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Developing a theoretical framework for the delineation of administrative boundaries within a rural context

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ABSTRACT

One of the major problems limiting the integration, comparison and transfer of data within Spatial Data Infrastructures (SDIs) worldwide is the current arrangement of administrative boundaries. Many of these boundaries have been created by individual agencies to meet their own specific needs with very little coordination. Due to this lack of co-ordination, current technologies for analysing geospatial information, such as Geographic Information Systems (GIS), cannot provide accurate results. As a result, there is a fragmentation of information over a series of boundary units. This fragmentation of information not only limits the potential uses for data collected but also the potential scope of GIS analysis possible between boundary layers.

This paper forms part of an ongoing research project. To date the issue of structuring metropolitan boundaries has been addressed and widely published. In contrast, this paper focuses on providing a theoretical framework for improving the structure of administrative boundaries within the rural environment.

KEYWORDS: Geographic Information Systems (GIS), Administrative Units, Spatial Data Infrastructure (SDI), Hierarchical Spatial Reasoning (HSR)

INTRODUCTION

Administrative boundaries are frequently used for the display and analysis of information related to the earth. Health, wealth and population distributions are all examples of spatial information commonly attached to administrative polygons. In fact there are few areas of the economy and environment, which do not rely either directly or indirectly on this kind of information for planning, maintaining or rationalising activities. As a result data based on administrative boundary units (such as Census Collection Districts (CCDs) and Postcodes) are essential for the efficient planning of resources within rural regions.

Traditionally administrative boundaries have been designed by individual agencies to meet their individual needs. Consequently the current lack of coordination between agencies designing administrative units means that when the boundary systems are drawn together, the boundaries do not align with one another. This practice has resulted in boundary layers that cannot be accurately cross analysed. Therefore, geospatial information is fragmented over a series of boundary units (Eagleson et al, 2000). Figure 1 illustrates the problem where two individual agencies have established independent sets of boundaries.

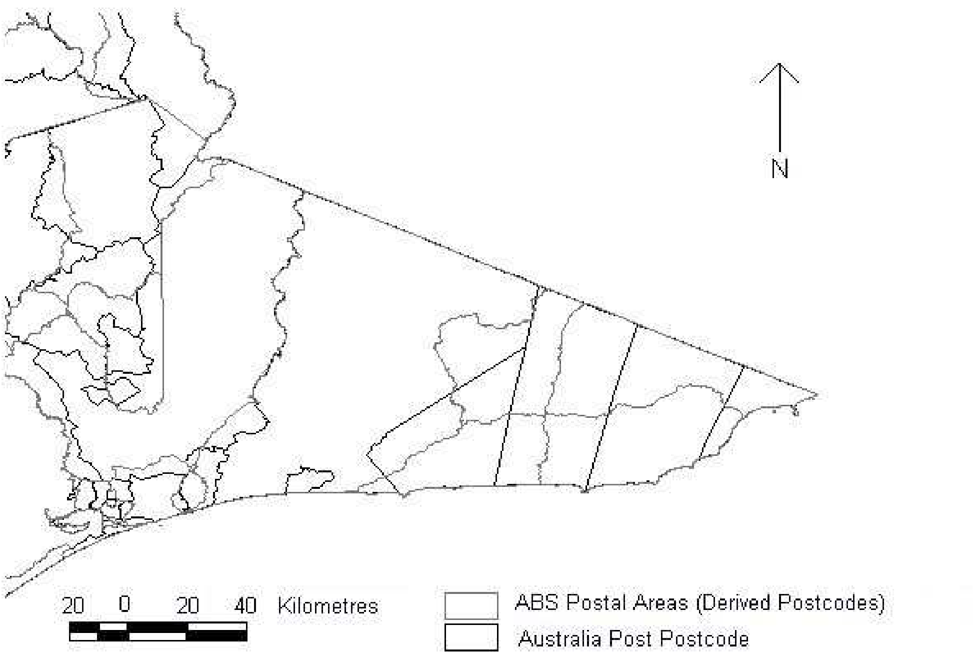


Figure 1. Illustration of two non-coterminous boundary systems, Australia Post Postcode and ABS Postal Areas (Derived Postcodes).

