Developing a Quasi-Temporal GIS for Archival Map Data

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Abstract:

Despite considerable research, GIS remain two-dimensional (atemporal), limiting historical research. A prototype, "quasi"-temporal ArcView 3.x extension adds temporal functionality for the capture, analysis and display of historical data derived from archival maps. While the composite database model used is inherently inefficient in terms of database structure, modern computer hardware is sufficiently powerful to overcome this limitation, making temporal analysis feasible.

A methodology of using archival maps for temporal information only (presence/absence or 'temporal location' as opposed to spatial location) expedites historical database construction.

A case study (Fairhaven, WA) illustrates the possibilities and limitations of the extension and archival map data.

Paper Outline

…we need to understand better what it means for a location to have not only space coordinates but also time coordinates… location in space cannot effectively be separated from the flow of time.

-- Hagerstrand, 1970, What About People in Regional Science, p. 9 [Hage70]

Geography and history are not only analogous, but complementary and interdependent, bound together by the very nature of things.

-- Meinig, 1986, The Shaping of America, p. XV [Mein86]

Many design proposals and even some intriguing prototype software solutions [have been presented]… However, not much has been accomplished in the real world, although potential applications of temporal GIS abound.

-- Ott & Swiaczny, 2001, Time-Integrative Geographic Information Systems, p. 3 [Ott01]

Introduction

This paper presents a prototype quasi-temporal extension developed for ArcView 3.x along and a data capture methodology for use with archival map data.[1]

The notion that archival maps hold potential as a data source for historians and geographers alike comes as no surprise. Archival maps contain a unique wealth of data (e.g., place names, locations of features that no longer exist, etc.) that is often difficult to find in other media. Unfortunately, this richness of history comes with a likewise unique array of challenges including varied scale, coordinate system, extent, purpose, physical size and cultural context. These challenges are in addition to the fundamental problems of limited accessibility and

[1] This work is a continuation of a 2003 Masters of Science thesis (Geography) for Huxley College of the Environment, Western Washington University, Bellingham, WA.

insufficient metadata inherent in almost all archival materials [Greg02b, Rums02].

Geographic Information Systems (GIS) offer the potential to overcome some of these challenges, providing an interface for compiling data derived from multiple maps. However, working with archival map data within a GIS is limited by a lack of temporal functionality. Beyond the creation of a series of static snapshots, little exists in the way of tools to compile information derived from a disparate collection of maps. Nor do well developed methods exist for cataloging archival map data for historical analysis. For the purposes of historical research, methods of extracting and compiling data relevant to a given study are lacking. In addition, a means of comparing and contrasting different maps, as well as of evaluating the similarities or differences is needed.

While GIS have recently begun to be used by historians as a research tool, the primary use, with regard to archival maps, has been as a means of incorporating static digital imagery. This paper examines the additional capabilities GIS technology offers for capturing and incorporating the archival map data itself for historical analysis. In particular, the potential of a simple quasi-temporal GIS extension is investigated as a tool that could address many of the challenges of archival maps. As a demonstration of this work, a prototype quasi-temporal GIS extension was developed for conducting historical research using archival map data. A case study of Fairhaven, WA (1880-1930) was conducted to evaluate this extension.

This work demonstrates that current computer processing capacities are sufficient to make the design and implementation of a quasi-temporal GIS application feasible, and that such an application could be employed for the development, analysis and display of spatio-temporal databases derived from archival maps, especially when used in conjunction with the data capture method as detailed below.

Paper Organization

The next section of this paper details the objectives and underlying theory of this work, followed by a brief discussion on the definition of 'time' within a digital database. Ways in which time has been included in GIS and tabular databases are discussed along with details of the tGIS extension and methodology developed for this work. Finally, a case study, conclusions and recommendations for further work are provided along with a bibliography.

Objectives

This paper addresses two related issues: the lack of temporal functionality within current GIS software, and the need for a mechanism for transferring spatial information from archival maps to digital databases.

'Quasi'-Temporal GIS

Despite considerable research and recent advances, current GIS software remains fundamentally two-dimensional (atemporal) [Chri02, Chris98, Couc99, Greg02b, Haze98, Ott01, Worb98]. While a variety of prototypical temporal GIS applications have been designed and/or implemented, mainstream software packages continue to lack true temporal capabilities [Crab99]. Nor is this expected to change in the near future [Abra99, Long99, Ott01, Peuq01]. Thus, temporal analysis, such as is possible at all, is dependent on inefficient data searching methodologies where time is treated as an attribute (of a spatial feature or of the entire data layer) rather than a coordinate of space-time. Advances in computer hardware, however, continue to make such computationally-intensive analysis feasible in spite of these inefficiencies. Thus, even without a true or full Temporal GIS (*TGIS*), limited or quasi-temporal GIS (*tGIS*) [2] applications have been proposed [Abra99, Egen98, Lang92, Ott01] that enable basic temporal analysis. What is needed is a database design and a user interface for entering, updating and querying a temporal component within existing GIS packages.

Data Capture from Archival Maps

The second issue addressed is that of data capture from archival maps and the need to move beyond simple scanned images to feature extraction. The most common treatment for archival maps has been simple rectification of scanned maps for use with other GIS layers and data [Rums02]. While an excellent first step towards making archival map data accessible, two primary limitations exist with this method: the map is simply a graphic image (i.e., there is no way to query the data on the map from within the GIS other than visual analysis), and such images do not lend themselves to map overlay or combination (one image masks out another, preventing even visual comparison of multiple maps).[3]

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[2] A note on the use of *TGIS* vs. *tGIS*: For the purposes of this paper a distinction is made between the abstract, hypothetical ideal of a fully temporal GIS software package (treating time as a coordinate of space-time rather than as an attribute of space) and the prototype temporal GIS extension developed for this paper. Throughout this work the 'ideal' of a temporal GIS is referred to as 'TGIS,' while the quasi-temporal GIS application developed here is referred to as 'tGIS.' The particular style of tGIS developed for this thesis has also been referred to as a "historical GIS," [Greg02b, Know02, Ott01] a term not used here due to use of the same term in reference to historical analysis being done with a GIS in general.

[3] A partial solution to this problem is to make the scanned images semi-transparent, enabling two or more to be combined [Rums02]. Depending on the amount of detail and color used on a given set of maps this can be useful for visually comparing two images, but has limitations for more complicated overlay operations.

An alternative to simple rectification of scanned images is to digitize the features of the map, creating GIS layers (using points, lines and polygons) to recreate key elements of an archival map. Relatively little work of this nature has been done to date, in part due to the labor intensiveness of manually digitizing data. This is exacerbated by the lack of temporal capabilities within current GIS, reducing the incentive for digitization.

For relatively recent archival map data,[4] a third option exists, though even less frequently employed. This method (which was successfully used with the tGIS extension for the Fairhaven case study) uses current GIS data layers in combination with archival maps. Spatial locations are established using current GIS data (streets, parcels, etc.), allowing the archival maps to be used exclusively for identifying the presence or absence of a feature at a given point in time. This "time stamp" information is then added as attribute data to spatial features which have been extracted from the GIS layer(s). This method has the advantage of eliminating a number of process steps (scanning, rectifying and digitizing the original map).

Present Work

Thus two separate GIS challenges exist: the inclusion of time and the capture of archival map data. The hypothesis explored in this paper is that with relatively simple scripting ('macro' programming available within existing GIS software packages) basic temporal capabilities can be added to currently available GIS software enabling the capture, query and display of temporal data extracted from

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[4] In general, maps from the nineteenth century or later would likely have the necessary spatial accuracy as well as sufficient thematic overlap (of mapped historical features and present day GIS features) to enable data transfer.

archival map sources.[5] The prototype tGIS extension and methodology developed here were designed to facilitate efficient archival feature extraction and the creation of spatio-temporal composite databases[6]. A major limitation of this type of database system is the inefficiency of treating time as an attribute rather than a coordinate of space-time [Lang92a, Ott01]. However, this work demonstrates that given modern computer hardware, such a system can be made functionally feasible, despite this inefficient data structure and the potentially large datasets inherent in historical databases.

The benefit of such a system is to bring the power of spatial analysis and user initiated (ad-hoc) spatial query and cartographic display found in current GIS further into the realm of archival maps and historical research. Composite temporal data layers (e.g., all roads or all buildings for a range of dates) allow the information from a multitude of disparate maps and archival data sources to be combined into a single dataset, providing a means for tracking a feature’s lineage or filiation (i.e., the history and/or future of a given feature through time).

It should be noted that such a database is not intended to replace archival maps, but rather to supplement them. Its main purpose is to provide a tool for historical query and analysis of data extracted from a combination of multiple map sources. In addition, by maintaining feature-level metadata within the tGIS, the database can serve as a spatial catalog for archival map data.

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[5] While the focus of this paper is temporal GIS as it relates to archival maps and historical research, this is by no means the only discipline that would benefit from temporal GIS development. Planning, demographics, health, archeology, geology, natural resource management and risk assessment are but a few of the fields of study using current GIS for temporal analysis despite its lack of full temporal functionality.

[6] The spatio-temporal composite data model is discussed further below.

The composite database design developed relies on temporal filters to retrieve data for a given time period, and is intentionally generic. While it was developed specifically to work with archival map data, it could be adapted to work with a variety of other temporal applications. The simple database design, using existing database formats, enables user-defined parameters while enabling a relatively rapid query and display of the data and a minimum of data redundancy.

To evaluate the usefulness as well as the limitations of the prototype tGIS extension, a case study of Fairhaven, WA (1880-1930) was conducted using archival maps as the primary data sources. For the most part the case study did not attempt to use the archival maps for deriving precise *spatial* information. Instead, archival data was used in conjunction with current GIS data as a source of temporal (as opposed to spatial) 'locations' (i.e., the presence or absence of the feature at the time of the archival map).

Time in a TGIS: Temporal Metaphors and Types

Before attempting to capture time within a GIS the definition of time itself (as it will be represented within the database) needs to be established. Two primary decisions are the conceptual model (or temporal metaphor) used to describe time and the type(s) of time to be recorded.

Four prevalent metaphors of time can be identified: linear time (the Newtonian time line, with time stretching forward into the future and backwards into the past), cyclical time (appropriate for the seasons of the year, bus schedules, etc.), branching time (hypothetical, paths which time might follow in a model of the future or past) and multi-dimensional time (rarely dealt with in a GIS, and best left for philosophers and disciplines of cultural, religious and metaphysical studies) [Clar95, Fran98, Haze98, Haze92, Lang93a, Vasi98]. By far the two most frequently used metaphors in Western cultures are linear and cyclical [Haze92, Tao95].

