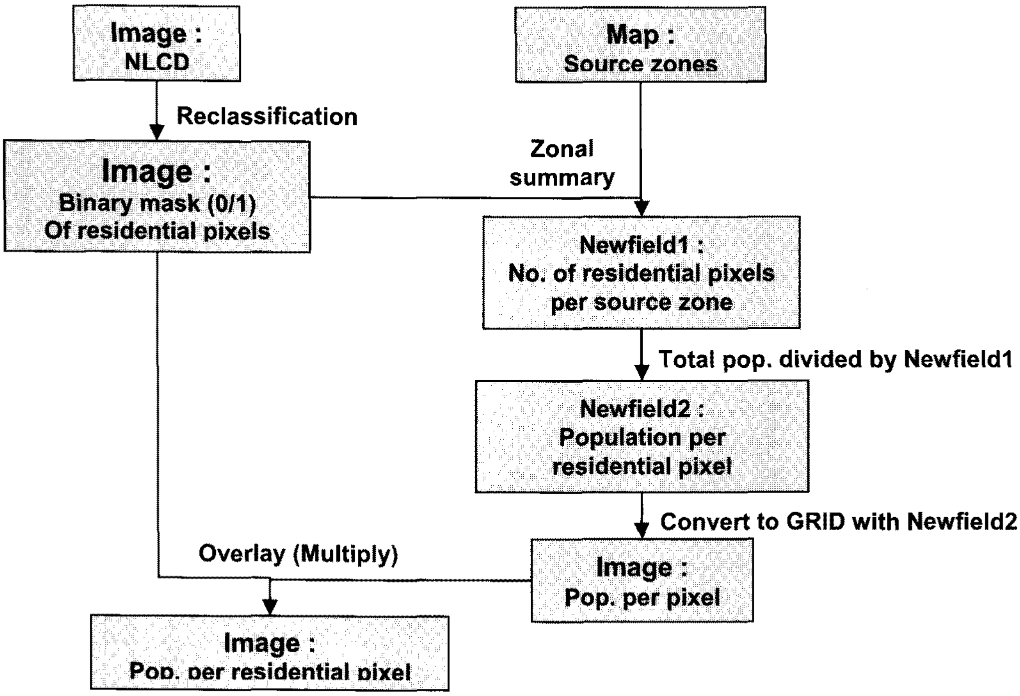



Figure 6. Dasymetric mapping process

each of those is from a different source zone regardless of their spatial adjacency.

Langford and Unwin (1994) pointed out that the initial dasymetric product is not particularly suitable for cartographic purposes due to the fine degree of spatial disaggregation and the consequent visual complexity of the resultant map. The discontinuity around the zone boundaries also can be added as one of those factors. To overcome these problems, the subsequent application of simple low-pass filtering operations to this output has been recommended to allow highly effective isarithmic and pseudo-three-dimensional products to be created (Langford 2003). Areal interpolation techniques can be used as the subsequent processing to create a smooth surface that takes the spatial adjacency into account.

### 2) Pycnophylactic interpolation

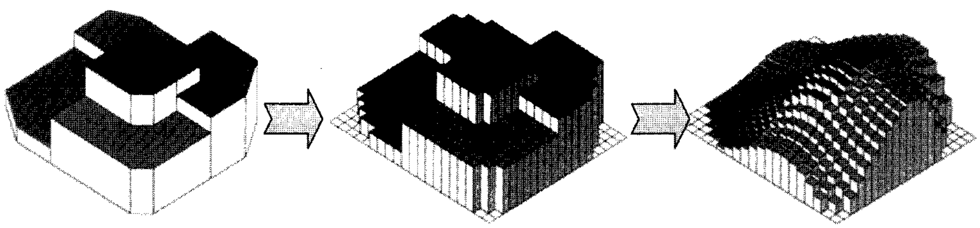
The pycnophylactic interpolation method was originally suggested by Tobler (1979) for isopleth mapping. The method assumes the existence of a smooth density function that takes into account the effect of adjacent source zones. The density function to be found must have the pycnophylactic, or volume-preserving, property, which can be defined in the following way. Let $p_k$ be the population of zone $k$, $A_k$ the area of zone $k$, $z_{ij}$ the density in cell $ij$, and $a$ the area of a cell. Set $q^k_{ij}$ equal to 1 if $ij$ is in zone $k$; otherwise set it at 0 (Lam 1983).

