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# An Overview of Selected GIS Methods Available for Use in Glacial Archaeology

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In recent years, increased levels of glacial retreat and ice patch melt due to a warming climate in high altitudes have revealed new opportunities to study glacial archaeology. When artifacts become exposed, they are vulnerable to decomposition and should be collected promptly to protect their (pre)historic properties. Therefore, there is urgency to locate potential archaeological sites to avoid the loss of culturally significant remains. Geographic Information Systems (GIS) can be used to help focus or predict potential glacial archaeological study areas based on their environmental and cultural characteristics. Here, an overview of the possibilities for glacial archaeological research using the spatial analysis methods of visibility, locational, and least-cost path analyses (LCPA) in GIS, is provided.

## Introduction

Some of the most well preserved and complete prehistoric remains have been discovered in frozen environments (Dixon, Manley and Lee 2005). Glacial archaeology pertains to the study of, and prospection for, these archaeological remains from glaciers, ice patches (sometimes referred to as snow patches in literature), and permafrost. Recent changes in global climate have produced regional warming events and subsequent glacial retreats that promote exposure of artifacts from ice. Because of the delicate nature of these artifacts, and in order to preserve their chemical and biological compositions, there is an urgency to collect these materials as decomposition begins almost immediately after exposure to the environment (Dixon, Manley and Lee 2005; Andrews and MacKay 2012). In an attempt to locate these valuable materials, spatial technologies and predictive methods can be used to determine archaeologically sensitive areas and to focus search efforts by incorporating geographic (e.g. topography, geology), cultural

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(e.g. knowledge of previous archaeological remains), and historic (e.g. archival texts and information about the past) parameters into Geographic Information Systems (GIS).

Since Kvamme and Kohler (1988) introduced the field of archaeology to the "enormous" (Sebastian and Judge 1988, 17) archaeological prediction potential of GIS and its methods, most archaeologists have embraced the technology. To date, several detailed reviews highlight the uses of GIS and spatial technologies in archaeology (Kvamme 1999; Ebert 2004; McCoy and Ladefoged 2009). Spatial technologies have clearly benefitted archaeological endeavors. As the field of glacial archaeology is relatively new, and only few GIS-based studies have been conducted (Dixon, Manley and Lee 2005; Andrews *et al.* 2012), it is appropriate to highlight the potential of GIS-based methods available to researchers. The purpose of this paper is to provide an overview of the current status of three GIS methods in archaeology: visibility, locational, and least-cost path (LCP) analyses. The aim is to stimulate the use of GIS methods for the specific purposes of frozen environments to potentially discover archaeological remains that will provide invaluable knowledge about (pre)historic cultures that traversed high altitude or mountainous terrains, but first I will briefly introduce the types of glacial archaeological environments and GIS.

## Glacial archaeological environments

It is important to distinguish the differences between the archaeology of glaciers, ice patches, and permafrost as each represents a different geosystem with distinct dynamics and characteristics that require unique prospection and spatial analysis methods. Ice patches are formed after the gradual compression of many years of annual net snow accumulation that have gradually been compacted into ice (Andrews *et al.* 2012); whereas glaciers are usually much larger systems that involve inputs and outputs from the atmosphere, oceans, and rivers. Due to large masses of ice and their topographic locations, glaciers have an inherent potential energy that forces ice downslope (Benn and Evans 2010). Unlike glaciers, where archaeological remains older than a few hundred years are not expected to be discovered due to their speed of movement and mechanics (Hafner 2012), ice patches left behind from receding glaciers may yield much older relicts. Permafrost, defined as bedrock, earth, or soil that has been below the freezing temperature of water for at least two consecutive years (Woo 1986), has also yielded significant prehistoric and historic archaeological remains (Rainey 1939). In the last century, glacial archaeology has revealed significant discoveries in high altitude, as well as in mountainous regions (Farbregd 1972; Farnell *et al.* 2004; Hare *et al.* 2004; 2012; Dixon, Manley and Lee 2005; VanderHoek, Tedor and McMahan 2007; Andrews *et al.* 2012; Callanan 2012; Hafner 2012; Lee 2012). Perhaps the most substantial frozen archaeological find to date has been a ~5300 year old frozen corpse in the Tyrolean Ötztaler Alps, bordering Austria and Italy that is now known as Ötzi (Seidler *et al.* 1992; Prinoth-Fornwagner and Niklaus 1994).

