A Spatio-Temporal GIS Database for Monitoring Alpine Glacier Change

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Abstract

Monitoring alpine glacier change has many practical and scientific benefits, including yielding information on glacier-fed water supplies, glacier-associated natural hazards, and climate variability. This paper describes the design and implementation of a spatio-temporal GIS database for monitoring glacier geometry and geometric change. The temporal component of the glacier data is managed through both a 'snapshot' and time-normalization approach to the relational data model in which glacier properties are organized according to their spatial and temporal dependencies. Because of the integration of diverse historic and contemporary data sources, metadata play a key role in managing data quality. For the initial population of the database, historic and contemporary map data on six glaciers on Mount Rainier, Washington were used to model glacier geometry and examined for geometric change over the period 1913-1971.

1. Introduction

The long-term monitoring of alpine glaciers has many practical and scientific benefits. Because glaciers play a central role in the hydrologic system of many mountainous regions and provide water for drinking, irrigation, and other uses in the form of glacial runoff, glacier monitoring also yields valuable information for the management of the water supply. Glacier monitoring also aids in risk assessment of glacier-associated hazards, such as floods and debris flows.. In addition, because glaciers respond to regional climate, glacier monitoring provides important information on climate variability and change (Dyurgerov and Meier, 2000). The mass loss from alpine glaciers account for about 1/3 to 1/2 of the currently observed sea level rise (Meier, 1984). For these reasons, glacier monitoring programs have been undertaken by the United Nations (UNESCO/IAHS, 1970) and the United States Geological Survey (USGS; Fountain et al., 1997). Representing glacier geometric change is of particular importance in glacier monitoring because it is related to changes in glacier mass (Krimmel, 1989) and glacier runoff (Fountain and Tangborn, 1985).

The current existing database for glaciers and glacier change is under the auspices of the United Nations' Environmental Program, International Snow and Ice Commission, World Glacier Monitoring Service (WGMS; UNESCO/IAHS, 1998). While the WGMS database contains the most comprehensive data on glacier change in the world, it is limited to scalar values such as glacier length, area for different elevation intervals, and values of mass change. Because glaciers are three-dimensional objects, conversion to scalar measures of glacier geometry loses information in the conversion to a description based on scalar values. To restore as much information as possible about the three dimensional nature of glacier geometry, with the emphasis on the sub-aerial surface, we developed a geographic information system (GIS) database for glacier monitoring. This effort is not intended to replace the database provided by the WGMS, but rather to complement it.

Our motivation for creating a GIS database for glacier change is to mine the wealth of data on historic glacier positions currently depicted on maps and aerial photographs. The systematic collection of glacier data is limited to a very small fraction of glaciers world wide. Thus, exploitation of data from maps and aerial photos presents an opportunity to expand our knowledge of the spatial and temporal variability of glacier change. Although attempts were made to inventory glaciers in the past (e.g. Post et al., 1971) such manual efforts were a long and onerous task. GIS allows for efficient data compilation, storage, retrieval, and analysis and therefore provides an excellent environment within which to develop a database of glacier change.

Currently, the use of GIS for the analysis and monitoring of glacier change is still relatively novel, although satellite and airborne remote sensing are well-established methods for gathering glacier data. Perhaps the most common application of GIS to glacier analysis is through the use of digital elevation models (DEMs). DEMs have been derived from, and have been used in combination with, aerial photography and other remotely sensed data for the analysis of glacier geometry (Aniya and Naruse, 1986; Allen, 1998). DEMs have also been used to calculate glacier volume and elevation change over time (Reinhardt and Rentcsh, 1986). In addition, GIS packages have been used to analyze remotely sensed imagery to investigate paleo-glacier extents in formerly glaciated alpine regions (Klein and Isaaks, 1996) and have served to integrate aerial photography and historic maps of glacier extent in order to develop a model of regional climate and glacier advance and retreat (Champoux and Ommanney, 1986).

These research projects demonstrate the potential that GIS holds for integrating diverse sources of data and modeling glacier geometric change. However, they also indicate a number of challenges that must be addressed when developing a long-term GIS database for glacier monitoring. First, because such a database handles glacier data for different time periods, including contemporary and historic data sources, diverse spatial data sets of varying accuracy must be integrated. Second, the temporal nature of the data and time-intensive analysis of glacier change demand efficient and robust management of the interrelated spatial and temporal components of glacier data. Finally, because a database for glacier change is intended to facilitate a variety of analytical applications, it must support flexible and multi-path spatio-temporal data retrieval schemes.

In this paper, we describe the design and implementation of a GIS glacier database that meets these challenges using the GIS package *ArcView* by Environmental Systems Research Institute (Redlands, California). As a case study and pilot implementation, the database described here is populated using historic and contemporary data describing the geometric properties of the primary alpine glaciers residing on Mount Rainier, a volcano located in the Cascade Range of Washington. We also demonstrate an analysis of geometric change for these glaciers, including calculations of glacier area and volume, over the years 1913-1971.