$$\sum_{ij} a z_{ij} q^k_{ij} = p_k,\ \sum_{ij} a q^k_{ij} = A_k, \text{ and } \sum_{k} q^k_{ij} = 1$$

The interpolation procedure begins by assigning the mean density to each grid cell superimposed on the source zones, and then modifies this by a slight amount to bring the density closer to the value required by the governing partial differential equation. The volume-preserving condition is then enforced by either incrementing or decrementing all the densities within individual zones after each computation.

In detail, the procedure is composed of 6 steps: 1) overlay a dense raster on a study area, 2) divide each zone's total value equally among the raster cells that overlap the zone, 3) smooth the values by replacing each cell's value with the average of its neighbors, 4) sum the values of the cells in each zone, 5) adjust the values of all cells within each zone proportionally so that the zone's total is the same as the original total e.g., if the total is 10% low, increase the value of each cell by 10%, 6) repeat steps 3, 4 and 5 until no more changes occur. The output is a continuously shaded map as shown in Figure 7. The pycnophylactic interpolation to create a grid map from population data in census units is implemented by the process illustrated in Figure 8 in this study.

Figure 9 shows the result of pycnophylactic interpolation. It doesn't take the uneven spatial distribution of populations within each source



Data polygons　　Rasterized　　Smoothed

Figure 7. Pycnophylactic interpolation process

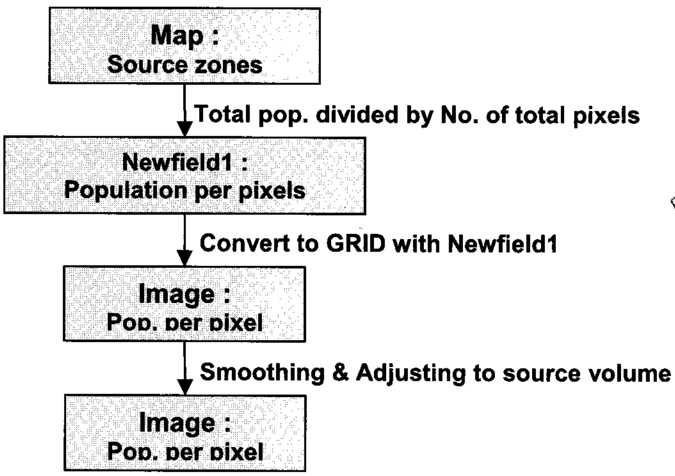



Figure 8. Pycnophylactic interpolation process

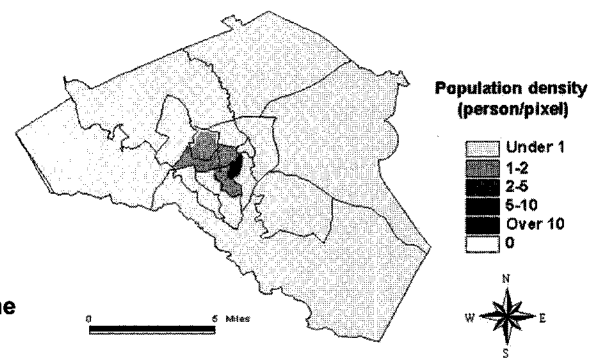



Figure 9. Result of pycnophylactic interpolation

zone into account so that the result is very similar to choropleth map of population density. It is different from the result of the conventional choropleth mapping or the simple dasymetric mapping in the point that the population density is smoothed. Therefore, it shows gradual, non-abrupt transition around zone boundaries.