Many authors have highlighted the relevance of investigating the problem of data integration between incompatible boundary systems. These authors include: Bracken and Martin (1989), Huxhold (1991), Fischer and Nijkamp (1993), Openshaw and Rao, (1995) and Eagleson et al. (2000). The significance of investigating this problem has been further emphasised in various forums in Australia, particularly the Victorian Geospatial Information Reference Group (GIRG) 1998 and the First Symposium of GIS in Health, Melbourne 1997 (Escobar et al., 1997). Each author and forum suggest that if Spatial Data Infrastructures (SDIs) are to reach their full potential, administrative boundaries must be designed in a coordinated fashion.

The research presented in this paper forms part of an ongoing overall research project being conducted by the authors into the design of administrative boundaries using HSR theory and GIS technology. An initial prototype has been derived and discussed for the design in metropolitan regions (Eagleson et al., 2000). Following on from initial research, this paper explores issues related to the design of administrative boundaries within a rural context. Administrative boundary design within a rural context presents many challenges. These challenges include preserving the heterogeneity and confidentiality of rural communities whilst designing functional administrative boundaries.

The significance of administrative boundaries within Rural Australia

“About 99 per cent of Australia's 7.7 million square kilometres is considered rural or remote and are home to 29 per cent of the population" (Australia Post, 2001). Due to the vast area and limited resources available within rural Australia, effective planning of resources is critical. In order to be effective the planning process often requires the integration of data from a variety of sources. Although the technology for data integration is available, the incompatible design of administrative units restricts cross analysis. This problem of incompatible boundary design is often termed the ‘spatial hierarchy problem.’

Victoria’s health service planning initiatives demonstrate the restrictive nature of the spatial hierarchy problem within the GIS environment. Medical institutions often attach data to postcodes, while demographic data is attached to collector district boundaries. However because the two boundary systems overlap accurate cross analysis between demographic and health statistics is extremely difficult, if not virtually impossible (Eagleson, et al., 2000).

Current Solutions to the Problem

Due to the wide extent of the spatial hierarchy problem solutions are being sought. Currently these proposed solutions involve either the interpolation of data from one boundary set to another (Goodchild et al., 1993), or the re-aggregation of point data into a number of different boundary systems. Unfortunately, due to the problems associated with confidentiality, accuracy and cost, neither data interpolation nor re-aggregation provides an optimal solution to the problems associated with uncoordinated boundary alignment (Eagleson, 1999). The solution proposed in this research involves the re-organisation of boundaries into a singular structured hierarchical system, eliminating the need for interpolation and reaggregation of point data.

HIERARCHICAL SPATIAL REASONING (HSR)

“Hierarchy is one of the most common forms of organising and structuring complex systems where a system is subdivided in smaller subsystems, and further subdivision of subsystems can be recursively repeated as long as the subdivision makes sense” (Car, 1997, Koestler 1967). Currently, hierarchical principles are used in an array of different disciplines to break complex problems into sub problems that can be solved in an effective manner (Timpf and Frank, 1997). Although spatial hierarchies are designed using the same principles – to break complex tasks into sub tasks or areas – relationships between levels within the hierarchies are complex.

In the past much research has focussed on the properties of two-dimensional hierarchical structures to model networks, such as road and drainage systems. This research however, aims to utilize the three properties inherent to hierarchies that make them adaptable in boundary design; the *Whole-Part property, Janus Effect* and *Near Decomposability.* These properties provide an insight into the way that each layer within a hierarchy interacts with each other and also with the whole system. This research aims to utilise each of these properties in the structuring of a polygon-based hierarchy.