2. Construction of the Database

2.1 Data Sources

Glacier data for Mount Rainier were acquired from the USGS and Mount Rainier National Park in the form of paper and mylar topographic maps. Data on the six largest glaciers for 1913 and 1971 were available: Nisqually, Carbon, Emmons, Winthrop, Cowlitz, and Tahoma (figure 1). Because Nisqually Glacier was historically monitored as part of a long-term Mount Rainier National Park research project, maps for Nisqually Glacier were also available for the years 1956, 1966, and 1976.

Many of the maps included only individual glaciers; others included the ice cover of the entire park. Two maps of Nisqually Glacier included only the lower portion of the glacier in an attempt to show the change in glacier extent. The scales of these maps ranged from 1:62,500 (the map of the entire park) to larger scale maps of individual glaciers at 1:12,000. For this reason, as well as because of the changes in survey techniques throughout the historic period of the database, the accuracy of the maps varied greatly.

In addition to this diverse collection of glacier data, a map describing the sub-glacial topography for all of these glaciers, with the exception of Cowlitz Glacier, was also acquired from the USGS. This 1:12,000 scale 200-foot contour interval map was created by Driedger and Kennard (1986) using ice radar to measure the thickness of the glacier at specific points. These authors manually interpolated the sub-glacial topography from their point values of ice thickness superimposed on an enlarged 1971 USGS topographic quad map.

2.2 The Representation of Glacier Geometry

All maps were georeferenced to the Universal Transverse Mercator (UTM) coordinate system. While the recent maps had sufficient benchmarks for registration, some of the older maps did not. Control was transferred from the recent to older maps by identifying prominent features on both the maps, such as road intersections, trail intersections, named isolated rock outcrops, buildings, and bridges. The UTM coordinate positions of these features were determined on the new maps and then used to register the older maps.

The glacier geometry properties included in the database were adapted from the glacier geometry monitoring guidelines described by Fountain et al. (1997). The strategy for representing a glacier's geometric character at a given time of record (we use the term 'time of record' to refer to the representation of a glacier at a particular moment in time) assigns individual geometric properties, or a group of like properties, to a specific 'layer' of spatial data. The data layer may be either a raster grid or a vector coverage. For example, the glacier boundary may be best represented as a discrete line and is therefore stored as a vector layer while the surface elevation of a glacier is continuous and so is best represented by a raster grid.

All glacier geometry data were initially generated through manual vector digitization (i.e. using a digitizing puck and tablet) from the paper and mylar maps. These digitized vector data were then later used to generate raster representations for those geometric properties for which it was appropriate. One set of the following named spatial data layers were digitized directly from the maps for each glacier for each time of record (figure 2): *glacier extent*, *debris extent*, and *original contour*.

The *glacier extent* layer represents the areal extent of the glacier. Outcrops of rocks surrounded by the glacier appear as 'islands.' For the pilot implementation of the glacier change database concerning the representation of glaciers on Mount Rainier, each of the *glacier extent* layers were divided into two polygons associated with glacier mass balance. The polygon on the upper portion of the glacier represents the *zone of* *accumulation*, where more mass is added to the glacier via snowfall (typically) than is lost through melting and evaporation over the course of a year. The lower polygon represents the *zone of ablation*, where the glacier loses more mass due to melting than is gained by snow accumulation (Selby, 1985). In the zone of ablation, the winter snow does not survive the summer (melt) season and glacier ice is removed as well. These two zones meet at the *equilibrium line*, where the annual net mass change is zero. The size of the zones and the position of the equilibrium line typically change from year to year depending on that year's climate of winter snow accumulation and summer melt.

Typically, the topography of the glacier is slightly concave over the zone of accumulation and convex over the zone of ablation because of the downslope flow of glacial ice (Porter, 1985). The rate of change in slope over the surface of the glacier produces a distinctive signature in the topographic maps of the glacier surface in which the contour lines form a 'U' shape over the zone of ablation and an inverted 'U' shape over the zone of accumulation. Around the equilibrium line, mapped contours appear to be nearly parallel and regularly spaced, straight lines. Based on these topographic properties, the location of the equilibrium line and zones of accumulation and ablation were interpreted by the authors from the topographic maps.

The *debris extent* layer represents the areal extent of the rock debris that may mantle some of the glacier surface. The debris originates from rock avalanches from valley walls and from subglacial rocks that are carried to the surface by the ice flow. Debris cover is typical for glaciers on volcanoes where over-steepened valleys and mechanically weak rock substrate, due to geothermal alteration, are common. The *original contour* layer represents the contour lines describing the glacier elevation that were digitized from the topographic map. While the digitization of every mapped contour line would retain the most information from the topographic maps, the time necessary to complete such a task was prohibitive. For this reason, digitization generally captured every fifth, or 'bold,' contour line on the topographic map. The actual digitized contour interval varied with the scale of the map.

A *terminus position* layer was also created for Nisqually Glacier that represents field measured positions of the glacier terminus or margin of the glacier furthest down valley (figure 2). In many cases, while historical records of the complete glacier extent are not available, historical records of terminus position have been recorded. In addition, paleo-terminus positions may be inferred from geomorphic features (moraines) in the ice-free terrain. Old positions of the glacier terminus are good proxy indicators of former glacier extent and therefore climate at that time. This data layer integrates this multi-temporal glacier terminus data into one data layer.