Two distinct 'types' of time are commonly identified as requiring treatment in a TGIS: *World Time* and *Database Time* [Cand95, Fran98, Lang92, Lang88, Raaf94, Worb98, Zhong96]. 'World time,' the more intuitively obvious of the two, refers to the time when an event occurred in the world (i.e., the time of creation, alteration or destruction of a feature or an event). 'Database time' refers to the time at which the information about a feature or event is entered into the database itself (typically sometime after the time of actual occurrence, but theoretically simultaneous or even prior to world time).[7] If a TGIS is to enable historical recall of past events or features it clearly must be able to discern between that which was in existence five years ago and that which currently exists (i.e., it must maintain world time). Both for analysis and display the ability to track world time is fundamental to a TGIS. However, in some cases database time may be of equal or even greater importance.[8] Given a TGIS that includes both world and database time, both the lifespan of an object or event, and the duration of the database's record of the object or event are retained, enabling the reconstruction of not only

[7] World and Database time have been referred to by a number of other terms, including: valid, logical, extrinsic, real and event time (in lieu of world time) and transactional, physical, recorded and commit time (in lieu of database time) [Lang88, Sarg98, Worb98].

[8] Examples such as bank deposit or the return of a library book are cases where the recorded time (database time) may be of greater significance than world time.

past (or future) states of world, but also different versions of the these different states, as was modeled by the database at different points in time.[9]

Moreover, there may be applications which require more than these two basic types of time. For example, the time at which a measurement of an event is made (variously referred to as measured, recorded or field time) may also be of value [Cand95]. In the case of human activities, such as a construction project, a TGIS may be required to maintain the conceptual or institutional time (of design or planning) and the time of implementation or construction time (which may overlap with the conceptual time), as well as the time of completion [Cand95, Jone96, Lest90].

Beyond the chosen metaphor and type of time, other more mundane decisions remain with regard to time, such as the temporal reference system (or calendar). Likewise, the temporal resolution or granularity of the database needs to be considered [Cand95, Lang92, Zhao97]. Similar to spatial data, temporal data can be described as having a “resolution” which will define the smallest unit of time that a database is capable of measuring or recording (or chronon) [Clar95, Peuq99]. Different applications of historical analysis can have very different requirements for temporal resolution (e.g., a geological database might have a chronon of a century, while that of insect migration might be an hour).

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[9] A TGIS capable of recording world time has been referred to as an historical database (or a historical GIS); one capable of recording database time can be referred to as a rollback system [Galic02, Mont95, Zhon96]. Those capable of maintaining both would be considered bitemporal [Sarg98, Worb98]. An atemporal or static GIS does not maintain either type of time structure (also referred to as a snapshot database) [Gali02].

Finally, there are a number of advanced temporal considerations and functions that an ideal TGIS should be able to address. These include temporal topology or relative time (e.g., before, after, during, etc.) [Barr91, Char95, Lang93a, Lang88, Peuq99, Sarg98, Tao95], the inclusion of ordinal time (in addition to interval time) [Fran98, Hall96, Peuq01], the option of time spans or intervals (in addition to discreet points in time) [Fran98, Peuq01], a mechanism for including "fuzzy" time (events with an undefined or gradual time of beginning, change or end) [Brim98, Imfe00, John97, Lang93a, Lang92, Long99, Peuq01] and temporal interpolation [John97, Zhan00]. These advanced requirements, many of which will require a fundamental revision of the underlying GIS software in order to implement, are not addressed by the prototype tGIS.

A fully functional TGIS should be capable of incorporating multiple temporal metaphors, varied temporal resolutions and reference systems and should be able to perform some of the advanced temporal requirements of fuzzy data and temporal interpolation. As the various temporal requirements are combined, the storage and processing demands upon the TGIS become increasingly complex (e.g., a system that is capable of performing temporal interpolation on fuzzy data using ordinal time increments for multiple branches of world as well as database time…). The ideal TGIS should be able to encompass all of the temporal aspects discussed above, though at present no GIS software packages do. In addition, while a generic TGIS must be able to handle multiple types of time, it should also be capable of selective elimination or emphasis of a particular aspect of time as necessary for a given application [Zhon96].

The tGIS developed here achieves the basic requirements of a TGIS through a series of attribute fields combined with a procedural methodology and Avenue scripts to facilitate data entry and recall. It adopts an ordinal timeline metaphor (Newtonian space and time), without branching or cyclical functionality. The temporal focus is on world time (the concepts of which could be applied to database time as well) using UTC (GMT) and the Western calendar as the temporal reference system. The temporal resolution is user defined (generic), with a one year chronon chosen for the Fairhaven case study. No temporal interpolation, generalization or fuzzy boundary functionality have been included at this point.

Temporal GIS Research

The majority of current GIS maintain a single representation of existing geographic data [Abra99, Belu99, Cand95, Peuq99, Zhon96]. Such databases are considered atemporal. These databases store what limited temporal data they may contain as attribute information.[10] A fully functional TGIS on the other hand, would treat time as a separate coordinate [Cand95, Lang92a, Wege00b]. Currently available GIS technology lacks such full temporal capabilities.

[10] Similarly, current GIS technology is not truly three-dimensional with regard to elevation. Locations of features are described by a two-dimensional X-Y coordinate system only, with elevation stored as an attribute. This limitation affects procedures such as searching for events or objects that are adjacent or coincident (in time or elevation). For example, given an object at spatial location X-Y it is possible to quickly search for other objects that might be found at neighboring locations (X ± 1 and Y ± 1). But if we know that the elevation of the object is Z, or the time of the existence of the object is T, there is no similarly simple method to search for neighboring objects in elevation or time since this data is stored as an attribute rather than a coordinate. The only way to find other objects at the same elevation or time is to check the attributes for *all* objects and/or locations in the database (a much more computationally intensive process). For these reasons, current GIS are sometimes referred to as "2 ½ dimensional" [Turn97].

Despite more than two decades of research, only a handful of commercial software vendors provide anything approaching a TGIS. Most of these are either designed for specific applications, work for only limited data types (i.e., point data only) or are "add-on" extensions to existing systems with limited functionality. None are truly temporal in the sense of including an additional temporal coordinate dimension within the system [Abra99, Chee00]. Nevertheless, these prototype TGIS offerings indicate the need and desire for such a product, even if the research on creating a fully three- or four-dimensional TGIS remains years away from implementation [Belu99, Haze98, Hall96, Mont95, Ott01]. Beyond these limited prototypes, researchers continue to address temporal issues using existing software. In short, TGIS remains a "current Holy Grail of GIS research" [Hall96].

Although the first TGIS attempts were developed in the late 1970's[11] [Lang88, Raaf94], the beginnings of TGIS as a field of research are often attributed to Langran and Chrisman's work in 1988 [Hall96, Imfe00, Mont95]. Langran expanded this research in 1992 in her seminal book *Time in Geographic Information Systems* [Lang92]. Langran's work continues to provide the foundation for most of the current TGIS research [Hall96, Mont95, Yuan96]. Much of the research since that time, whether of a practical or theoretical nature,

[11] Basoglu and Morrison designed a computerized spatio-temporal database for tracking U.S. county boundaries from 1790 to 1970 [Baso78]. Relatively simple by today's standards, this work represented a formidable undertaking, both in terms of the technical requirements at the time and the sheer workload of the project.

provides refinements, addresses specific temporal challenges and/or develops themes initially introduced by Langran.[12]

Within the field of temporal GIS research there are two somewhat parallel and often overlapping research efforts. The first (present work included) is largely concerned with the practical application development challenges of including time in *existing* GIS formats [Belu99, Cand97, Cand95, Hall96, Lang92a, Lang88, Raaf94, Zhon96]. These efforts acknowledge the limitations of such databases (the inherent problem of attempting to add third- or fourth-dimensional functionality to a system fundamentally designed to handle only two) but seek to devise methods of working with temporal data within the context of these limitations. A number of prototype temporal GIS have been implemented, though many of these have had a specific application focus as opposed to being a generic TGIS [Abr99, Cast98, Buch97, Greg02b, Hall96, Hoge00, Knoe98, Masu96, Zhon96]. With regard to the ultimate goals and ideals of TGIS, this branch of research has exhibited a willingness to compromise some of the TGIS "ideals" in order to achieve current functionality.

The second group of researchers have focused more on the theoretical goals of a TGIS aside from any specific current system architecture or application [Chri02, Clar95, Grif01, Grum01, Haze98, John97, Lang93, Lang92a, Mill96, Peuq96, Tao95, Worb98, Yuan96, Zhon96]. These research efforts, some of which are entirely theoretical, have worked towards the development of new TGIS software that may well be qualitatively unrelated to existing systems. Given the focus of this paper the emphasis is on the work of the former group.

[12] Langran's work continues to provide not only the initial, but frequently the most recent, word on many of the basic issues that arise with the attempt to add time to a GIS.

Adding Time to Existing Geographic Information Systems

In general terms, a TGIS should be able to answer queries such as the following (listed in a rough order of increasing complexity):

- When did Feature X exist or cease to exist?
- What existed at Location A at Time T?
- What happened to a given feature or location between Time T1 and T2?
- Did Event A exist before or after Condition X (or Event B)?
- What patterns exist between Events A-B-C and Features X-Y-Z?
- Given data for Feature Y at Time T1 & T3, what was the likely state of this Feature at Time T2?
- What will be the likely state of Feature X at Time T?
- What is the predicted outcome following Event A after Time T?

To date, four relatively achievable methods for including temporal data within a current two-dimensional GIS have been proposed. The basics of each of these four methods were introduced by Langran and Chrisman [Lang88] and/or Langran [Lang92] with refinements here adapted from Candy [Cand95], Halls and Miller [Hall96], Peuquet et al. [Peuq01, Peuq99, Peuq94b] and Yuan [Yuan96]. These methods are the Snapshot model, the Time Cube model, the Base State with Amendments model and the Space-Time Composite model.

Snapshot Model

The snapshot method, perhaps the most basic level of temporal storage, simply creates an entirely new copy of the database (a "snapshot" of the database and/or reality) each time an update or alteration is made (see Figure 1). Thus the time "stamp" of the snapshot model is applied not to the individual features but to the entire dataset. A snapshot model can be implemented with either a raster or vector based GIS. This method is extremely simple in concept and implementation, and is the only temporal capabilities that many GIS applications maintain (via archival back-ups of the database). The drawbacks of such a system are that it is extremely inefficient in terms of data storage (all features are included in every snapshot regardless of whether or not there has been any change to the feature), and offers very poor historical or database rollback analysis with no ability to track changes, patterns of change or incremental changes to the features.