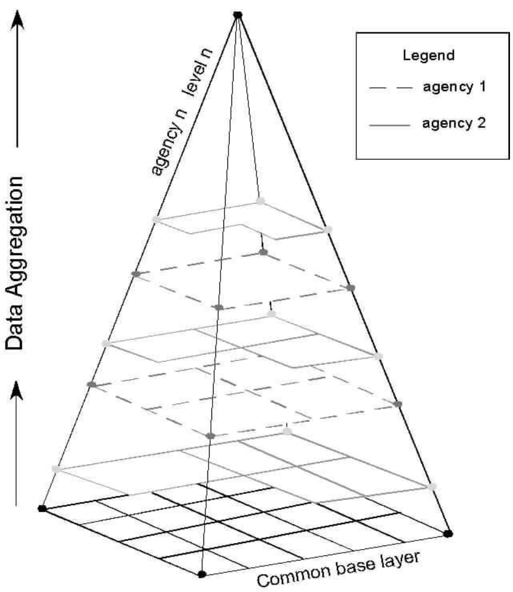


Figure 2 Abstract illustration of the ideal spatial hierarchy. Each agency is able to utilise the common base layer for the construction of individual layers within the hierarchy.

HSR theory applied to administrative polygons

It is envisaged that the application of HSR theory to co-ordinate various agency boundaries, within a common hierarchical spatial framework, will provide the capability to revolutionise data integration and analysis methods. Figure 2 illustrates the proposed solution. Through the application of HSR theory the spatial boundaries of different agencies are organised in a coordinated hierarchical system (Car 1997). Data exchange and aggregation is possible within, and amongst individual agencies providing aggregated data at all levels.

Modifiable Area Unit Problem

One of the major arguments against aggregating socioeconomic and demographic data to administrative polygons is the fact that the design of polygons can influence the overall results. This is also known as the Modifiable Area Unit Problem, (MAUP). The MAUP is "a form of ecological fallacy associated with the aggregation of data into areal units for geographical analysis. This aggregated data is then treated as individuals in analysis," (Openshaw and Taylor, 1981). The MAUP can be divided into two parts, level of aggregation, and zoning configuration (Fotheringham and Wong, 1991). This problem is fundamental in the display of demographic data as the information people perceive can be altered by the size, shape, and scale that is used for display (Fotheringham and Wong, 1991).

Haslam-McKenzie (2001) details an example in rural Australia, where the display of aggregated data in rural western Australia results in an interpretation of misleading information. The overall population of the region from Geraldton south to Esperance in Western Australia, excluding the metropolitan area, has increased in the years between 1961 and 1991. The Australian Bureau of Statistics' (ABS) twelve statistical divisions show fairly steady population growth and politicians and bureaucrats often cite these statistics as evidence of growth within the region (Haslam-McKenzie, 2001). However, when ABS statistical subdivisions are closely analysed, it is obvious that the increase in population has not been uniform. A small number of subdivisions show a significant population increase while the majority of inland subdivisions have experienced depopulation. These inland subdivisions, which are limited to agricultural production and can be defined as completely rural, exhibit a persistent decrease in population (Haslam-McKenzie, 2001). For those rural dwellers living in the wheatbelt that stretches inland from Geraldton to Esperance the 'misinterpretation' of the statistics has meant that regional issues and concerns have not been properly understood by policy makers (Haslam-McKenzie, 2001).

This research aims to address these problems by providing a range of spatial solutions to the MAUP. In the past, because boundaries were assumed fixed, researchers had to use whatever boundaries were available (Openshaw and Rao, 1995). Consequently the user had little, if any, control over the MAUP. However, as Openshaw and Taylor (1979) explain, it is now possible for data users to exert some influence over the MAUP. In doing so it is recommended for analysts to:

1. 1. Start from the smallest divisions available, or the smallest they can process,
2. 2. Aggregate these in a fashion relevant to their investigation,
3. 3. Assess the repeatability of their results for several aggregations.

The solution proposed in this research is directed towards the development of a framework so data analysts are able to design boundaries for specific applications (where possible) thereby reducing the influence of the MAUP. This framework addresses the three points recommended by Openshaw and Taylor (1979).

SUMMARY OF THE METROPOLITAN BOUNDARY PROJECT

Previous research has been undertaken into the delineation of metropolitan administrative boundaries. Due to the relative uniform density of the population in metropolitan regions, road ceterlines were used to form meshblocks[*] for the aggregation of boundaries according to a range of agency constraints. These constraints were based on the requirements of Australia Post and ABS (Eagleson et al., 2000) and include:

- • The preservation of topographic barriers. Examples of barriers include large rivers and roads that may obstruct delivery mechanisms. Additionally, these boundaries often divide different community groups and these differences are imperative to many planning activities and should where possible be preserved.
- • In order to preserve confidentially, the ABS state that each CCD unit must cover approximately 200 households (ABS, 1996).