## A brief introduction to Geographic Information Systems (GIS)

A GIS is a computer software system that can be used for data processing, database management, statistical analysis, and a visualization and mapping interface for georeferenced data which represents real-world entities (Longley *et al.* 1999). GIS data are characterized by their geometric properties, attributes, and topology (how the objects relate to each other in space) (Burrough and McDonnell, 1998). Georeferenced GIS data "know" where they are in space and can be overlaid, calculated, manipulated and analyzed along with other data layers that use the same coordinate system, and are the basis of all GIS analysis. GIS data comes in two structures: vector and raster. Vector layers represent discrete features in space in the forms of points, lines, and polygons, while raster layers represent continuous data, such as elevation.

The roots of GIS were established in the 1960s when the process of linking map layers was originally conducted (Tomlinson 1989). Afterwards, GIS grew into a natural resources development platform in the 1970s and 1980s along with the rise of the microcomputer and an increased interest in environmental issues by governmental institutions (Tomlinson 1989). During the past two decades, the use of GIS has increased exponentially into a robust data creation, storage, and analysis platform, and has expanded to incorporate various disciplines, such as earth science, urban planning, civil engineering, law enforcement, medical sciences, as well as archaeological prospection and prediction (Burrough and McDonnell 1998). Before GIS was used for predictive modeling in archaeology, predictive analyses were performed using algorithms and programming on an advanced calculator (Kvamme 1983; 1984; 1985; Verhagen and Whitley 2011). The rise of popularity and accessibility of GIS methods and tools in the 1990s saw more archaeologists embrace the diverse functionalities of the platform's spatial technologies and predictive models (Verhagen and Whitley 2011) as programs and softwares become more user-friendly, less labour intensive, and more reliable (Kvamme 1999). Spatial technologies can help to determine general or specific areas of archaeological interest in order to save time in the field, or to discover new archaeologically significant locations. These methods can act as a filter to narrow large study areas into smaller, more specific areas with potentially greater archaeological potential (Gietl, Doneus and Fera 2008). In the following sections, visibility, locational, and LCP analyses will be discussed in terms of how they can be integrated in glacial archaeological research in order to locate potentially significant archaeological remains.

## Visibility analysis

The use of GIS for visibility analysis in archaeology has been an efficient method for helping to better understand how (pre)historic people gave meaning to, and viewed, space (Wheatley 1995; Wheatley and Gillings 2000; Paliou, Wheatley and Earl 2011). It has been speculated that humans relate to and interpret their landscapes through visibility, thus the analysis of this social characteristic has been investigated repeatedly in archaeological endeavours (Chapman 2006; Murrieta-Flores 2010). By associating vision with movement, visibility analyses could be beneficial for predicting hunting patterns between settlements and ice patches or for understanding commerce or migration routes over mountain passes. For example, in North America and Europe ice patches were used as refugia by caribou during the warm summer months as an escape from the heat and insects of lower altitudes (Ion and Kershaw 1989). Hunters were aware of these movement patterns and would travel to ice patches in pursuit (Farbregd 1972; Kuzyk *et al.* 1999; Farnell *et al.* 2004; Hare *et al.* 2004; 2012; Dixon, Manley and Lee 2005; VanderHoek, Tedor and McMahan 2007; Andrews *et al.* 2012; Callanan 2012; Lee 2012). The visibility between settlement locations and ice patches were of particular importance for monitoring and tracking game (Lake, Woodman and Mithen 1998). In the Yukon, Canada, ice patch hunting locations were situated within a three hour walk from the adjacent valley bottom (Hare *et al.* 2004). Therefore, it could be assumed that hunters moved to ice patches when game were observed. Visibility analyses in glacial archaeology could also be applied in the Pennine Alps between Switzerland and Italy. For thousands of years, people have used high altitude mountain passes in this region to traverse terrains for migration and commercial purposes (Harriss 1970; 1971). Various archaeological remains dated to the Neolithic period have been found in ice patches and near glaciers of this region (Hafner 2012). From the tops of mountain passes such as Theodulpass (3301 m asl) valley bottoms can be seen. Perhaps visions of distant settlements encouraged travel for commerce, protection, or migration. This type of scenario could be of potential interest for future visibility research endeavours in glacial archaeology. In fact, glacial archaeological studies could be the perfect candidate for visibility analyses. For example, glacial archaeological sites are located in frozen environments, thus, high latitudes and/or altitudes where there is naturally little vegetation, which leads to fewer obstructions for visibility analyses. In the Swiss Alps region, the current regional treeline is about 2200 m asl (Berthel, Schwörer and Tinner 2012), and between 8,700 and 5,000 calibrated carbon years before present (cal. BP) (Wick and Tinner 1997) the uppermost position of the treeline was 2,420 and 2,530 m asl, respectively (Tinner and Theurillat 2003). Therefore, sites located above these levels, which is not uncommon (Hafner 2012), can be assumed to have been free of trees for thousands of years and a Digital Elevation Model (DEM) based on modern landscape topography could be used in visibility analysis as a sufficient representative for the paleoenvironment at high altitudes in the Swiss Alps region.