In the cases where the maps of Nisqually Glacier described only the glacier's lower reaches, these contours were digitized and then 'appended' onto the digitized upper contours for Nisqually Glacier at a 'nearby' time of record to create a full contour layer. The time of record of this concatenation is assumed to represent the glacier at the time of the lower elevation mapping. Most glacier geometric change over short time scales (i.e. decades) occurs in the glaciers' lower reaches as the glacier advances or retreats and change in the upper reaches is relatively small (Schwitter and Raymond, 1993). While having complete maps at regular and closely spaced time intervals would be ideal, this is often not the case, and we feel that this approach makes best use of the limited spatial and temporal data available. The resulting data layer of the 'append' procedure is called the *appended contour* layer.

The *original contour* layer (or *appended contour* layer, where appropriate) provided an irregularly spaced 'lattice' of elevation points by extracting a regular sample of the 'shape points,' or vertices, along each contour line. These elevation points were used to interpolate a 20-meter resolution raster grid of elevation for each glacier for each time of record. Interpolation of a raster surface from points digitized along contour lines presents problems due to the irregular distribution of sample points (Clarke, 1990). This applies especially to glaciers, where glacier slopes can change abruptly along the longitudinal profile. This creates varying degrees of sample point density along the longitudinal profile, while the distance between points along the contour lines (transverse) remains basically unchanged.

Often, the result of this problem is a 'wedding cake' effect in which the elevation surface exhibits a series of step-like plateaus (Clarke, 1990). While there are other, perhaps more accurate, sampling schemes with which to generate elevation grids from topographic maps (e.g. Eklundh and Martensson, 1995), it was part of our strategy for the initial population of the database to preserve the original contour data in digital form. Since it would be impractical to digitize the same elevation data twice using two different strategies, elevation data derived from digitizing contour lines provided the basis for generating the glacier elevation grids.

There are a number of interpolation techniques available in *ArcView* for creating raster elevation grids from sampled elevation data, including spline, kriging, and distance weighted. Spline interpolation fits a piece-wise function to set of sample points within the neighborhood of the location for which a value is being estimated. Kriging uses the variogram to determine the neighborhood of influence used for the estimation of a value at given location. Distance weighted estimates a value at a given location by taking the average of the values of those sample points located nearby, weighted according to the square (or other function) of their distance from the interpolated value.

We briefly examined each of the interpolation methods offered in *ArcView* to determine the most appropriate interpolation technique for generating raster data layers of glacier elevation. We found that kriging required prohibitively extensive 'tuning' due to the complex topographic properties of the glacier elevation surface. The distance-weighted method had the opposite problem; while relatively simple to manipulate, it was unable to sufficiently capture the complexity of the topographic surface of the glacier. Spline interpolation was revealed to possess the best combination of desired accuracy and ease of use required for this pilot implementation. Spline was therefore used to generate the raster elevation grid, called the *glacier surface* layer, for each glacier for each time of record. The same interpolation technique was applied to the digitized contours of the sub-glacial topography map created by Driedger and Kennard (1986) to create a raster *basal topography* layer for each glacier for which sub-glacial data were available.

2.3 Representing Non-Geometric Glacier Properties

In addition to the spatial data layers described above, there are various types of attribute data stored in the database. Attributes such as the area of each polygon in the vector data layers and the value associated with each grid cell in the raster data layers are calculated and stored in *feature attribute tables* (FAT) and *grid attribute tables* (GAT), respectively. In the FAT, each record represents a particular geometric feature and in the GAT each record represents a particular grid cell value. These tables are generated automatically by the *ArcView* Relational Database Management System (RDBMS) when the spatial data layers are created.

The glacier change database also stores a number of other attributes that describe the properties of each glacier in the database. These properties can be broadly classified as attributes concerning glacier geomorphometry, location, or metadata. Geomorphometry attributes include information such as the area of the zones of accumulation and ablation, total glacier area, the accumulation area ratio (ratio of the accumulation area to the total glacier area – AAR), and other geometric properties. Location attributes concern where the glacier resides, including its host country, state or province, mountain range, and mountain. Metadata attributes include information such as the date the field data were collected (i.e. date of the photographic surveying), a description of the original data source, who created the digital data, and when the data were digitized.

2.3 Managing Temporal Information

There are two primary temporal data handling issues of concern to the glacier-monitoring database. The first concerns the ability to compare glacier characteristics from one time of record to another and extracting information about the change. The second issue concerns the ability to construct spatial and temporal queries on the database. For instance, one user may be doing an analysis on the change of one glacier through time while another may require the position of all glaciers in a region at one time. A third person may want information on one glacier at one time. Each of these data retrieval goals demands a different spatio-temporal query strategy.

A number of novel approaches to spatio-temporal data management have been suggested, including 'event-based' models (Peuquet and Duan, 1995) and temporal extensions to the vector topologic model (Langran, 1992; Worboys, 1992). However, the most common approach is the 'snapshot' method in which a spatial data layer, referred to as a snapshot, is 'tagged' to represent a specific moment in time (Langran, 1992). A series of spatially and temporally registered snapshots of the same area forms the spatio-temporal representation.