[*] Meshblock – A spatial unit formed through the intersection of road centreline data.

- • To facilitate delivery mechanisms it is important that the boundaries are in alignment with the road network and are identifiable on the ground. Using the meshblock for the aggregation assures this constraint is met.
- • To ensure uniformity across the area it is important that the boundaries are contiguous and provide complete coverage across the area without gaps or overlaps.
- • Although there is no formal definition of boundary shape it was decided that the boundaries should be constructed in a manner that enabled them to be compact. To ensure the boundaries established are compact the model tests each boundary based on the circularity index devised by Tomlin (1992).

In undertaking this initial research it became clear that it is possible to design a spatial hierarchy of administrative boundaries within the metropolitan landscape. However, metropolitan and rural landscapes are very different. In direct contrast to the metropolitan landscape, the rural landscape is large, parcel sizes vary and roads often unite rural communities. Table 1 highlights some of the differences in the infrastructure of rural and metropolitan landscapes.

	Urban	**Rural**
Address Point Database	Complete	Incomplete
Cadastral Parcel Size	Typically small	Highly variable
Large topographic Features	Divide communities	Unite and divide communities
Administrative boundary accuracy	High	Low
Meshblock	Uniform unit size	Variable unit size
Roads	Divide Communities	Unite Communities

Table 1 Differences between the rural and urban landscape.

These differences highlight the need for the development of a distinctly different model from the one developed for use within metropolitan areas.

RURAL

The following section highlights the agencies investigated and the development of a model for the automated delineation of rural administrative boundaries within a spatial hierarchy.

Agencies

Although it is well recognised a number of boundaries systems exist the focus of this research is to test the concept of integrating the needs of three selected agencies into one common spatial hierarchy. Therefore for this purpose the relevant boundary systems selected for investigation are the Census Collection Districts (CCD), Country Fire Authority (CFA) units and Postcode boundaries. These boundaries have been selected due to their national coverage and acceptance in both the geospatial and public sectors. The following discussion outlines the function of administrative boundaries for each of the agencies and the current boundary hierarchies used by these agencies respectively.

Australian Bureau of Statistics Census Collector District Boundaries

The ABS has devised CCD as the smallest unit within the Australian Standard Geographical Classification (ASGC), where the ASGC is a classification derived by the ABS for the collection and dissemination of statistical data (Mc Lennan, 1996). The ASGC divides Australia into numerous hierarchical levels to facilitate statistical functions. These levels are based on six interrelated classification structures. These are:

- • Main Structure
- • Local Government Area Structure
- • Statistical District Structure
- • Statistical Region Structure
- • Urban Center/Locality structure and;
- • Section of the State structure

The Main, Statistical Region and Section of the State Structures each cover the whole of Australia without gaps or overlaps. The remaining structures cover only part of Australia. In the formation of the ASGC, the smallest of the spatially defined units is the CCD. Consequently, the CCD has been used in the aggregation of the six classification structures outlined above.

In designing CCD boundaries there is a number of specific criteria that are imperative to their effectiveness both operationally and as display units for the analysis and display of population related statistics. To be effective as collection districts it must be possible for census collectors to cover the entire area of the CCD within a two day period. To guarantee confidentiality each CCD must contain an aggregation of approximately 200 households. Additionally, for the CCD boundaries to be effective for the display of demographic related data the boundary design must ensure the heterogeneity of the rural population can be represented.

Country Fire Authority boundaries

CFA delivers services to the community through 1,218 fire brigades distributed throughout rural, semi-urban and urban Victoria (CFA, 2001). To effectively manage and administer its resources the CFA utilises a number of boundary systems. These boundary systems can be divided into two types each with distinctly separate functions. The first are the 12 CFA area boundaries; these areas are used for the allocation of headquarters and aid in the distribution of resources (such as staff, finance, and equipment). CFA areas are formed through the aggregation of 21 CFA regions. CFA regional boundaries are used for administration activities such as of public education and fire prevention campaigns (CFA, 2001).