The two GIS visibility analysis methods, line of sight (LOS) and viewshed are calculated from a DEM. These methods have been used in previous archaeological studies to aid and provide archaeologists with insights about ancient security systems (Gaffney and Stančič 1991), Celtic road systems (Madry and Rakos 1996), prehistoric settlement locations (Jones 2006), the intervisibility between site locations (Ozawa, Kato and Tsude 1995; Lock and Harris 1996), and the defensibility of sites (Lock and Harris 1996; Smith and Cochrane 2011). LOS, which is the most basic form of visibility analysis, is used for calculating the intervisibility between two locations (Kvamme 1999; Ebert 2004). If no obstructions occur along the viewing plane between two locations the result of the LOS analysis will be positive, and the target can be observed from the original point of interest, or negative if it cannot (Wheatley and Gillings 2002). Viewsheds calculate the visible area surrounding a point of interest. Viewsheds are made up of lines of sight spanning 360 degrees from the point of interest (Kvamme 1999; Ebert 2004), and result in a binary raster that is either visible or not from the point of interest. Drawing from the methods used in previous archaeological studies, similar visibility analyses could be used in glacial archaeology to calculate the LOS or viewshed area from known hunting sites at ice patches to predict where settlements may have been located, or for simulating possible travel routes over mountain passes based on the principle visibility between locations.

## Locational analysis

Locational analysis in GIS is valuable for identifying patterns in landscapes and ultimately determining archaeological potential of an area (Sebastian and Judge 1988; Kvamme 1999; Ebert 2004; Dixon, Manley and Lee 2005; Madry *et al.* 2005; Conolly and Lake 2006; Krist 2006; Howey 2007; Whitley and Burns 2008; Egeland, Nicholson and Gasparian 2010; Kondo, Omori and Verhagen 2012; Carleton, Conolly and Ianonne 2012; Carrer 2013). Uniquely, it considers a wide range of data layers from a variety of disciplines that include biological, cultural, physical, geological, historical, and paleoenvironmental. In glacial archaeological research, Dixon, Manley and Lee (2005) were first to incorporate locational analysis using a weighted combination of biological, cultural, and geologic raster layers (Table 1) to successfully determine archaeological potential of specific ice patches in Alaska, U.S.A. Factors influencing and restricting the discovery of remains were analyzed separately and then combined into a final cost raster. The locational analysis method which was created in this research helped aid archaeological research in the field. A total of nine historic and five prehistoric sites were located using their method. Similarly, Andrews *et al.* (2012) used locational analysis along with inputs of remotely sensed data to define areas of archaeological potential in remote mountainous areas in the Northwest Territories, Canada. Their selected criteria (Table 1) allowed for the identification of eight ice patches of archaeological potential that were not previously known, and subsequently resulted in the discovery of throwing-dart, bow and arrow, snares, and faunal remains.

| **Influencing criteria** | **Restricting criteria** | **Reference** |
|---|---|---|
| Habitat ranges (e.g. caribou, sheep, goats) | Debris covered ice | Dixon, Manley and Lee 2005 |
| Mineral licks | Ice | |
| Lithics | Snow | |
| Trails | Barren ground | |
| Proximity to documented sites | Slope | |
| | Aspect | |
| | Distance | |
| Multi-year ice | Areas below 1524 m | Andrews *et al.*, 2012 |
| Presence of caribou dung | | |
| Altitudes between 1676–1981 m | | |
| North-facing slopes | | |
| Bowl or cirque shaped ice patches | | |
| Caribou habitat range | | |
| Traditional landuse patterns | | |

Table 1 List of criteria used in locational analyses in glacial archaeological studies.