In the glacier change database, we distinguish between the management of the temporal component of the spatial data and the temporal component of the attribute data. For the spatial data, we take the snapshot approach because it supports the data management and analytical goals of the database and is comparatively straightforward to implement in a 'hybrid' GIS such as *ArcView* that stores attribute data in an RDBMS and spatial data in a separate storage format. For each glacier, the spatial data for each time of record is represented by one set of snapshots, including the *glacier extent*, *debris extent*, *original contour* (or *appended contour*, where appropriate), and *glacier surface* data layers. All of the layers are spatially registered with the other temporal representations for that particular glacier. Analysis of glacier geometric change takes place through vector topologic or raster overlay of two or more temporal snapshots. For example, two *glacier extent* layers (snapshots) that describe the same glacier at different times of record may be overlaid to extract the change in glacier area over that time period.

While the snapshot approach is used to manage the temporal component of the spatial data in the database, management of the temporal component of the *attribute* data requires a different strategy. Note that all attributes in the database vary according to their spatial and temporal character. Some glacier attributes may apply to an entire glacier coverage, such as the total glacier area, and some may only apply to one polygon or line within a vector-based glacier data layer, such as the area of the ablation zone. Analogously, some glacier attributes may apply to a glacier for all times of record while others may apply for only one time of record. For instance, the name of a glacier remains unchanged throughout the historic record of the database, while the glacier area applies to a glacier at only one specific time of record. Based on these distinctions, we identify three different types of attribute data:

- *Feature-based* attribute data, associated with a line or polygon feature found within a vector glacier data layer representing one time of record (e.g. the area of the zone of accumulation).

- *Glacier-based, time-dependent* attribute data, associated with an entire glacier at one time of record (e.g. the AAR).
- *Glacier-based, time-independent* attribute data, associated with an entire glacier for all times of record (e.g. the glacier name).

To facilitate data management and retrieval, the attribute data are organized in a manner analogous to the 'time-normalization' approach described by Navathe and Ahmed (1993) for extending the relational data model to handle temporal data. This technique utilizes the idea of 'temporal dependency' in which tables are normalized so that each record in the table contains a set of attribute values that are considered to be 'true' during the exact same time period or moment in time. In this approach, each table contains an attribute that represents a 'time-stamp,' or the moment in time for which all the attribute values for a given record are applicable. All attributes in the table are therefore 'temporally dependent' on the time-stamp attribute.

In the glacier change database, the time-normalization approach is implemented so that the attribute data are organized into separate feature-based; glacier-based, time-dependent; and glacier-based, time-independent tables. This organization scheme ensures that all of the records in each table share attributes that have a common temporal (and spatial) dependency. For instance, all records in the glacier-based, time-dependent tables have attributes that apply to an entire glacier at one specific time of record. Through *join* and *link* operations offered by the *ArcView* RDBMS, each of the different types of attribute tables are related to the appropriate spatial data and to each other through the identification of common values found in foreign key fields designed specifically for this purpose.

Figure 3 shows the relationships between a spatial data layer and tables that represent these various types of attribute data. This figure demonstrates how a particular polygon in the 1913 Carbon Glacier *glacier extent* data layer, representing the zone of accumulation, is related to a particular record in its associated feature-based attribute data table (FAT). This table includes attributes such as the type of zone the polygon represents (i.e. ablation, accumulation, or exposed rock; the ZONE field) and the median elevation (the M ELEV field) and down slope length (the LENGTH field) of that polygon.

The feature-based attribute table also includes the field METAKEY, whose value is unique for each glacier for each time of record. This field acts as the foreign key that allows the feature-based table to be related to a glacier-based, time-dependent attribute table, such as the *Morphology* table shown in figure 3. The *Morphology* table includes geomorphometry attributes that apply to an entire glacier for a particular time of record, such as the fields NAME (the name of the glacier), ELA (equilibrium line altitude), and AAR. The *Morphology* table also includes the field WGMS, which refers to the World Glacier Monitoring Service, the glacier monitoring program undertaken by UNESCO/IAHS (1998). The value for this field is a WGMS-assigned number that is unique for each glacier in the world. Note that the value for the METAKEY field is the WGMS number followed by the survey year.

The *WGMS* field acts as a foreign key that allows the time-dependent attribute tables to be related to the time-independent attribute tables, which also contain the WGMS field. Figure 3 shows an example in which the *Morphology* table is linked to the glacier-based, time-independent *Location* table, which also includes attributes that describe the glacier's name (the NAME field) and location, including its state (the STATE field), mountain range (the RANGE field), and the mountain on which the glacier is located (the MOUNT field). In this way, all the different types of attributes about Carbon Glacier may be linked across various tables to facilitate data retrieval.