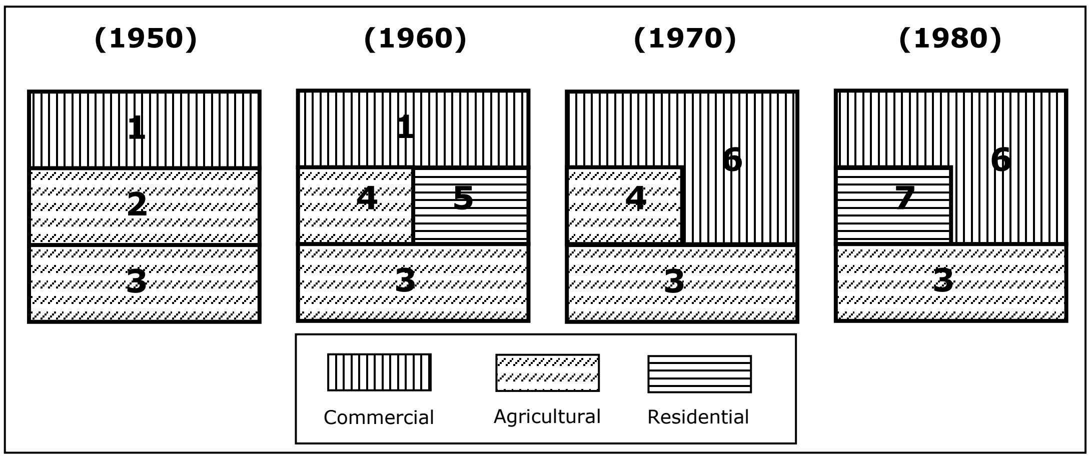


Figure 1 Snapshot model for a parcel layer with a new version of the entire GIS layer for each temporal increment. Note the redundancy of data created by the requirement of an entirely new snapshot, regardless of change activity or lack thereof. Two types of feature change are illustrated: spatial changes such as the splitting of parcel 2 to create parcels 4 and 5, and attribute changes such as a change of landuse in 1980 for parcel 4 (becoming parcel 7).

While the archival snapshot model may suffice for systems that rarely require historical recall of data, from the standpoint of historical analysis such a system is extremely awkward. Even the simplest of queries (e.g., "When did a feature begin or cease to exist?") require an evaluation of the presence or absence of a feature for each incremental snapshot to determine the beginning or end date of the feature in question.

Time Cube Model

Conceptually similar to the snapshot method, the time cube creates a three dimensional model with time substituted for what is traditionally the Z or elevation dimension. In effect the time cube is not unlike a series of time slices (or snapshots) stacked together (see Figure 2). Again, in theory such a model could be constructed with either raster or vector data, though it is more often applied to raster based systems. Given a time-cube database, a user would be able to "drill" down through time for a given location. The main advantage of the time cube model over that of the snapshot model is that historical information could be retained in a single GIS data layer. However, the time cube model suffers many of the same drawbacks of the snapshot model, the foremost being the high data storage requirements. Not only is a complete data layer stored for each time increment, but if a uniform time increment is to be maintained multiple layers of storage may be included without recording any change whatsoever.

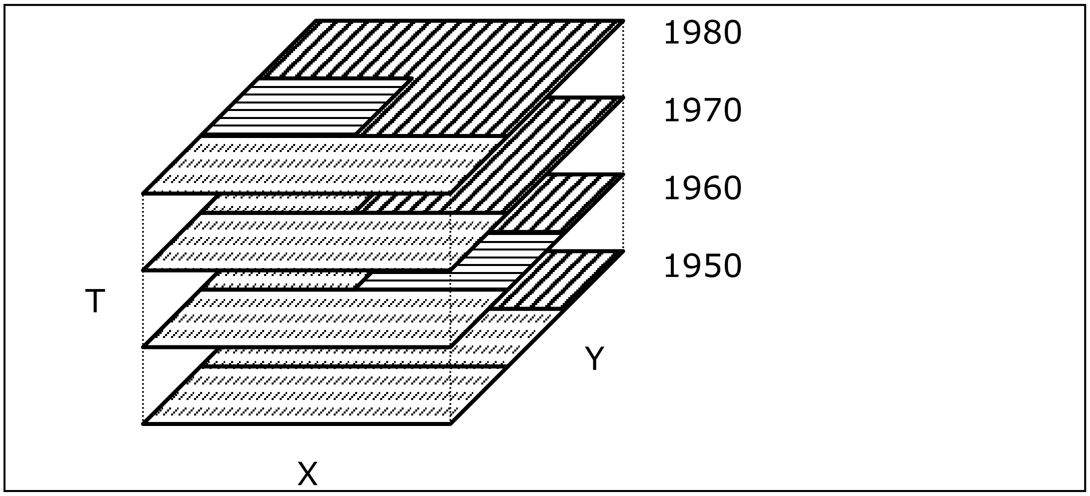


Figure 2 Time Cube model for a parcel layer with temporal layers (snapshots) “stacked” on top of one another. Note the redundancy of data created by the requirement of creating an entire snapshot for each temporal layer, regardless of change activity or lack thereof.

Base State with Amendments Model

The base state with amendments model uses an initial “base state” data layer which is created (again either raster or vector) for the earliest time to be included in the database. From this base layer, any alterations (but *only* the features that actually changed) are stored in a separate database (or series of databases) (see Figure 3). To recreate the events/features for a given time period, the base state is sequentially altered by the necessary amendments until the required date is achieved. Conversely, the ‘base’ state to be maintained could be the most current database, with each outdated feature being transferred to an “archive” database (see Figure 4). In this case, the current base state is sequentially dismantled until a desired point in history is achieved.

Periodically, it may be beneficial to recreate a new base state from which to build, creating a compromise between a pure base state model and that of a snapshot model. When compared to the snapshot model, the base state model clearly reduces the storage needs enormously. However the requirement of recreating previous data versions (and rebuilding topology for topological systems) from multiple databases is a cumbersome strategy at best.

In addition, the ability to detect temporal or spatial errors is hampered by the relative isolation of the altered features stored in the separate amendment database. Storing extracted components in their own database creates amendment layers that are neither time nor space 'filling,' increasing the possibility of topological errors (spatial as well as temporal). Still, for applications which rarely require historical or rollback queries such a method can provide an efficient means of maintaining a current database (in terms of storage) without losing previous data versions in the update process.

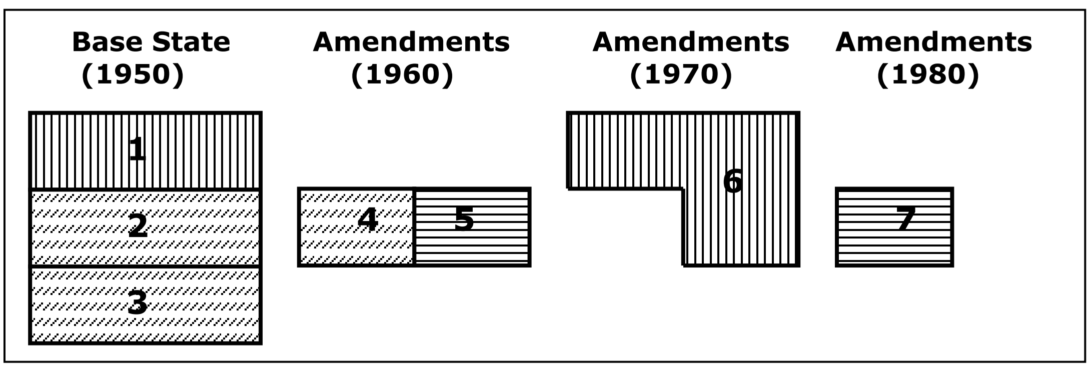


Figure 3 Base State with Amendments model for a parcel layer. Amendments could be stored in separate amendment layers or in a composite layer.

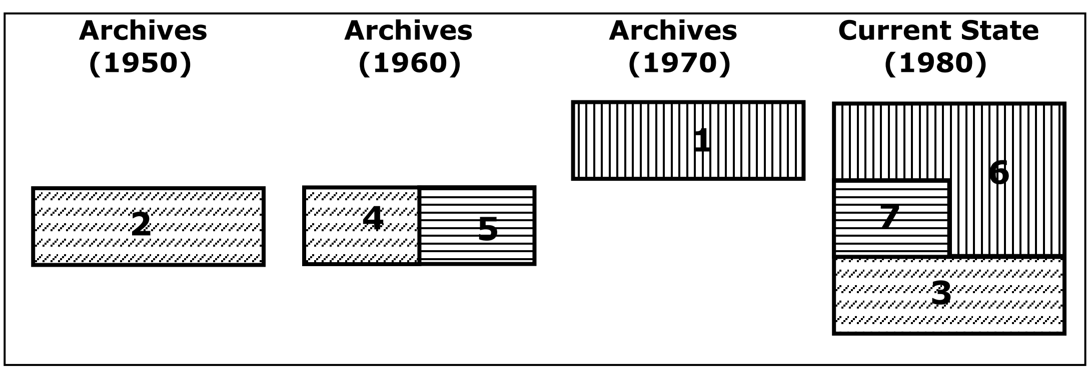


Figure 4 Current State with Archives model for a parcel layer. Archives could be stored in separate archive layers or in a composite layer.

Space-Time Composite Model

The space-time composite model is similar in many ways to the base state with amendments model. The difference is that the amendments are stored within the same database as the original base state (see Figure 5). In essence, although updates are made to the database, nothing is ever deleted or removed. Each individual feature has its beginning and ending dates recorded as attributes, enabling the display of a given point in time by simple selection of features with appropriate time stamps.

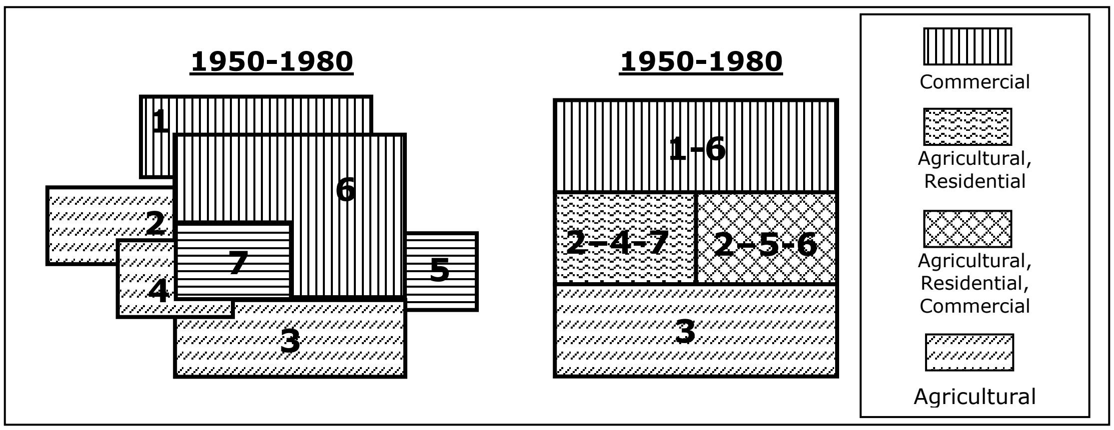


Figure 5 Space-Time Composite model for a parcel layer. This diagram shows two separate attempts to illustrate the composite nature of multiple generations of parcel boundaries co-existing on top of one another. On the left is an "exploded" diagram, on the right is an overlay composite.