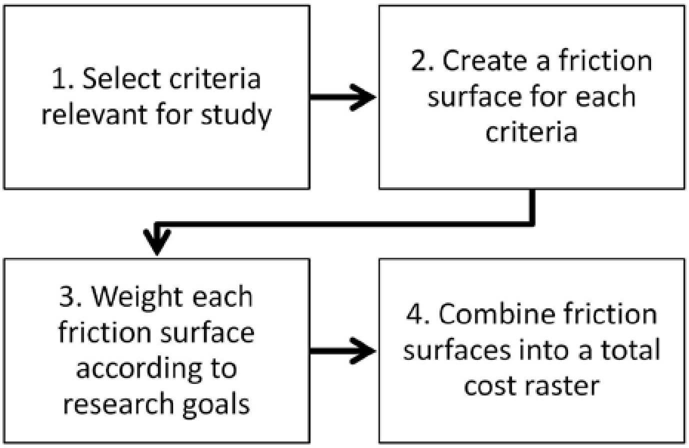

Figure 1 Process of building a cost raster for locational and least-cost path analyses. Altered from Howey (2007).

In the previously discussed studies, the main goal was to perform locational analysis by creating an archaeological potential model in the form of a cost raster which was the culmination of multiple weighted inputs. To build an archaeological potential model using locational analysis, the first step in the process is the selection of relevant criteria (e.g. Table 1), followed by reclassification of each criterion into a friction surface (Figure 1; Table 2). Each friction surface is a raster that represents the level of archaeological potential of each particular cell (or pixel) based on the respective criteria. In regard to the basic example in Table 2, the slope and landcover values were originally classified in degrees and landcover type, respectively. After reclassification into integer values, the new friction layers represented the calibrated level of archaeological potential based on the original slope or landcover properties. The probability of finding archaeological remains near steep slopes or in lake or swamp environments is lower therefore the friction values are higher in those situations. All friction layers should use a consistent measurement scale for calibration purposes and to maintain a direct comparison among layers (Howey 2007). For example, criteria should have the same friction value if they represent similar friction levels (e.g. steep slopes and lakes or low slopes and grassy terrain). Next, weights should be assigned to each friction layer to denote their percentage of importance to the total cost raster which should equal 100% in the end. For the example in Table 2, slope was believed to be more indicative to the model than landcover (e.g. 60% versus 40% in the final cost raster) therefore a heavier weight was given to the slope layer. Finally, weighted layers are combined to create the total cost raster with all input layers. In the Dixon, Manley and Lee (2005) study, a similar process was followed for reclassifying and weighting criteria, but also included the accumulated cost of crossing terrains (see least-cost path analysis (LCPA) section) into each friction layer. In glacial archaeology, further studies using locational analysis could benefit site location and archaeological prospection in the field.

| Criteria | Classes | Friction Value | Weight |
|---|---|---|---|
| **Slope** | 0–8.5 | 1 | 60% |
| | 8.6–15.4 | 2 | |
| | 15.5–21.6 | 3 | |
| | 21.7–27.1 | 4 | |
| | 27.2–32.2 | 5 | |
| | 32.3–37.1 | 6 | |
| | 37.2–41.9 | 7 | |
| | 42.0–47.4 | 8 | |
| | 47.5–54.2 | 9 | |
| | 54.2–72.8 | 10 | |
| **Landcover** | Grass | 1 | 40% |
| | Scree | 2 | |
| | Shrub | 4 | |
| | Rock | 5 | |
| | Forest | 6 | |
| | Swamp | 9 | |
| | Lake | 10 | |
| Total | | | 100% |

Table 2 Example of reclassifying criteria into friction layers and weights of each layer.