The second set of boundaries used by the CFA is termed 'operational' and aid in the dispatch of fire brigades. These boundaries are essentially based on the area of coverage a CFA brigade can reach within a specific time limit.

The alignment of CFA boundaries with ABS boundaries has many potential advantages. For example the combination of CFA boundaries with demographic and agricultural data collected by the ABS is beneficial for fire prevention and modeling (Garvey, 2001).

Australia Post Postcode boundaries

"Of the 7.66 million addresses that Australia Post's letter service goes to, 2.3 million are in the country, outback or on islands. The letter service links people in rural and remote Australia with the rest of the country and the outside world" (Australia Post, 2001).

Postcode boundaries have been derived by Australia Post to facilitate the delivery of mail. The initial allocation of postcode boundaries was on a semi ad hoc basis, and the method of allocation varied between states. Initially there is a division between City, Suburbs and Country areas. These are further split into regions with groups of codes allocated to these regions. These initial postcodes were allocated radially along major transportation routes to facilitate the delivery of mail. Today postcodes are (where possible) being brought into alignment with suburb and locality boundaries. Postcodes are extremely important administrative units as they are often used as a common identifier for the aggregation and storage of different information types.

The role of road centrelines for boundary delineation within rural regions

Within the process of designing a model for the automated allocation of boundaries in a spatial hierarchy, there are a number of constraints that need to be incorporated into the model. These constraints are used to guide the allocation of boundaries into a position that ensures that each boundary meets the function for which it is required. Hugo et al (1997) have produced a detailed report on the review of the current design of boundaries highlighting the impact of designing boundaries based on incorrect constraints. This report also provides recommended changes for the boundary delineation system in an effort to improve the relationship between the social, physical and economic realities of the rural landscape (Hugo et al., 1997).

One primary example where constraints can be used to improve the design of administrative boundaries in rural regions is the appropriate use of road centerline data. In the past, road centerlines were used in the delineation of CCDs, dividing rural communities, which are of similar constitution, combining them with the diverse outer rural regions. As a result, the overall aggregation of population statistics to the demographic boundaries reveals homogeneity between units when in fact they are very different. Figure 3a and 3b illustrate a town and the effect of using road centerlines to establish boundaries can have in these areas, (Hugo et al., 1997). In some instances the town is divided by a single road running through the community, in other instances a number of roads radiate out from the center segmenting the town structure from the center out. As a result, the administrative units contain data from the town center and the outer rural regions. When data for these regions is aggregated populations appear homogeneous when in fact they are not. The importance of roads in the allocation of boundaries is reinforced by the system used in Sweden for boundary allocation as Smailes (in Hugo et al., 1997) states:

"In rural areas the subdivisions … should be bounded so that a road, if possible, can form the life line of the area. The roadway in rural areas has a central integrating function for the settlement pattern as well as population movements', while physical barriers like larger forest area, hill ranges, rivers, lakes etc. form natural barriers for people and, therefore can be used as boundaries" (Smailes in Hugo et al., 1997 p156).

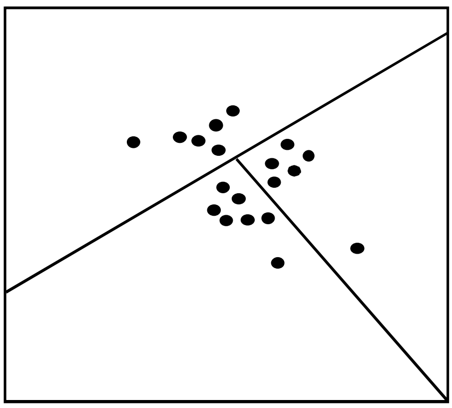


Figure 3a Collector districts assigned by road centrelines. As a direct result the township is segregated and demographics of residents are combined with the people in rural areas.

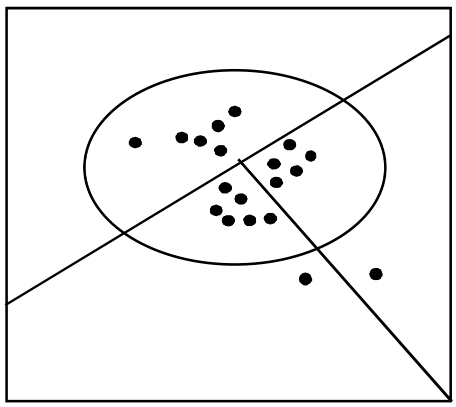


Figure 3b Collector districts are defined around the town, therefore the demographics of the town can be distinguished from the demographics of people living outside the town.