In a spatially topological GIS (e.g., the ArcInfo Coverage data model), however, as additional updates are made to the database the geographic features (polygons and/or lines) are gradually broken down into ever-smaller spatial entities. On the other hand, in a non-topological GIS (e.g., the ArcView Shapefile data model) there are an ever increasing number of features potentially coexisting simultaneously at a single location. Either of these situations produces a database that is very difficult to use without an application specifically designed to display a subset of the data while filtering out the rest.

While appropriate for relatively stable or limited historical databases, this inherent degradation/compounding of the data can prove unwieldy. Including both world and database time in the composite further complicates the database design.

In spite of its limitations, however, Langran (1992) concludes that the space-time composite model provides the greatest potential for immediate construction of a functional TGIS [Lang92].

RDBMS Temporal Database Designs

Despite pioneering research efforts into future TGIS architectures, most of the practical TGIS innovation is taking place within the context of existing GIS software packages based on a relational database design [Cand95, Mont95, Sarg98, Peuq01]. While the object-oriented data model may provide greater customization and flexibility for the capture of temporal data in the long run, most current GIS packages continue to be based on the relational database model. Moreover, extending the relational database has been shown to be effective for limited temporal data capture and analysis, especially when "the temporal dimension is conceptually linear in form" [Peuq01]. The primary drawback of the relational database, besides limited customization options, is an inefficient data storage mechanism resulting in an excessive amount of redundant data. Within the context of an RDBMS (either a GIS or a non-spatial database) there are three basic methods of recording temporal data commonly referred to as Relation-Level, Attribute-Level and Tuple-Level [Lang92, Raaf94, Zhon96].

The following temporal database examples illustrate the different types of temporal attribute tables for a four parcel GIS layer including ownership and land-use information (see Figure 6). For the purposes of the following discussion the examples and tables used below (Figures 6-9) depict entirely non-spatial changes to the database (i.e., changes to the attributes only). Spatial modifications can be incorporated using similar methods but are not included here for simplicity and clarity.

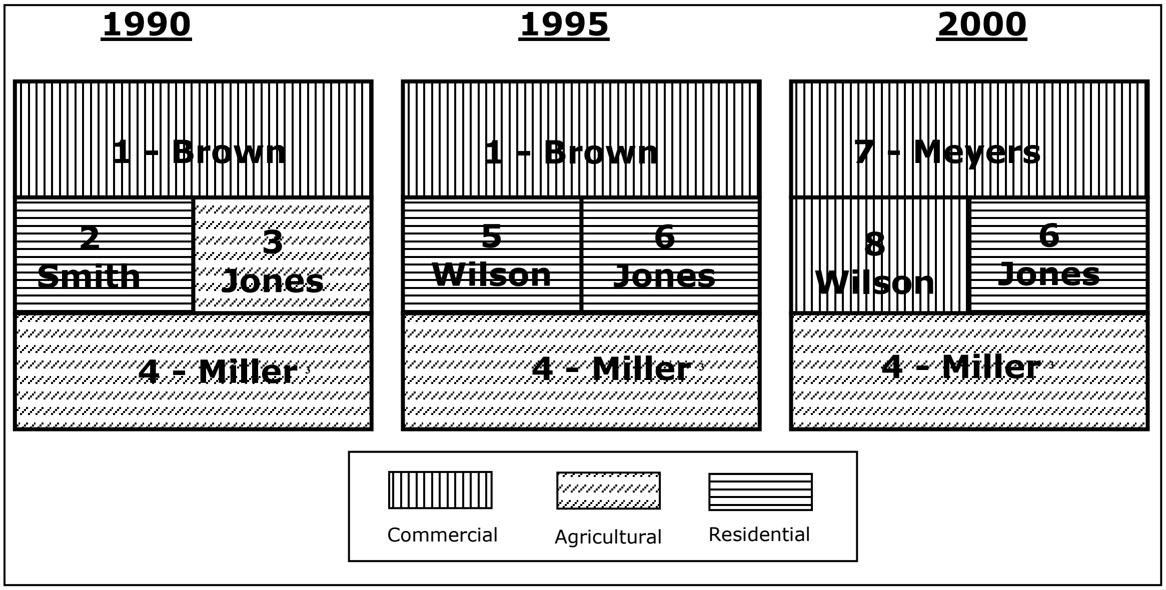


Figure 6 Simplified example of a GIS layer containing ownership and land-use information for four parcels of land between 1990 and 2000. Note that parcels can change ownership as well as land-use and the parcel 4 has no change during this period of time.

<u>Relation-Level</u>

The relation-level method is analogous to the snapshot data model. Each time attribute data needs to be updated an entirely new table is created (see Figure 7). This model, while conceptually simple, suffers from an obvious inefficiency in terms of redundant data storage. In the majority of situations only a few of the total number of features in a database change between any two versions, so the creation of an entirely new table requires excess storage capacity.

Original Database (1990)

ID	OWNER	LAND-USE
1	Brown	Commercial
2	Smith	Residential
3	Jones	Agricultural
4	Miller	Agricultural

First Update (1995)

ID	OWNER	LAND-USE
1	Brown	Commercial
5	Wilson	Residential
6	Jones	Residential
4	Miller	Agricultural

Current Database (2000)

ID	OWNER	LAND-USE
7	Meyers	Commercial
8	Wilson	Commercial
6	Jones	Residential
4	Miller	Agricultural

Figure 7 Relation-Level temporal database for parcel example (see Figure 6 above). Note that a new table is required for all features, regardless of a lack of change (e.g., parcel 4 is included in each table without any changes). Changing attribute information has been underlined for emphasis.

Attribute-Level

The attribute-level of tracking a feature's history maintains a single record for each feature with multiple attribute entries for different instances or incarnations of the feature (see Figure 8). This system offers the most efficient means of data storage.

	ID (1)	OWNER (1)	LAND-USE (1)	START-DATE (1)	END-DATE (1)	ID (2)	OWNER (2)	LAND-USE (2)
A	1	Brown	Commercial	1990	2000	7	Meyers	Commercial
B	2	Smith	Residential	1990	1995	5	Wilson	Residential
C	3	Jones	Agricultural	1990	1995	6	Jones	Residential
D	4	Miller	Agricultural	1990	Current			

Feature	START-DATE (2)	END-DATE (2)	ID (3)	OWNER (3)	LAND-USE (3)	START-DATE (3)	END-DATE (3)
A (con't.)	2000	Current					
B (con't.)	1995	2000	8	Wilson	Commercial	2000	Current
C (con't.)	1995	Current					
D (con't.)							

Figure 8 Attribute-Level temporal database (in two parts) for parcel example (see Figure 6 above). Note that while there are only four records total, a new ID, OWNER and LAND-USE field must be added for each potential time that a feature may change. Thus, while the attributes for feature "B" change twice (requiring new fields for the subsequent ID, etc.), feature "D" never changes. Such a database design requires that either additional fields are added to the entire database to account for all possible iterations, or that the record for each feature be variable length (not currently possible with the standard RDBMS software used by most GIS packages). Start and End Date fields for each update are also required to identify the duration of each feature.

The drawback of the Attribute-Level method is that it requires variable length records (i.e., an undefined number of fields for each record, since a feature could potentially have an unlimited number of incarnations or changes to its attributes). This violates a basic design principal of current RDBMS structures, effectively eliminating this option from most GIS applications.

Tuple-Level

The tuple-level (or record-level) design is a compromise between the simplicity of the relation-level and the efficiency of the attribute-level designs (see Figure 9). With this method an additional record (with a corresponding GIS feature for spatial databases) is created each time a feature is modified. This requires the duplication of some of the feature's attribute data, but only for features that have actually changed. Moreover, all of the data is maintained in a single table, simplifying attribute query, sorting and filtering processes.

Tuple-level temporal systems of one form or another constitute the majority of prototype TGIS applications to date, present work included.

ID	OWNER	LAND-USE	START-DATE	END-DATE	Previous ID	Future ID
1	Brown	Commercial	1990	2000	N/A	7
2	Smith	Residential	1990	2000	N/A	5
3	Jones	Agricultural	1990	1995	N/A	6
4	Miller	Agricultural	1990	Current	N/A	N/A
5	Wilson	Residential	1995	2000	2	8
6	Jones	Residential	1995	Current	3	N/A
7	Meyers	Commercial	2000	Current	1	N/A
8	Wilson	Commercial	2000	Current	2	N/A

Figure 9 Tuple-Level temporal database for parcel example (see Figure 6 above). Note that all instances of a feature's history are included in a single table, including information no longer current. In addition to Start and End Date fields, filiation tracking fields have been added to illustrate a means of identifying previous and past versions of a feature.

The Foreseeable Future for TGIS

While it can be expected that the two tracks of TGIS research, that of practical application and adaptation and that of long range theoretical development, will continue to gradually draw closer together, such trends are indeed gradual [Mont95]. Halls and Miller note that recent temporal developments and research have not kept up with other (spatial) GIS enhancements [Hall96]. In 1993 Langran concludes with the following statement:

> *The first priority for moving spatial analysis into the temporal domain is to have temporal storage and retrieval capabilities. But to gain a true understanding of geographic change requires that it also be possible to examine the relationships in space and time, to generalize the information available, and to reconcile disparities in the information available.*
>
> -- Langran, Analyzing and Generalizing Temporal Geographic Information, p. 386 [Lang93a]

Nearly ten years later, while progress has been made, especially with regard to her first priority, much remains to be done before true temporal GIS will be readily available. In 2001 Peuquet stated:

> *Even with much activity over the past decade, including organized efforts on both sides of the Atlantic, the representation of both space and time in digital databases is still problematic and functional space-time systems have not gone beyond the limited prototype stage*
>
> -- Peuquet, Making Space for Time: Issues in Space-Time Data Representation, GeoInformatica 5:1, p. 11 [Peuq01]

Until such time as a true Temporal GIS, as envisioned by both Langran and Peuquet, become available the GIS community is left to develop quasi-temporal functionality within the context of existing software. The remainder of this paper details the development and testing of one such effort, aimed specifically at the inclusion of archival map data within a GIS database.