### 3) Combined method: Hybrid Dasymetric-Pycnophylactic Technique

Compared with the choropleth and areal weighting method, the pycnophylactic method represents conceptual improvements since the effects of neighboring source zones have been taken into account. Moreover, homogeneity within zones is not required so that it can be effectively utilized as a subsequent areal interpolation with the dasymetric mapping approach. The pycnophylactic interpolation divides each zone's total population value among the raster cells that overlap the zone, by which varying population densities for different land uses can be taken into account.

In this study, a combined method of dasymetric mapping and pycnophylactic interpolation is developed by modifying the Avenue script originally coded by Riedl (1998). Census population data are disaggregated into population grid map using residential information extracted from remotely-sensed imagery. More specifically, population grid surface is built by pycnophylactic interpolation in which the assumption of uniform distribution within each zone is substituted by the dasymetric principle. The mapping procedure of the method is similar to that of dasymetric mapping except the last operation (modified pycnophylactic interpolation) which substitutes the simple overlay operation of dasymetric mapping. Modified pycnophylactic interpolation comprises the four sub operations: a) counting of residential pixels within each source zone, b) calculation of population density of residential pixels in each zone, c) smoothing function with adjacent pixels within specified distance parameter, and d) value adjustment process for volume preservation and iterations.

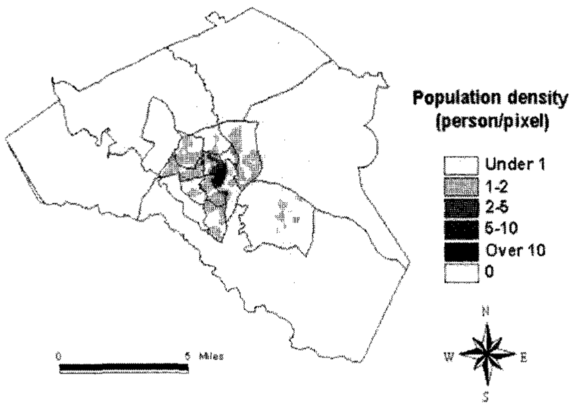



Figure 10. Result of the hybrid method

Figure 10 shows the result of the combined method. By incorporation of the dasymetric approach, the internal variation within each source zone is well represented. And, after the subsequent pycnophylactic interpolation procedure, the abrupt density transitions between source zones are smoothed so that the similarity of population density between adjacent pixels is also well taken into account. Moreover, the volume-preserving characteristic of pycnophylactic interpolation holds in check the possibility of excessive averaging of original population which can be caused by smoothing process.

## 4. Results

Three different population grid maps were generated by dasymetric mapping, pycnophylactic interpolation, and the combined hybrid method. Conceptually, these grid maps