Summary of Constraints

It is important when defining spatial boundaries that the administration units created are not only functional but may be used for the display and analysis of a wide number of social and economic attributes without displaying bias. In an attempt to meet these requirements, the following constraints have been established.

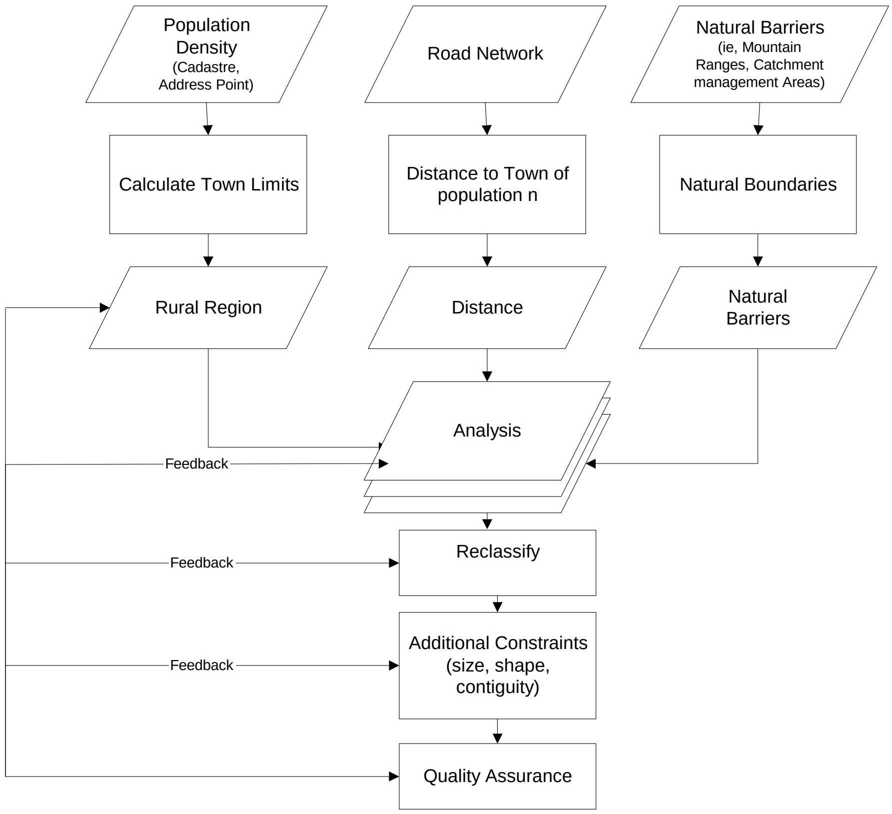
- • The primary importance to each of the agencies is the preservation of town boundaries. Therefore towns shall be delineated according to **population density** or if possible existing town or locality boundaries maybe investigated for use.
- • As each of the administrative agencies used the boundaries to facilitate the distribution of resources, the **distance** travelled along the road network within a unit will be crucial for determining functional administrative boundaries. For example to be effective as collection districts it must be possible for census collectors to cover the entire area of the CCD within a two day period.
- • Large topographic features, which form **natural barriers** between communities, should be preserved.
- • To ensure the **confidentiality** of individuals, the ABS specifies that collector districts must contain approximately 200 households (ABS, 1996).
- • To be effective administrative the units crated must be **contiguous** across the state.

- • Similar to the metropolitan regions there is no formal definition of boundary **shape**. However it is anticipated that the model derived should facilitate the delineation of compact administrative units. The index of circularity developed by Tomlin (1992) will be used to assess the compactness of the administrative boundaries developed.
- • To ensure complete coverage across the region each of the administrative units shall be contiguous across the state without gaps or overlaps.

The following section outlines the incorporation of these constraints into a model for the automated delineation of administrative units within the rural environment.