The Prototype tGIS Extension

The tGIS extension was designed to facilitate the creation and use of temporal databases derived from archival maps. Four key features can be identified as specific goals of this extension:

1. The ability to create temporal point, line and/or polygon feature layers using temporal attributes. This would include functionality for:
    a. Temporal data entry and editing
    b. Retroactive insertions/edits of data
    c. The ability to track spatial changes such as feature relocation, changes in shape, splits or mergers as well as changes in non-spatial attributes
2. Temporal queries and display of the data (temporal filtering)
3. The ability to track feature filiations, or lineage
4. Maintain feature-level metadata linking individual features to archival data sources

Development Platform

Given that writing entirely new code for a fully TGIS software application is beyond the scope of this project, the first step in developing the tGIS extension was to determine which of the currently achievable GIS software packages to use. Included with this decision is the choice of which of the methods of including temporal data in an existing RDBMS GIS system would be most appropriate for historical analysis using archival map data.

ArcView 3.x and Avenue were chosen as the development platform for the tGIS extension due to the large user base and script library available for Avenue. In addition, the 'whole polygon'[13] structure of the Shapefile (native to ArcView 3.x) was desirable due to

[13] The term 'whole polygon' is an informal description of a non-topological data model (e.g., the Shapefile), referring to the fact that each polygon is stored as a complete graphic entity (as opposed to a topological model whereby two adjacent polygons share a common line that separates the two). Though referred to as a whole *polygon* model, such data models affect both polygon and line features. With a non-topological data model lines and/or polygons can overlap or intersect.

the non-topological nature of this data model. While ArcGIS and VBA offer some specific advantages to temporal query and cartographic endeavors, the choice of ArcView 3.x was made in part due to the timing of the project (begun prior to the release of ArcGIS and developed as the early versions of ArcGIS and the Geodatabase data model were being introduced). [14]

Partly as a result of this changing software environment, an effort was made to simplify the extension, making use of standard data file formats. The likelihood of potential translation of the extension in the future favors a design that relies as little as possible on complex extension coding and/or tabular relationships.[15]

Data Model

The space-time composite was selected as the data model for the tGIS extension because of its database design simplicity, especially with regard to temporal query and display. Having all of the features included in a single thematic layer eliminates the need for complex relationships between layers. The composite model increases the long-term, cross-platform accessibility of the data, in that while accessing the information is enhanced by the tGIS extension, it is not dependent upon such an extension (i.e., the file could be opened with any GIS capable of reading the basic file type). The main limitations of this model are the inefficiency inherent in combining all the temporal data in a single database. As file size increases (potentially infinitely with a

---

[14] While Avenue and VBA are similar programming languages in style, the actual syntax is different, preventing an automated translation between the two. See further discussion on the possibilities of migration to ArcGIS below.

[15] As the primary investigation of this paper is the feasibility of creating a simple tGIS extension to facilitate the use and analysis of archival maps in a GIS, the software platform is in some sense inconsequential. Having demonstrated the possibilities using ArcView 3 and Avenue, similar applications could likewise be developed for other, comparably sophisticated GIS software packages.

large enough temporal range) there is inevitably a decline in processing speed. The hypothesis of this work is that current computer processing speeds have sufficiently increased so as to make this limitation no longer an issue.

The composite data model also has certain advantages with regard to working with archival map data, providing a common spatial and temporal reference system for a multitude of data sources. The flexibility of the composite data model is beneficial given the varied spatial extents, scales, and sporadic time interval between available maps. This model also has the advantage of being able to include retroactive insertions of data.

A major obstacle for the composite model in the past has been the issue of maintaining spatial topology [Greg02, Lang92]. In a GIS using a topological data model, the need to constantly split and re-aggregate polygon features (e.g., as parcels are subdivided or merged over time) to re-create new topology for each temporal query or display creates an inefficient and problematic challenge. The Shapefile's 'whole polygon' data model, however, does not require spatial topology to be built or maintained

The prototype tGIS extension makes use of a feature/tuple-level temporal database design, creating a new spatial feature with an associated record in the attribute table each time a feature changes. These changes can be either spatial changes (e.g., a subdivision of a parcel or an extension of a road) or non-spatial (e.g., a change of parcel ownership or the change of a street name). While this involves a certain amount of data redundancy, especially for non-spatial feature changes, the benefits of maintaining a single database outweigh the performance costs.

Feature editing tools were developed for the creation of new features as well as the modification of existing features. In the case of new features unique ID value(s) are automatically assigned. The editing and filiation tracking capabilities were also designed so as to enable retroactive insertions and edits to the database.

Attribute Fields

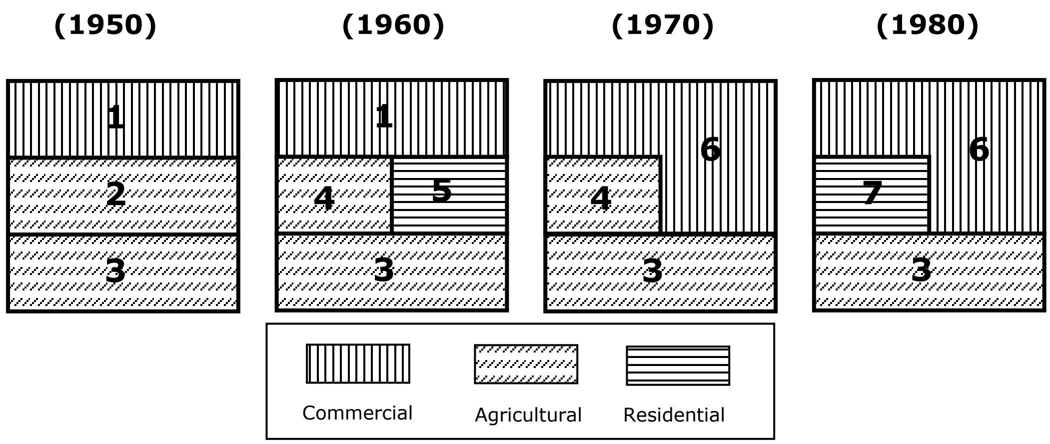
The tGIS extension relies on a series of pre-defined attribute fields to track, analyze and display spatial features based on temporal data. The tGIS extension itself is comprised of a series of Avenue scripts, compiled into a single package that makes use of these tGIS fields facilitating temporal data entry and recall.

The most basic temporal function, maintaining a time stamp for each spatial feature, is achieved by the use of *Start-Date* and *End-Date* fields (both of which use world time). These two fields enable the selection of features by date (i.e., a query of all buildings built before or after a certain date) as well as temporal display (i.e., show the features in existence at a certain date by filtering out (not showing) all features not in existence at that date). In addition, an *Edit-Date* field maintains the date of the creation of (or most recent edit to) a record.[16]

Feature filiation (or lineage) is tracked within the database by the inclusion of three additional fields: *EID*, *PID* and *FID*. The *EID* (Entity ID) field contains a unique, permanent ID number for each feature in the database, assigned at the time of creation. The *PID* (Previous ID) field contains the *EID* value of the "parent" feature, while

[16] The *Edit-Date* field is essentially a sub-set of Database time, tracking last edit as opposed to beginning and end of database relevance.

the *FID* (Future ID) field contains the *EID* value of the "child" feature. Thus for a parcel that was purchased by Owner B from Owner A, Owner A's parcel would show the *EID* of Owner B's parcel as the *FID*, while Owner B's parcel would show the *EID* of Owner A's parcel as the *PID*. See Figure 10 for an illustration of the use of *EID*, *FID* and *PID* fields, and Figure 11 for an example of a filiation graph based upon the parcel data contained in Figure 10.



PID	EID	FID	Start-Date	End-Date	Land Use
NA*	1	6	1950	1970	Commercial
NA	2	S*	1950	1960	Agricultural
NA	3	NA	1950	NA	Agricultural
2	4	7	1960	1980	Agricultural
2	5	6	1960	NA	Residential
M*	6	NA	1970	NA	Commercial
4	7	NA	1980	NA	Residential

Figure 10 Simplified parcel database illustrating filiation tracking (*PID*, *EID* and *FID* fields) along with *Start*- and *End-Date* fields.

***** Features in existence at the beginning of the database (1950) and/or still active contain a 'NA' in the appropriate field(s). An 'S' indicates a Single parent feature that was Split into multiple child features. An 'M' indicates a feature created by a Merger of Multiple parent features into a single child feature.

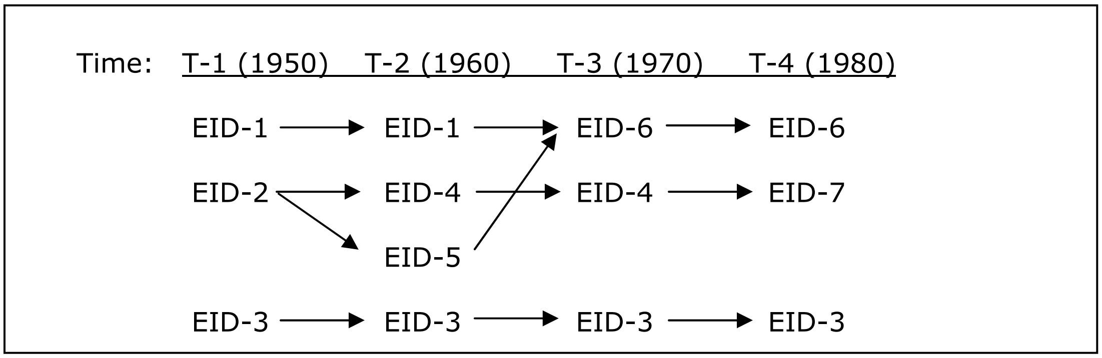


Figure 11 Filiation graph derived from the sample parcel data shown in Figure 10 illustrating the lineage of each feature at different points in time. Note the split of parcel EID-2 as well as the merger of parcels to create EID-6.

The inclusion of these three separate ID fields enables tracking of feature filiation through time. Thus a street that changes names over the course of its history could be analyzed by selecting the street in addition to all of it's parent(s) and/or child(ren) using the *PID* and *FID* fields respectively. In the case of a feature having either no parent(s) or no children, special numerical values are used to indicate this in the tGIS database. Likewise, in the case of a feature being split into multiple children, or merged from multiple parents, special numerical values are also used to indicate this.