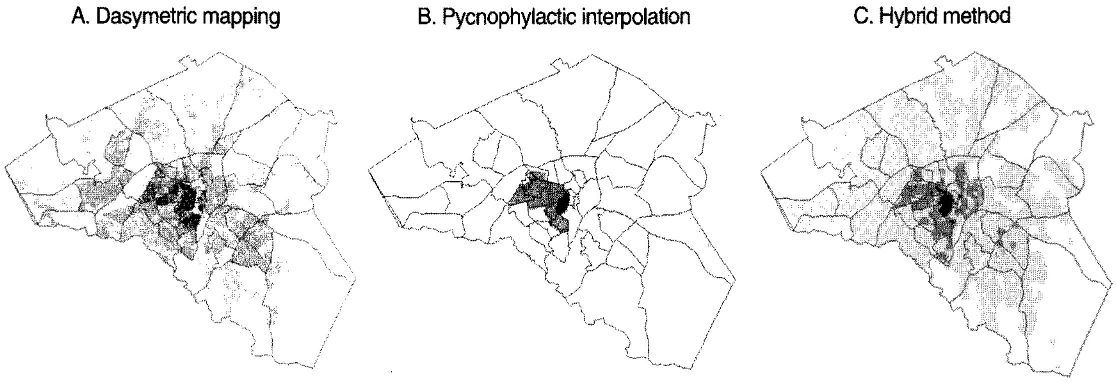



Figure 11. Zonal summation to Census block group level

can be aggregated to any spatial unit which is used for various analysis purposes if the unit size is considerably larger than the pixel size of those grid maps. In this study, for the purpose of verification and comparison of the three methods, these grid maps were aggregated into census block groups. This is mainly because the original population data of the target zones are used for accuracy assessment purpose. The census block group is a smaller spatial unit than the census tract that is used as the source zone so that it is reasonable to verify the performance of data transfer from the latter to the former, although the inverse doesn't make sense. To aggregate grid population density into census block groups, the block group map was overlaid on each population grid map and the values of pixels that fall into each target zone was summed for each block group. Figure 11 shows the population density surface maps produced from the three modeling methods. In Figure 11(A), the result of dasymetric mapping shows interspersed populated and vacant pixels. In addition, population densities radically change around the source zone boundary, though in reality such drastic changes along artificial boundaries are rarely seen. This is a manifestation of the discussed limitations of dasymetric mapping. The result of pycnophylactic interpolation in Figure 11(B) represents gradual density transition around source zone boundaries by applying a smooth density function across boundaries. However, without ancillary information to reveal internal variations of land use and land cover, it looks merely a smoothed representation of a choropleth map. In Figure 11(C), the hybrid method delivers estimation results that combine the advantages of both previous two methods. The internal variations are very well represented while abrupt density transitions are smoothed out.

Estimation errors for block group level aggregation are measured by the root mean squared error (RMSE) of the population estimates, as defined in following equation.

$$RMSE=\sqrt{\frac{\sum_{j=1}^{n}(P_{ej}-P_{aj})}{n}}$$

Where $P_{ej}$ is the estimated population of the $j^{th}$ target zone, $P_{aj}$ is the actual population of the $j^{th}$ target zone, and $n$ is the number of target zones. Also, three other measures of error were used to assess the accuracy of aggregated populations. Results from the three different methods were

Table 1. Comparison of census block group level aggregation results

| | Dasymetric mapping | Pycnophylactic interpolation | Combined method |
|---|---|---|---|
| RMSE (Coefficient of variation) | 342 (0.21) | 689 (0.42) | 314 (0.19) |
| Mean absolute percent error (MAPE) | 21.57% | 37.94% | 19.92% |
| Max relative error | 126.16% | 320.08% | 114.26% |
| Min relative error | -54.62% | -65.68% | -52.76% |

Note: mean population in target zones=1,622

summarized in table 1.

In table 1, the coefficient of variation is the ratio of RMSE to mean population value of target zone which is 1,622. As expected, pycnophylactic interpolation was the least accurate method, incorrectly allocating 38% of the population on average as shown by MAPE. It's almost same in RMSE measures. The other two methods which incorporated the population distribution within each source zone shows about a half in error measures of the pycnophylactic interpolation. Of both, moreover, the hybrid method shows slightly better result in all measures. In summary, the dasymetric approach shows much better result in transfer of population data between different spatial units than the pycnophylactic interpolation which is one of areal interpolation technique incorporating volume-preserving characteristic. And, the combination of both methods tested in this study has shown a little but consistent improvement over the simple dasymetric mapping method in terms of error measures as shown in Figure 12.