Figure 3 demonstrates how this database schema facilitates flexible and multi-path spatio-temporal data retrieval through four separate avenues: 1) by glacier location, 2) by specific glacier, 3) by time of record, and 4) by specific glacier at a time of record. For example, a query on the *Location* table may yield information on all the glaciers in a particular mountain range or country. By linking the *Location* table to the *Morphology* table through the WGMS field, this query can be extended to retrieve data on those glaciers for a particular time of record. The *Location* table may likewise be queried to retrieve data on a particular glacier, for instance by querying on the NAME field. If one is interested in a particular time period, one may query on the field that describes the glacier survey date in the glacier-based, time-dependent *Metadata* table (not shown). The *Metadata* table may also be used to retrieve data on a specific glacier at a particular time of record using a compound query on the fields that record the survey date and name of the glacier.

3. Analysis of Glacier Geometric Change

This section of the paper describes how the database may be used to analyze glacier geometric change over time. Glacier area and volume were found for all glaciers in the database, except Cowlitz Glacier, for the years 1913 and 1971. In addition, area and volume were found for Nisqually Glacier for the years 1956, 1966, and 1976. Changes in area and volume between times of record were also calculated.

The area of each glacier was found by summing the areas of the zones of ablation and accumulation polygons for each glacier. The area of each zones is calculated automatically by *ArcView* when a vector data layer is created. To find the volume of each glacier, the *basal topography* layer was 'subtracted' from each *glacier surface* layer for each time of record. This results in a raster grid that represents the thickness of the glacier, a *glacier isopach* layer, in which each grid cell represents a three dimensional volume. As an example, Figure 4 shows the Carbon Glacier *glacier isopach* layer. The volume of each grid cell is defined by the multiplication of its length, width, and depth. Because of the way *ArcView* handles attributes for raster data layers, each record in the GAT associated with the *glacier isopach* layer represents one grid cell value (of glacier thickness) and also describes the number of grid cells that have that particular value. Therefore, the volume of all grid cells that share the same glacier thickness value can be found by multiplying a record's value by the grid cell area (400 m^2) and then by the number of grid cells that share that value. For example, if five grid cells have a value (glacier thickness) of ten meters, their volume can calculated as 20,000 m^3 (5 grid cells x (10 m x 400 m^2)). In this manner the total volume for each glacier for each time of record was calculated. Temporal changes to glacier area and volume were found by subtracting the earlier glacier area and volume figures from the later. Another way to calculate volume change, if the sub-glacial topography is unknown, is to subtract two *glacier surface* layers that represent two different times of record for the same glacier. Although total volume cannot be calculated using this method, volume change can still be derived.

Table 1 describes the area and volume for each glacier at each time of record as well as the 1913-1971 area and volume change. Glacier area, and area change, for the years 1913 and 1971 are graphically presented in figure 5. Throughout the historic record of the database, Carbon Glacier remained the most voluminous and extensive with a 1971 volume of 762,603,947 m^3 and a 1971area of 11,015,370 m^2. Cowlitz Glacier lost the most area of all glaciers during this period, 2,424,185 m^2.

4. Managing Data Quality

Because all spatial data contain some degree of uncertainty, issues of data quality apply to every spatial database. These data quality issues generally concern the accuracy and precision of the spatial data and the 'correctness' of the attribute data, as well as the completeness of the spatial coverage, the logical consistency of the data, and the lineage of the data. Data uncertainty may be introduced during data collection, manipulation, or during the use or application of the data (Thapa and Bossler, 1992). These issues of data quality are compounded in the glacier database because of the integration of historic and contemporary data sets and the spatial overlay of temporal snapshots for glacier geometric change analysis.

Sources of data uncertainty in the analysis of glacier geometric change on Mount Rainier include the positional error inherent in the source maps that were used to derive the digital glacier representations as well as positional error that was incurred during the registration of those maps. In addition, the digitization of glacier properties demands significant cartographic generalization by the person doing the digitizing. In many cases, the glacier boundaries were constituted of many small 'fingers' of snow, some of which were connected to the main glacier body at one time of record and disconnected at another. Because time constraints prohibited the detailed digitization of every slight permutation of the glacier boundary, it was up to the person digitizing to decide on the placement and density of the digitized shape points that describe the glacier boundary. Further data uncertainty was introduced through the interpolation of the *glacier surface* layers. The use of different interpolation techniques, and the use of different parameters for a single technique, will produce different interpolations of elevation surfaces.

As a means to investigate the effect of the uncertainties on the accuracy of the glacier geometric change analysis, we compared our calculated area and volume for each glacier in 1971 to that found by Driedger and Kennard (1986; Table 2). This comparison does not provide an absolute measure of data accuracy but, rather, indicates the inconsistency between the two studies. Both studies used much of the same source data, including the 1971 USGS topographic map of Mount Rainier National Park and the basal topography. While the approach used for calculating glacier area was essentially the same for both Driedger and Kennard's (1986) study and ours (although they used analog methods), their methodology for calculating glacier volume differed significantly. They modeled each glacier as a series of contour interval 'steps' in which each step volume was calculated and summed to find the total glacier volume.

Generally, our glacier area and volume measurements are found to be consistent with the results of Driedger and Kennard (1986), who report an error range of 20% for their volume estimations. The calculation for Tahoma Glacier stands out as the one case in which the two studies produce noticeably different results. This difference can be attributed to variation in the interpretation of the glacier boundary, as indicated by the proportional difference in both glacier area and volume between Driedger and Kennard's (1986) analysis and ours. This issue emphasizes the need for consistency in interpretation for determining glacier extents and highlights the need to clearly understand how previous researchers have defined glacier extent.