A third design feature incorporated into the tGIS extension is the ability to maintain feature-level metadata for each spatial feature in the database. This is achieved by the use of a *FMD* (Feature-Level Metadata) field in conjunction with the attribute table of an additional Metadata layer. The Metadata layer consists of simple polygons approximating the spatial extent of each archival source map used. The Metadata attribute table contains an *FMD-ID* field and information for each archival source including the original publication date, storage location, etc. of the archive. This table is then related to the tGIS layer(s) by virtue of the *FMD* field for each spatial feature, which contains the appropriate *FMD-ID* value for the feature's archive data in the Metadata table. The use of related tables allows rapid query of metadata information from within the GIS, with a minimum of data storage requirements. This tabular linkage is the only place where the tGIS design uses multiple tables requiring a tabular relationship to be established. While the entire feature-level metadata could have been included within the tGIS layers (a simpler database design), the high degree of data redundancy this would require is not warranted given the relative infrequency of the need to access this information. An example of a tGIS attribute table and the related records from the Metadata attribute table are shown in Figure 12 below.

tGIS Table

EID	FMD
1	1
2	5
4	1
5	3
6	3

Metadata Table

FMD-ID	Pub Date	Location	Map Title
1	1908	CPNWS	Birds-eye Map of F.H.
2	1922	HML	USGS Topo Quad
3	1911	CPNWS	Padden Short Plat
4	1895	CPNWS	Town of Fairhaven
5	1920	HML	Bellingham Streets

Figure 12 Excerpt of a tGIS layer's attribute table containing an *FMD* field and an excerpt of a Metadata layer's attribute table containing an *FMD-ID* field. Arrows illustrate the relationship between the tGIS features and the Metadata table, based on the *FMD* and the *FMD-ID* fields. Note that while many records in the tGIS layer may have the same archival map source and thus the same metadata, the information is only recorded once (i.e., a "one-to-many" type of relationship is used), minimizing data redundancy.

The Metadata layer also functions as a spatial catalog of all the archival maps used for a tGIS study. This layer provides the ability to generate a list of maps that relate to a given location or time period. In addition, the inclusion of the *FMD* field enables the individual tGIS layers to also serve as a reference for archival sources. Should the original archive for a particular spatial feature be needed for further study, a user can select that feature from the tGIS layer and access the metadata information for that feature from the Metadata table. This ability to maintain a connection with the original source documents becomes especially important with composite databases derived from multiple archival maps having varied sources.

A more complete Feature-Level metadata tracking schema might include information regarding who and/or when the data was entered (or edited) in the TGIS database as well as a mechanism for storing links to multiple records in the Metadata table. For the prototype tGIS extension the single *FMD* field (in addition to the *Edit-Date* field mentioned above) was used, capturing the essentials of feature-level metadata.

The choice of which data to include or exclude in a database is an ongoing compromise. More fields require additional storage capacity and slow both processing speed and data entry. Fewer fields may limit the functionality and usefulness of the database itself. In addition to the tGIS fields discussed above, two final fields were included: a *TType* (for the tGIS Type of feature) and a *TName* (for the tGIS Name) field. These two fields were included to allow for the incorporation of common feature attributes (e.g., the type of building or road, or the name of a street) in a consistent manner.[17] Thus, the fields that were included for each tGIS thematic layer are:

Field Name	**Type**	**Description**
• EID	#	Unique, permanent Entity ID
• PID	#	Linage tracking field – Previous EID
• FID	#	Lineage tracking field – Future EID
• Start-Date	#	Creation/beginning of existence
• End-Date	#	Alteration/end of existence
• Edit-Date	Date	Database Edit Date (auto entry)
• TType	List	Possible types for the theme
• TName	Text	Common name for the feature
• FMD	#	Feature Level MetaData – ID-Link to the Metadata Layer

[17] It should be noted that additional fields can always be added as needed. Those discussed here are simply the fields that were deemed essential for the tGIS extension functionality.

Methodological Discussion

In addition to the technical implementation of the tGIS extension was the development of a methodology for working with archival maps. The main decision made in this regard was that of using the archival maps in conjunction with current GIS data. In this schema, the archival maps were used to assign temporal "location" only, as opposed to temporal and spatial location. The use of this method limits the type of features that are included in the tGIS to those that meet these criteria (e.g., features which are found on both archival maps and current GIS data layers such as streets, buildings, parks, etc.), but greatly reduces data entry time.[18]

tGIS Summary

The final tGIS extension as it was developed for this work is a relatively simple extension for ArcView 3.x using Avenue and the standard Shapefile data format. Specific attribute fields were designed to track temporal data, lineage and metadata for each feature. The data model chosen was a composite database, using the tuple or feature-level method to track spatial and/or attribute changes. The resulting Shapefiles are completely compatible with ArcView 3.x, ArcGIS, or any other GIS capable of using Shapefiles, with or without the tGIS extension (although their ease of use is greatly enhanced by the tGIS extension). Moreover, the full functionality of the GIS software (be it ArcView or some other GIS package) is maintained with regard to spatial analysis in addition to that provided by the tGIS extension.

[18] There is nothing inherent in the tGIS extension design requiring this method to be adopted. Given enough time (as well as an adequate supply of archival maps), additional features such as changes in hydrology could also be created, using the archival maps for spatial location data as well as temporal information.

The tGIS extension is essentially a development of Langran's work and recommendations from the early 1990's [Lang92, Land88]. Two key factors make it worthy of exploration and development at this point in time: the first of these is the increase in computer processing speeds; the second is the use of a non-topological data model.[19] In addition, the methodological decision to limit the archival map data to primarily non-spatial information (i.e., temporal and attribute data) played an essential role in creating a feasible tool for working with archival maps. Thus, three specific hurdles were identified with regard to temporal GIS and archival map data: the database and processing inefficiency of treating time as an attribute of spatial features; the issue of maintaining spatial topology in a composite database; and the effort required to transfer spatial data from archival maps to a digital database (typically scanning, rectifying and/or digitizing features from archival maps). The tGIS extension and methodology (in combination with current computer hardware and data models) address each of these issues.

[19] The Shapefile data model (introduced in 1992 with the release of ArcView 1) did not exist at the time when Langran concluded that the composite model offered the greatest potential if the problem of topology could be overcome [ESRI, Lang92].

Fairhaven Case Study: 1880-1930

A case study of Fairhaven, WA (now a part of Bellingham, WA, located on the shores of Bellingham Bay in Whatcom County), was conducted using the prototype tGIS extension. The purpose of this study was to evaluate the feasibility of the tGIS extension and methodology for historical research using archival map data. It should be noted that this case study is not a comprehensive historical geography in itself, but rather a demonstration of the possibilities and limitations of a tGIS extensions and methodology specifically designed for working with archival map data.

The spatial, temporal and thematic extents of the case study were defined as follows:

- **The Town of Fairhaven, Washington** (and portions of the original **Town of Bellingham, Washington** which merged with Fairhaven in 1890)
- **1880-1930**
- **Thematic Features** commonly found on archival maps of the late nineteenth century, including:
    - Land Subdivisions (Donation Land Claims, Plats, etc.)
    - Streets
    - Railroads and Street Car Lines
    - Buildings
    - Government Jurisdictions (Territory, State, County, City)[20]

A temporal resolution (chronon) of one year was selected (i.e., time is stored in the database in one-year increments). This chronon was chosen due to the fact that many of the archival sources (both maps and textual) provide no more than the year of publication, if that. Indeed many of the maps do not have a date listed at all but were

---

[20] The Government Jurisdiction layer is an exception to both the spatial and temporal extents of the case study. Data for the city, county, territory and state boundaries were extended (both spatially and temporally), to capture the larger context of European-American settlement. This also provided an opportunity to illustrate the workings of the tGIS extension for broader historical analysis.

rather dated (approximately) by later historians. As such, a resolution finer than one year would require a greater level of precision than most of the data sources were capable of supporting.

Data Sources

The main data sources for the case study were archival maps (both paper and digital) obtained from local collections,[21] supplemented by a variety of textual and personal historical resources. GIS data used for comparisons with archival maps was obtained from the *City of Bellingham* and *Whatcom County* Planning Departments.

The dispersed physical locations of the map collections illustrate one of the primary difficulties in using archival maps for historical analysis (and the potential benefits of a tGIS database). Each collection maintains its own schedule and protocols for access to the maps, many of which are stored in closed stacks not accessible to the general public for browsing. The tGIS extension provided a means of incorporating incremental pieces of historical information into a database that gradually grew to encompass over 100 sources. The inclusion of the Metadata layer enables the connection between the information in the tGIS database and the archival data sources to be maintained.

The archival maps used for the Case Study included Coastal Surveys, Plat Maps (one of the earliest and best sources of map data due to their role in the legal development and sale of property, see Figure 13), 'promotional' maps (aimed at real estate development or tourism), Bird's-Eye View maps, Sanborn Fire Atlases, county atlases

[21] Notably Western Washington University's Huxley Map Library and the Center for Pacific Northwest Studies in Bellingham, WA.

and street and streetcar maps. In addition, oblique photographs[22] were used when available (see Figure 14), as were Polk City Directories. Finally, historical maps and texts (created after the fact from archival materials by other historians) were used to supplement the archival data. These various data sources were used in conjunction with one another in an attempt to validate (or refute) the sometimes optimistic use of cartographic artistic license (especially with regard to urban development).

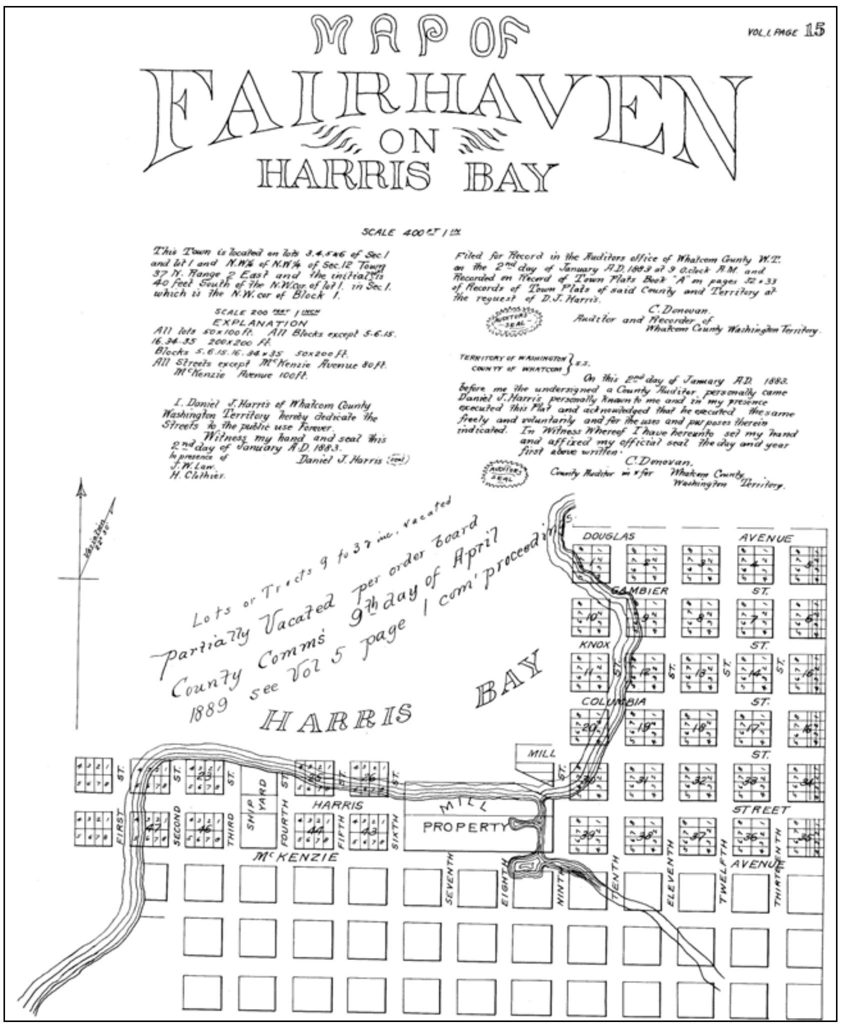


Figure 13 1883 *Map of Fairhaven on Harris Bay*, the original plat of the town of Fairhaven.