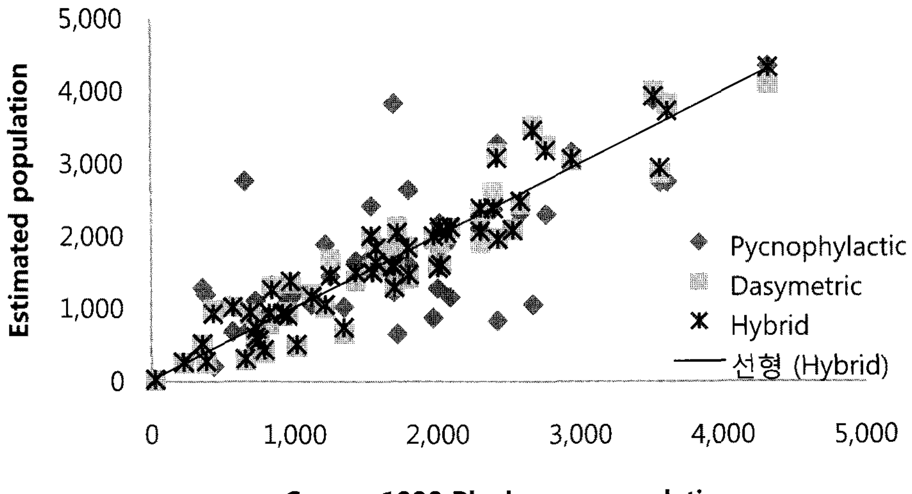



Figure 12. Scatter plot of the census block group population with estimation result

## 5. Summary and Conclusion

Population data are invariably collected and published according to some spatial aggregation. Therefore, they need to be converted to the other corresponding spatial unit the study objectives. The pycnophylactic interpolation is one of the transformation techniques and has been appraised as a conceptual improvement since the effects of neighboring source zones have been taken into account rather than conventional methods such as polygon overlay and simple areal weighted methods. It also has an advantage volume-preserving characteristic which is an essential requirement for accurate interpolation. However, the simple pycnophylactic interpolation is based on the assumption that the population is evenly distributed throughout the zone, which is in common with choropleth approach of cartographic representation. The dasymetric approach is an alternative to the choropleth approach to represent the varying population distribution within the zone which assumes that the people recorded by a census as present within the zone will reside in the houses that make up the residential areas that is critical for population distribution.

In this study, a combined hybrid method of dasymetric mapping and pycnophylactic interpolation in which census population data are disaggregated into population grid map using census data and residential information extracted from remotely-sensed imagery was presented. The resultant population grid maps with much more spatial detail than can be provided by the census data and their conventional representation like Choropleth map. Such a grid map is readily integrated with other GIS data, and could be beneficial to a variety of analysis applications. One of the key obstacles to the evaluation of such grid maps is the absence of definitive high resolution population data against which to compare. So, results were evaluated by comparison between original zonal population of smaller spatial units (Census block group) and aggregated population of the grid map built from larger spatial units (Census tract). To summarize, dasymetric approaches (dasymetric mapping, hybrid method) showed much better accuracy in aggregated population than the pycnophylactic interpolation. And, the hybrid method suggested in this study showed consistent improvement over the other two methods in terms of the four error measures hired for evaluation.

Given that the hybrid method has shown itself to be an effective method for data transfer between different spatial units and population mapping, what lies in the future in terms of methodological development? The resultant errors in modeled population grid map can be attributed to two major sources. The first is through the incorrect identification of residential area in the remotely-sensed data. Misclassification of residential area makes population to be distributed into places where it should not be present and vice versa, which directly degrades the quality of resultant grid map. So, to get more accurate population grid map, it is indispensable to improve the classification accuracy of remotely sensed imagery, perhaps with high resolution images. The second source of error is in the calibration of the dasymetric density. In a binary density map the assumption is made that people reside only in residential area and all residential areas in a source zone have the same population density. Despite this seems logical, in reality, there is likely to be some degree of variation in housing type, occupancy and thus population density within a source boundary. It is already plausible to distinguish between several residential categories when classifying urban areas from satellite imagery. Further methodological development to allow such multiple residential classes to be effectively incorporated into the process is needed for improvement of dasymetric approach to population grid mapping.

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