Model Development

The implementation of a spatial hierarchy requires a technical solution. Taking into consideration the constraints outlined above the following section outlines a model for the automated delineation of rural



boundaries within a spatial hierarchy. Figure 4 provides a flow diagram of the inputs, decisions and processes utilised within model development.

Figure 4 Inputs, decisions and processes utilised within model development

The following section describes each of the main stages of development.

1. 1. Input Data

At this stage input data consists of three primary layers. Each of the data layers has been selected because of the key attributes contained within the layer as outlined below:

a) a) Because this model is based on rural regions it is important to filter out any regions that are classified as urban. In this research density will be used to filter and delineate the urban and rural areas. The rural regions will then be used as input into the model (the urban regions can be subdivided using the metropolitan model previously researched (Eagleson et al., 2000)).

b) b) Distance along the road network is vital in routing for each of the agencies. Therefore distance modelling will ensure that the travel time from points of distribution (ie town centers) to outlying regions is incorporated within the model.

c) c) Natural barriers in the landscape, which divide communities, will be preserved. In this instance this layer will incorporate Catchment Management Areas (CMA) as defined for Victoria. These boundaries have been chosen because they have been defined along many topographic boundaries that naturally divide the landscape. Additionally, these boundaries are used by a number of users for environmental planning and modelling across the state.

The data structure selected for each of these data layers is raster. Raster data layers have been selected because of the availability of data and the variety of cartographic modeling functions available for raster data within GIS.

2. 2. Analysis

Once the initial input data has been processed against each of the relevant constraints (ie rural regions, distance and natural barriers) the analysis phase will take place. The analysis involves the overlay of each of the input layers. The resulting values are weighted and reclassified in order to facilitate combination of the different output layers. As a result a new grid is produced and an integer value calculated for each cell based on the overlay of the three initial data layers.

Following the previous phase the data layer is reclassified to aggregate cells of homogenous value. The algorithm used during this phase will depend upon additional agency constraints such as size, contiguity and shape as detailed above.[R1]

3. 3. Quality Assurance

The final stage of the model has been designed to provide quality assurance testing in order to ensure the output conforms to the required constraints. If any of the units designed by the program fail to meet the initial constraints then the quality assurance routine is able to locate the problem regions and alert the operator. In some instances the model may need to be rerun using weights to aid in the boundary allocation process.

It is envisaged that once the model has been applied, the output layer can then be used as input for the next level of the hierarchy, using different or modified criteria. A prime example of a hierarchical set of boundaries is the ASGC where the base unit is the Census Collection District (CCD). The CCD is then aggregated to form Statistical Local Areas (SLAs). SLAs are aggregated to form Local Government Areas (LGAs) and LGAs are aggregated to form state and territory boundaries.

Current research will include the formalisation of the model into a GIS. This formalisation phase will take place through the development of an algorithm using the programming language Avenue, an object-oriented programming language that operates under ArcView. Due to the importance of the model in determining the position of boundaries, it will require extensive testing. The testing phase will asses the capability model to firstly, meet the spatial requirements of the agencies and secondly, the effectiveness of the model for creating a spatial hierarchy.

Results from the model testing will be used to further refine and develop an optimum model. Once completed, it is anticipated that the model will provide a systematic and rigorous method to the task of boundary delineation within the rural environment.

CONCLUSION

This paper outlines ongoing research into techniques for the automated delineation of administrative boundaries using GIS technology. Extensive research has been completed into the derivation of boundaries in an urban environment. This research has been widely presented both nationally through the AUSLIG, Australian SDI Partnership Grants Program and internationally through the URISA 2000 and GIS Research UK 2001 conferences. The research presented in this paper goes beyond this, building on these concepts and extending them to the re-organisation of administrative boundaries within rural Australia.

It is well known that the attributes of the rural landscape are vastly different from the attributes of an urban landscape. The model under development aims to incorporate these differences along with agency requirements into a cohesive model for the effective development of a rural spatial hierarchy.

With the increased demand for geospatial information, it is proposed that the realignment of administration boundaries based on HSR will overcome many of the present data fragmentation issues. In order to achieve this objective however, it is important that agencies realise their boundaries provide fundamental units for the display and analysis of social, demographic and environmental data.

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