[22] The earliest vertical aerial photos for the area are from 1947.

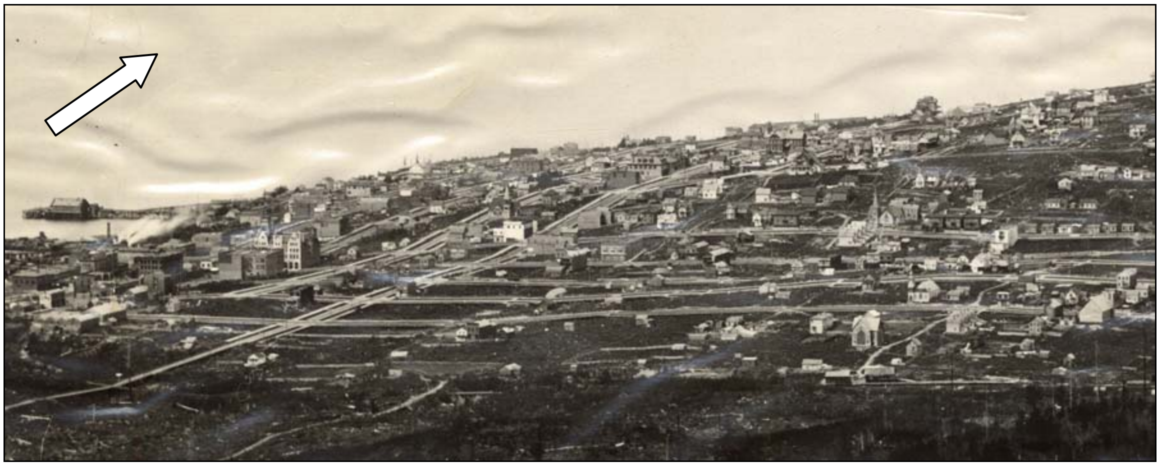


Figure 14 Section of a circa 1895 photograph of Fairhaven from Chuckanut Mountain (photographer unknown). Photo courtesy of the *Whatcom Museum of History & Art* from the Tweit Collection. Although the entire area shown here was platted at the time of the photo many of the streets were not actually built until the early 20th century. (Arrow indicates North.)

<u>Data Issues</u>

In compiling archival map information a number of data reconciliation and definition issues emerged. For example, the distinction between a platted parcel and a developed lot is difficult to distinguish from most archival maps (i.e., platting of land does not always correlate immediately with urban development of the land). Likewise platted right-of-ways and constructed streets are difficult to differentiate (see Figure 14). Indeed, the definition of what constitutes a navigable street itself has changed dramatically over the last 150 years. Changing names of streets (or streets with multiple names) also presents a challenge for database entry and recall as does the occasional relocated feature such as buildings that were physically moved.

Hydrological features were, for the most part, not included in the tGIS databases due to their changeable nature (precluding the direct spatial correlation with current GIS features) which would require the use of archival maps for spatial as well as temporal location.[23] In the case of shorelines, an additional challenge exists in not knowing the definition of 'shoreline' that was used to produce the map (i.e., high-, low- or mean-tide).[24]

Queries, Analysis and Cartographic Output

Perhaps the most basic use of any GIS database are queries as to the locations of features. Examples include questions such as "Where is Columbia St.?" or "Where is the Fairhaven Hotel?" Similar queries can also be made as to the attributes of a particular location or feature (i.e., a "What is here?" or "What is this?" type of query). With the addition of temporal information these queries can be expanded to include temporal parameters (e.g., "Where was the original fire station?" or "What street was here in 1910?") These queries can also be made more complex by pursuing the question of the future and/or past history of a feature (e.g., "At what locations did the Post Office exist between 1890 and 1920?" or "What were the previous names of this street?").

Moving beyond 'what, when and where' types of questions, thematic overlays and associations of data layers involving spatio-temporal analysis are also possible. By selectively combining the tGIS layers (or temporal subsets thereof) the tGIS can serve as a tool for unraveling historical mysteries. This process incorporates standard spatial analysis (e.g., GIS tools such as proximity, buffer, overlay,

[23] Given the changeable nature of hydrologic features, it is difficult to differentiate between a shift in a feature's location and the results of imprecise surveying and mapping.

[24] Hydrological Surveys, particularly in later years, typically provide the definition used in establishing the water's edge. Plat maps and city street maps almost never include such information.

etc.) combined with a temporal element. This analysis is aided by the ability to selectively visualize multiple layers of historical data simultaneously. Topics such as the relationship of Donation Land Claims, Land Plats and City Limits can be explored, as can the relationship between residential development and the construction of streets and/or electric street car lines.

In addition to spatio-temporal analysis, the tGIS database opens new possibilities for cartographic output. While not the focus of this paper, it is worth briefly noting some of these possibilities. These include interactive maps (allowing user initiated spatial and temporal query, panning and zooming), animations (using time to depict time, either within the GIS software or exported as a stand alone file) and maps with linked texts and/or graphics (enabling the tGIS to serve as a temporal link to more detailed archival materials). Each of these could include internet deployment as well.

Conclusions

This paper has presented the challenges of archival maps, a discussion on the theoretical implications of time with regard to GIS, the lack of fully temporal GIS applications, the range of methods used to date with regard to designing a temporal GIS and a prototype tGIS extension and data capture methodology developed as a research tool for working with archival map data.

Lessons from the Fairhaven Case Study

The Fairhaven case study demonstrates the feasibility of using the tGIS extension for historical analysis using archival maps. Even with somewhat limited (or 'quasi') temporal functionality, the ability to create a composite database from multiple archival sources, and to rapidly extract historical information from the same, were well worth the effort required. The possibilities of spatial and temporal analysis as well as of cartographic output were beneficial to both the research and communication aspects of the study.

The adoption of a methodology whereby archival maps were used primarily for identification of a feature's temporal presence or absence (as opposed to determining spatial location) was a key element in the feasibility of the Fairhaven case study. While by no means a requirement of the tGIS extension, this methodology proved to be an efficient strategy, greatly expediting the data entry process.

Despite the many advantages of the tGIS extension, however, the effort required to develop a tGIS database should not be underestimated. While the tGIS extension itself can be seen as a one-time, relatively achievable task, developing a historical database can easily become an almost infinite undertaking. Given the sheer quantity of effort required it is understandable why the most successful historical GIS projects to date have been collaborative efforts (e.g., *The Great Britain Historical GIS*, *The TimeMap Project*, and *The Electronic Cultural Atlas Initiative*). While the tGIS extension greatly aided data entry and quality control, the time and effort required for locating archival maps and transposing and verifying data were considerably greater than the author's naive expectations.

Much of the effort required was not so much in the data entry phase *per se*, but in the data identification and interpretation process. Identifying specific features and resolving the inevitable conflicts between multiple sources required considerable time and assessment that no computer tool can hope to alleviate.

Conversely, as the tGIS data layers begin to develop, each additional piece of information increases the likelihood that later data can be rapidly identified and entered. If history is to be seen as a puzzle, the tGIS extension and methodology are excellent tools for assembling the pieces.

Working with Archival Maps

Regardless of the tools used for analysis, many of the intrinsic challenges of working with archival map data remain. Issues of incomplete data coverage (spatial, temporal or thematic), insufficient metadata and limited access to map collections all persist. Moreover, the fundamental task of validating and reconciling the information contained on archival maps (which may conflict with that of other maps and/or data sources), continues to be a sizeable undertaking. At the same time, however, the tGIS extension includes features that can minimize many of these challenges. Foremost is the ability to compile information from multiple, disparate maps into a single database for ongoing analysis and display. The ease with which digital databases can be shared with other researchers further increases the benefits of this functionality. The ability to perform retroactive insertions and edits to the database is also a valuable component of the tGIS extension, as archival information is rarely available in a complete, concise and chronological format.

The use of archival maps facilitated the creation of a spatio-temporal database for the Fairhaven case study and clearly illustrated the wealth of information this type of data contains. It should be noted, however, that while this paper has focused specifically upon the use of archival maps as a primary data source, attempting to use archival maps exclusively would typically be neither feasible nor desirable. Not only are archival maps rarely available in sufficient quantity to suit a given project, those that do exist frequently contradict one another. In both cases additional information (e.g., textural sources, current GIS layers, etc.) is required to supplement that which is derived from the archival maps.

The tGIS Extension & Methodology

The tGIS extension developed for this paper provides a tool for historical research using archival maps. Though only a prototype, this extension was relatively simple to develop and implement, illustrating that such a tool can be affordably developed and utilized.

Based primarily on the work of Langran [Lang93a, Lang92a. Lang88], the design of the tGIS extension included one significant difference from her proposals. This variation is the use of a non-topological data model (i.e., the ESRI Shapefile). The use of a 'whole polygon' data model avoids many of the more problematic issues of temporal database design, greatly simplifying the tGIS extension. In addition, the increased computational capacity of current computers overcomes some of the processing inefficiency that is inherent in storing temporal information as an attribute of spatial features. Finally, the methodology adopted for the Fairhaven case study whereby archival maps were used as a mechanism of dating features that can be located using current GIS data layers (thus eliminating the need to use the archival maps for spatial location) greatly enhanced the feasibility of the tool.

It is noted that the entire Fairhaven case study could have been completed with standard GIS tools (i.e., manual entry and tracking of all temporal attributes), though at considerably greater effort. The tGIS extension provides a tool to facilitate the process, lessening the chance of data error and the workload of the researcher (the better able to focus on the data as opposed to the data entry).

Finally, the use of the tGIS extension as a tool for cataloging historical archives provides a significant benefit. This direct association of individual features with their archival data source can serve as an ongoing resource for historical research. By virtue of the tGIS extension, this metadata catalog is accessible via spatial, temporal or thematic searches to identify the source(s) used to establish a feature's spatial and temporal properties. This link enables a researcher to evaluate the source of information used for analysis as well as to locate the original document should further inquiry be required. Expanding this aspect of the tGIS extension is perhaps the foremost recommendation in terms of relatively easily achievable enhancements that could be implemented.