Another significant data quality issue was revealed in the analysis of glacier volume. Maps of the *glacier isopach* layers showed the presence of grid cells with negative depth values, i.e. negative values of glacier thickness (e.g. figure 4). Negative depth occurs when the basal topography is modeled as higher in elevation than the glacier surface elevation. Clearly this is a logical inconsistency as there must be at least some glacier volume associated with each cell in the *glacier isopach* layer.

Table 3 demonstrates one way to assess the relative impact of negative depth cells on a given glacier volume estimation by revealing the fraction of cells which are negative and the average negative cell depth for each glacier. While the average fraction of negative depth cells for the 1971 *glacier isopach* layers is 6%, this figure rises to 22 % for the 1913 *glacier isopach* layers. In both years, the Nisqually Glacier *glacier isopach* layer contains the highest percentage of negative depth value cells, reaching 51 percent in 1913, enough to render meaningless any derived volume calculation (note that Nisqually Glacier was the only glacier which was calculated to have gained volume between 1913-1971).

We don't know precisely which of the three data sets (1913, 1971, or radar-derived basal topography) causes the negative depth values to occur. That the 1913 *glacier isopach* layer yields a larger error than the 1971 *glacier isopach* layer when subtracted from the *basal topography* layer indicates that the 1913 *glacier isopach* layer is less accurate. This is a reasonable conclusion, particularly for the upper reaches of the glaciers at high elevations, because methods in 1913 were restricted to ground-based instruments and relatively low altitudes. By the 1970s, aerial photogrammetric techniques were well developed and provide a much better overall mapping of high altitudes. However, photogrammetric techniques suffer significant errors over uniformly illuminated featureless terrain, such as snowfields. The radar-based glacier data is also subject to error, the most significant of which is the interpolation error from relatively sparse data. As previously mentioned, only a few radar points were acquired in the upper reaches of the glaciers and the inferred basal topography was subject to guesswork (Driedger and Kennard, 1986).

Given the significant data quality issues illustrated here, and the fact that the database is intended to be used for a variety of applications, it is particularly important that the user be aware of all of the potential sources of error. Our overall strategy for managing data quality is to provide sufficient metadata so that the user may decide the data's 'fitness for use' considering the demands of a particular application. The metadata includes information on how we digitized the maps (e.g. every 500 foot contour interval), a qualitative discussion on how closely the glacier boundary was digitized (was every small 'finger' of snow included), and our assessment of the quality of the original data source. Therefore, we feel strongly that the metadata aspect of the database is of equal importance to the data itself because it summarizes the data quality issues for the otherwise uniformed user.

5. Conclusion

This project has demonstrated how GIS can be used to integrate diverse historic and contemporary sources of glacier data in order to model glacier geometry. A GIS database of glacier geometry facilitates the analysis of glacier geometric change, a task that may otherwise be cumbersome and time consuming. Although there are data quality issues associated with the spatial inaccuracies inherent in the source data and the process of interpolation, this data error is recognized and managed for the informed analysis of glacier geometric change. In addition, we have also demonstrated a GIS database design that facilitates multi-path spatio-temporal data retrieval. Ultimately, we intend for this database to evolve into a rich glacier data management and analysis resource that will contribute to the worldwide glacier monitoring effort by facilitating data sharing among researchers in the glaciological community. We hope that this database will increase the efficiency of using map-derived products for the analysis of glacier change towards understanding the role of glaciers in natural hazards, water resources, climate change, and global sea level rise.

To date, our database has been used to compile and examine data acquired exclusively from historic paper maps. While this largely untapped source is rich in historic information, it has a finite supply, which has been exhausted at Mount Rainier and will soon be exhausted in neighboring regions. Clearly, the future of the database is to incorporate data derived from satellite imagery. In the 1970s and 1980s few satellites were operational, making repeated passes infrequent, and therefore image acquisition was highly weather dependent. In recent years, however, many more satellites are now orbiting and operate in the visible (e.g. Landsat 7, Aster) and active microwave regions (e.g. ERS-2, RadarSat). The resolution of these platforms is also greatly increased, by at least a factor of two, making remote sensing of glacier change over short periods (i.e. a few years) feasible. In addition, the all-weather day-night capability of the active-microwave satellites enhances our efforts to image glaciers in mountainous regions where cloud cover is common. With both high-resolution visual imagery and interferometric synthetic aperture radar (active microwave), topographic maps of the glacier surface can be derived. Thus, we can acquire both glacier outline and topography with time.

While our current database structure can incorporate remote sensing-derived glacier outlines and topography, the incorporation of the remote sensing images themselves within the database remains a challenge. To incorporate digital imagery we need to develop protocols for imagery extent and file size. With continued rapid reduction in the cost of computer memory, and equally impressive gains in computer speed, we anticipate that storage of the imagery will not problematic. A greater challenge, however, concerns the integration of remotely sensed imagery with the other glacier data stored in the database and the support for integrated data retrieval and analysis. This issue may be addressed by developing metadata protocols for imagery, including a description of spatial and temporal extent, and incorporating those metadata and related image files within the database schema. Recent developments in object-oriented spatial data modeling hold particular promise for supporting the integrated management of diverse data types, such as remote sensing imagery and vector and raster data layers.