Database Efficiency

The tGIS extension and methodology proved to be useful tools for capturing, analyzing and displaying the information derived from archival maps. One of the main questions regarding the implementation of the tGIS extension was that of the processing capacity of current computer hardware with regard to a fundamentally inefficient database design. While the Fairhaven case study was by no means an exhaustive test in this regard, it does provide initial insight into the issue, as will be discussed below.

The implementation of the tGIS extension depends upon scripts that perform a number of filtering and sorting operations upon the database. Each time a date query or ID search is implemented, the code executes an evaluation of each record in the database. Depending on the particular script, the entire table may need to be included for certain portions of the analysis, while other scripts (or portions of a script) may require only a subset of the database to be included. Indeed, certain scripts require this filtering and unifying (as well as sorting and searching) of the database to be performed multiple times. As the database increases in size, this process inevitably requires more time to be completed. The question, from the standpoint of evaluating the tGIS extension, is whether or not the time delay is minimal enough to not be a deterrent to its use as a research tool for historical analysis.

By current database standards (GIS or otherwise), the tGIS data layers developed for the Fairhaven case study were relatively small. As such the inefficiencies of the scripting were scarcely noticed. Day to day operations of data entry and query were executed rapidly and well within the acceptable range of performance standards. Notable, however, was the amount of time required for some of the more computationally intensive database-validation functions (e.g., a script that analyzes the *EID*, *FID*, *PID*, *StartDate* and *EndDate* values for each record, comparing the attributes of each feature to those of its parent and/or child feature(s) to validate the integrity of the database). While this type of "error-trapping" operation is performed infrequently, the duration required for the execution of this type of command is an indication that all computational processes require a certain amount of time to be performed. As the number of processes and/or records to process increases, so to does the total time required. While this fact never became an issue within the context of the Fairhaven case study, given a large enough database it most certainly would.[25]

[25] In addition to system performance, increasing file sizes also have implications for database storage, backup and transfer requirements.

Two approaches exist to address the issue of database size and performance. The first of these is the use of improved code-writing techniques in terms of the filtering, sorting and searching scripts. Considerable research has been (and continues to be) conducted on the subject of improving the algorithms used for these types of database functions. Developed as a prototype, the tGIS extension was concerned foremost with functionality, and only secondarily with performance speed. The performance could, undoubtedly, be significantly improved by a concerted effort to include more efficient code, taking advantage of strategies available from the larger computer research community.

The second means of addressing this issue is that of ever larger, faster and more powerful computers. If recent computer history is any indication, it is safe to assume that the processing speed and capacity of computers in the future will continue to increase. Moreover, it appears likely that this increased computational power will be sufficient to handle the demands of larger temporal databases and the analysis of the same. As the coding used for analysis and query is likewise improved, these two enhancements should continue to work in tandem to better meet the needs of temporal analysis.

Analytical and Cartographic Possibilities

In comparing the tGIS extension with traditional analog techniques used for historical research, both the analytic and cartographic capabilities were greatly enhanced. While the types of questions asked (and maps produced) may be qualitatively similar to those of geographers and historians sans-GIS, the quantity and depth of analysis and cartography that can be easily performed is greatly improved.

By automating much of the mapping and analytical process, the tGIS extension provides the ability to display user-specified combinations of geographic themes and/or time periods. This efficient means of exploring a wide range of thematic overlays can greatly facilitate the search for correlations and patterns between events or time periods. Having visually identified potential patterns, one can then begin to probe deeper, asking the ‘why’ and ‘how’ questions. In this phase, too, the tGIS extension can be of assistance. Initially, the tGIS can provide more in-depth analysis by including additional thematic layers, expanding or contracting the time frame, or altering the spatial scale or extent of the study area in search of further insights. The tGIS can also facilitate quantitative analysis for comparisons and further spatial inquiry, making use of existing GIS tools.

Finally, having gained historical insights, the same tGIS database that was used for the analytic stages can be applied to the creation of maps, charts and graphics (either digital or analog) to convey the results of the research to others. Once again, the ease of which multiple maps and charts can be generated facilitates more comprehensive comparisons and illustrations of a topic, enhancing the ability to communicate with a broad audience.

With the introduction of a digital display, options for animated presentation take this ability to depict spatio-temporal changes even further. The benefit of using a map (or a GIS) for the process of spatial analysis is that it uses space (typically a two-dimensional graphic) to model and depict real-world space. With the addition of temporal capabilities, a tGIS potentially enables the use of time (in the form of animated display) to model and depict real-world time.

Recommendations for Further Work

The Fairhaven Case Study

The Fairhaven case study presents numerous opportunities for further development, including expanded spatial, temporal and thematic study extents. The incorporation of a greater degree of information from non-archival map sources could also be explored as a means to refine the temporal resolution to a more precise time stamp than the one-year chronon that was used.

Due to the case study's focus on archival map features, it constitutes a spatial history of primarily physical features as opposed to social and demographic information. Given adequate data resources, however, there is no reason why many of the elements of social history could not be included into the project as well.

The tGIS Extension

The tGIS extension was developed as a prototype to examine the possibilities of temporal additions to existing GIS software. As such, while it demonstrates the feasibility and functionality of such an application, it is far from a finished product. Beyond the possibilities of increased processing efficiency by the use of improved algorithms, a number of enhancements would be required prior to release of this type of application for widespread use. Foremost of these would be improved code-writing to remove minor bugs and add 'error-trapping' scripts to prevent a user from inadvertently misusing the application. In addition, improvements to the user interface would make the extension easier to learn and operate.

Functionally, there are a number of refinements to the existing application that could be made. These include an expansion of the metadata tracking mechanism (enabling the ability to catalog multiple archival maps which contain information for a given feature). This would increase the usability of the Metadata layer as a general catalog of archival map data. Another improvement would be the inclusion of multiple types of time (database and/or construction time in addition to world time). The realm of cartographic output could also use further enhancements including temporal-viewing mechanisms for creating ad-hoc animations as well as the ability to produce interactive maps.

Additional user interfaces and customizations also could be developed to make the tGIS extension suitable for use in other disciplines (e.g., anthropology, geology, humanities, etc.).

Other enhancements would require a more substantial development investment (and begin to enter the realm of designing a true TGIS as opposed to a tGIS extension). These include the ability to incorporate time ranges as well as ordinal temporal associations. More advanced functionality that would be desirable includes the ability to incorporate temporal (as well as spatial) uncertainty and temporal interpolation. Finally, an interface to facilitate modeling, of either the future or the past, could be developed, making use of the temporal database for automated analysis of 'what if' types of questions.

<u>Migrating to ArcGIS (VBA)</u>

In addition to improvements to the existing extension, a logical undertaking would be the migration of the extension from Avenue to ArcGIS (using VBA). While ArcView 3.x and Avenue served as an appropriate development platform for the tGIS extension, the current industry trend is towards ArcGIS. Though no effort has been made at this point to translate the application to VBA there are a variety of reasons why this would be a worthy effort.

Perhaps the largest incentive for migrating to ArcGIS is the fact that VBA is a more widely used programming language than Avenue, and thus has greater potential for code-writing support and assistance. While the Avenue code-writing community has the advantage of being specifically focused on GIS applications, the VBA community has much to offer by virtue of its size, particularly in the arena of code improvements (e.g., bug and error trapping code as well as efficient algorithms). There is also a growing group of researchers focusing on temporal (though not necessarily spatial) databases, many of whom are using VBA, presenting further opportunity for beneficial collaboration.

In addition, as the most recent software release from ESRI, ArcGIS has a number of enhancements (beyond the adoption of VBA) that could benefit the development of a tGIS extension. These include improved user customization features (additional toolbars, etc.) and cartographic enhancements (including semi-transparent overlays of images and dynamic labeling of features). The ArcGIS package also introduces a new data model (the Geodatabase), that promises to be more extensible and customizable than the Shapefile.[26] The Geodatabase offers increased functionality, in terms of database rules, relationships and integrity built into the data model that could be used to streamline both the code-writing and implementation of the tGIS extension.

Commercial TGIS Product(s)

While the tGIS extension developed for this paper was never intended for commercial release, it is easy to see the advantages of

[26] While a direct translation of Avenue to VBA does not exist, it *is* possible to directly convert a Shapefile (including the tGIS fields) to a Geodatabase.

such a product. Beyond the obvious benefit of not having to create a custom application for a given research project, a commercial product would (presumably) include many of the advantages of efficient code-writing, debugging and error-trapping that require extensive testing and expertise on the part of the code writer(s). Assuming that such an extension would be customizable to a certain extent, the remaining task would be for a researcher to choose the particular parameters relevant to a given study before commencing with data entry.

Beyond this immediate benefit to an individual researcher or project, a commercial product could also facilitate the establishment of an industry standard for temporal database design. Such a standard would greatly increase the ability to share data between projects, and thus would be a further incentive for creating temporal databases.

Final Comments

The tGIS extension demonstrates that temporal information derived from archival maps can be incorporated into existing GIS databases. The Fairhaven case study illustrates both the wealth of information that is contained on archival maps, and the fact that the capture of this data remains no small task, even with the assistance of a tGIS extension.

As was noted with the Fairhaven case study, the development of temporal databases (not to mention the tGIS extension itself) requires considerable effort on the part of the researchers. With regard to a particular research project, the decision as to whether or not to develop a tGIS application and/or database needs to weigh the costs of development against the analytical benefits of having ongoing access to the derived information. As was noted above, the development of a commercially available TGIS product (and database standards) would greatly encourage the development of temporal databases for all types of analysis.

It has been said that history is geography's laboratory.[27] Geographers and urban planners are rarely able to conduct large-scale laboratory-style experiments with regard to urban planning and development. Instead, they are left to study what currently exists and the history of the same. By more fully understanding what has occurred in the past, researchers can hope to be better able to predict the effects of current decisions. By improving historians' ability to ask geographical questions and display the results of their analysis, temporal GIS have the potential to be a powerful tool, assisting both the general public and government officials to better understand the implications of human activity on the natural and social landscape.

The creation of spatio-temporal databases presents new opportunities for data exploration, including both analysis and cartographic display. As a means of historical reconstruction, the tGIS extension proved to be a useful tool for compiling and cataloging a diverse range of data sources into a single series of temporal databases, accessible from a common user interface. As history rarely presents a complete story in a single data source, the ability to create and update a composite database provides substantial benefits for ongoing historical analysis. The tGIS extension enables the rapid creation of custom map displays (regardless of the existence or non-existence of an individual archival map meeting the spatio-temporal parameters required) using the best information available, drawing from multiple data sources.

[27] Source unknown.

This paper has examined issues involved with extending existing GIS software to better accommodate temporal data derived from archival maps. While considerable work remains, the feasibility and desirability of including time within a GIS have been shown. By facilitating the assembly and recall of information from an array of data types and sources, the prototype tGIS extension clearly demonstrates the potential benefit that temporal GIS offers historical analysis using archival maps.

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