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Glacier	Year	Area m^2	Area Change	Volume m^3	Volume Change
Carbon	1913	13,233,767		862,028,350	
	1971	11,015,370	-2,218,397	762,603,947	-99,424,403
Emmons	1913	12,622,860		812,707,453	
	1971	10,942,403	-1,680,457	628,081,706	-184,625,747
Nisqually	1913	6,547,537		250,659,840	
	1956	6,284,827	-262,710	238,052,871	-12,606,969
	1966	6,682,383	397,556	251,907,718	13,854,847
	1971	6,072,045	-610,338	257,833,629	5,925,911
	1976	6,358,650	286,605	276,141,825	18,308,196
Total			-188,887		25,481,985
Tahoma	1913	9,071,095		492,410,579	
	1971	7,591,711	-1,479,384	404,574,231	-87,836,348
Winthrop	1913	10,070,800		582,739,745	
	1971	8,927,386	-1,143,414	477,871,174	-104,868,571
Total	1913	51,546,059		3,000,545,967	
	1971	44,548,915	-6,997,144	2,530,964,687	-469,581,280

Table 1. 1913 and 1971 glacier area and volume and the change to each.

Glacier	Area	Area D&K	% Dif Area	Volume	Volume D&K	% Dif Vol.
Carbon	11,015,370	11,213,030	-2	762603,947	798,060,000	-5
Emmons	10,942,403	11,166,580	-2	628,081,706	673,540,000	-7
Nisqually	6,072,045	6,057,080	0	257,833,629	274,510,000	-6
Tahoma	7,591,711	8,630,410	-14	404,574,231	455,630,000	-13
Winthrop	8,927,386	9,113,490	-2	477,871,174	523,550,000	-10
Total	44,548,915	46,180,590	-4	2,530,964,687	2,725,290,000	-8

Table 2. A comparison of 1971 glacier area and volume as calculated by the present study and Driedger and Kennard (1986), indicated by 'D&K' in the table. The percentage of the difference between the two calculations as compared to our area and volume results is also presented.

Glacier	Year	% of Total Grid Cells with Depth < 0	Mean Depth (meters) of Grid Cells with Depth < 0
Carbon	1913	24	-114
	1971	4	-29
Emmons	1913	11	-56
	1971	3	-57
Nisqually	1913	51	-105
	1956	15	-90
	1966	14	-89
	1971	9	-89
	1976	11	-86
Tahoma	1913	18	-59
	1971	3	-24
Winthrop	1913	8	-117
	1971	3	-28

Table 3. Percent of total grid cells with negative cell depth and the mean depth of those grid cells for the 1913 and 1971 *glacier isopach* layers.

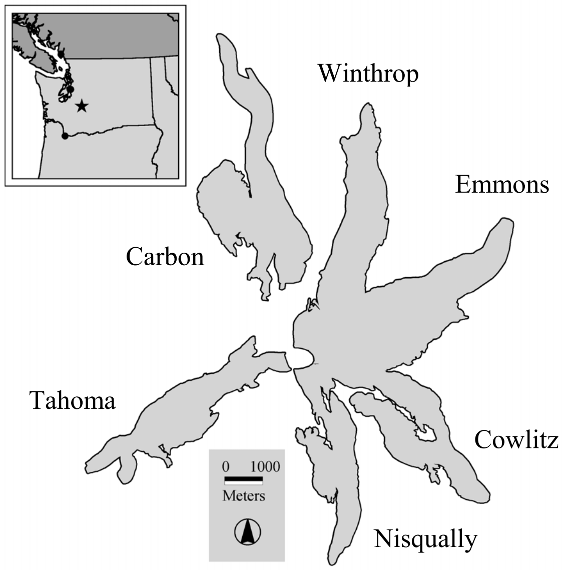


Figure 1. The location of Mount Rainier, Washington in the Pacific Northwest, United States (inset) and the six glaciers used to populate the glacier database. The glacier areas shown here are for 1971.

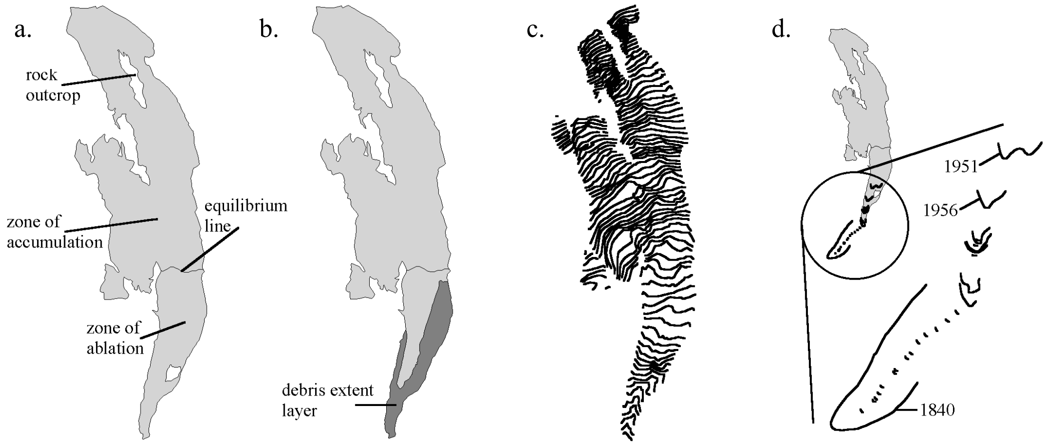
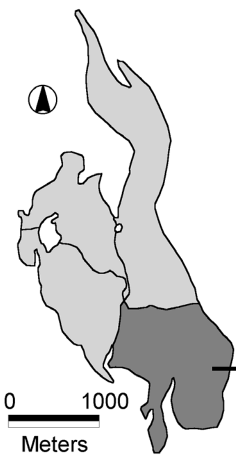


Figure 2. The spatial data layers digitized from the maps for each glacier at each time of record: *glacier extent* (a), *debris extent* (b), and *original contour* (c). The example data layers shown here are for Nisqually Glacier, 1956. Also shown is the *terminus position* data layer for Nisqually Glacier (d), showing dates for a few of the many terminus positions recorded in the layer.



1913 Carbon Glacier *glacier extent* layer

1913 Carbon Glacier *glacier extent* table (feature-based - FAT)

ZONE	**M ELEV**	**LENGTH**	***METAKEY***
ablation	2038	1814	1020201913
accum.	2809	2683	1020201913

Morphology table (glacier-based, time-dependent)

NAME	**ELA**	**AAR**	**METAKEY**	***WGMS***
Nisqually	2136	0.68	1020271913	102027
Carbon	2251	0.46	1020201913	102020
Cowlitz	1866	0.68	1020251913	102025

Location table (glacier-based, time-independent)

NAME	**STATE**	**RANGE**	**MOUNT**	***WGMS***
Tahoma	WA	Cascade	Mt. Rainier	102027
Carbon	WA	Cascade	Mt. Rainier	102020
Cowlitz	WA	Cascade	Mt. Rainier	102025

Figure 3. This diagram demonstrates how the spatial data and attribute tables in the database may be linked or joined to facilitate data retrieval. Note that not all actual records nor fields for these tables are shown in this example. The 1913 Carbon Glacier *glacier extent* layer appears in the upper left and potential links between tables are indicated by arrows. See text for full explanation.

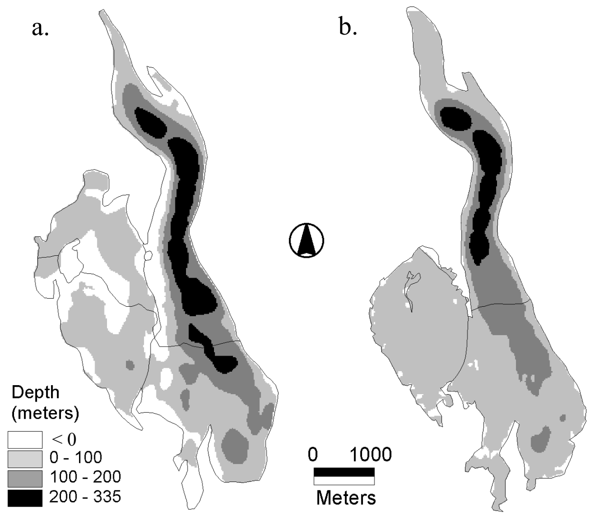


Figure 4. *Glacier isopach* layers that describe glacier thickness for Carbon Glacier, 1913 (a) and 1971 (b), overlain with the *glacier extent* layer.

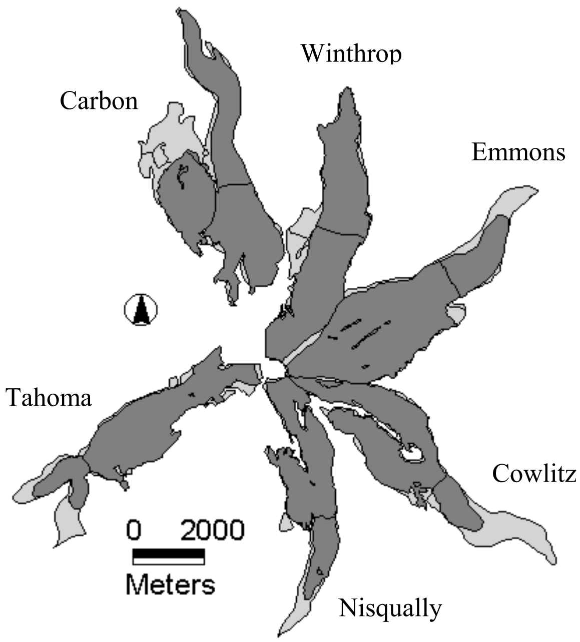


Figure 5. The change in glacier area as demonstrated by the 1971 *glacier extent* layers (dark gray) overlain on top of the 1913 *glacier extent* layers (light gray). All glaciers experienced area loss.