## Least-Cost Path Analysis (LCPA)

Least-cost paths are based on the assumption that human movement follows the least physically demanding route possible when traveling from one location to another (Gorenflo and Gale 1990; Gaffney and Stančič 1991; Anderson and Gillam 2000; Bell and Lock 2000; Llobera 2000; Hare 2004; Rees 2004; Howey 2007; Egeland, Nicholson and Gasparian 2010). The topic of movement across terrains and landscapes is a well-studied area of research stemming from various models of geographic theory (Tobler 1993) as movement is a mechanism through which humans organize their landscape (Llobera, Fábrega-Álvarez and Parcero-Oubiña 2011). Thus, human movement and least-cost paths have recently become a popular research topic in archaeology (Murrieta-Flores 2010; 2012; Verhagen and Jeneson 2012), and could be applied in the field of glacial archaeology to aid in the discovery of potential travel routes across mountainous terrain. LCPA can supplement previous research in glacial archaeology (Dixon, Manley and Lee, 2005; Andrews *et al.* 2012) by utilizing the multi-criteria cost rasters in LCPA. This could be particularly interesting for studying movement patterns of hunters between settlements and ice patches, as well as paths which traversed mountain passes for the purposes of migration or commerce. LCPA could be used to simulate travel routes over glaciated passes at high altitudes using known archaeological sites as start and end points, or for determining patterns of movement through different landscapes and environments which can help to reveal important aspects of (pre)historic movement patterns (Murrieta-Flores 2010). When no sites of archaeological potential have been previously identified, LCPA could promote insight about optimal paths or corridors based on terrain alone. For example, to identify hunting, migration, or trade routes over high altitude passes in the Pennine Alps between Switzerland and Italy used by (pre)historic people (Harriss 1970; 1971; Lugon 2011; Hafner 2012).

The calculation of the cost raster, which represents the amount of effort required to cross one cell, is the first step in the LCPA process and can be based on one or more criteria. For example, previous archaeological studies have used LCPA to predict locations of (pre)historic travel routes using cost rasters based solely on the slope of the terrain (Gorenflo and Gale 1990; Gaffney and Stančič 1991; Bell and Lock 2000; Egeland, Nicholson and Gasparian 2010; Kondo and Seino 2011; Herzog and Posluschny 2011; Verhagen and Jeneson 2012), slope and LOS information (Madry and Rakos 1996), slope and roughness (Anderson and Gillam 2000), or slope, land cover, and waterways (Howey 2007). Although slope is the fundamental component of how people choose to travel across landscapes, it is by no means the all-encompassing decision factor in movement (Bell and Lock 2000; Murrieta-Flores 2010) and natural, social, and cultural features of the landscape should be taken into consideration to find the optimal, or the LCP, to move from one point to another (Lee and Stucky 1998; Howey 2007). Most authors agree that the cost of travel should incorporate multiple criteria into the cost raster, including both isotropic and anisotropic frictions (Bell and Lock 2000; van Leusen 1999). Isotropic frictions represent the cost of moving across a surface with equal friction in all directions (van Leusen 1999; Wheatley and Gillings 2002), for example, landcover. The cost of crossing a certain landcover type is the same irrespective of the direction of travel (Conolly and Lake 2006). Anisotropic modeling incorporates the cost of travel based on variable frictions with respect to the direction of movement (Bell and Lock 2000; Wheatley and Gillings 2002). Slope, which is calculated from a DEM, should be modeled using an anisotropic surface as different frictions are incurred when traveling up, down, or perpendicular to slope (Eastman 2003). The resolution and accuracy of the DEM also play important roles in the model (Herzog and Posluschny 2011).

After all relevant factors have been considered and calculated together, the LCP is calculated from the accumulated cost raster which represents the amount of effort required to reach a destination from a defined starting point (Kvamme 1999; Bell and Lock 2000; Ebert 2004; Verhagen and Jeneson 2012) with longer distances and steeper slopes having higher costs. This second step of LCPA is calculated from the cost raster using a software or user-defined algorithm (Bell and Lock 2000; van Leusen 2002; Wheatley and Gillings 2002; Chapman 2006; Conolly and Lake 2006; Herzog and Posluschny 2011; Kondo and Seino 2011; Verhagen and Jeneson 2012). The majority of LCPA studies input Tobler's (Tobler 1993) equation for walking speed in hilly terrain into GIS to determine the amount of time required for crossing terrains (e.g. Gorenflo and Gale 1990; Whitley and Hicks 2003; Hare 2004; Verhagen and Jeneson 2012). However, it has been speculated that modeling movement based on energy consumption is more efficient due to differing perceptions of time among societies and eras, thus other algorithms have been used to reflect those issues (Llobera and Sluckin 2007; Herzog and Posluschny 2011; Kondo and Seino 2011).

## Discussion

GIS-based methods can be used to enrich and enhance archaeological investigation and prospection in frozen environments to prevent the loss of potentially significant archaeological remains. In this paper, the three GIS methods of visibility, locational, and LCP analyses were discussed in regards to their relationship to the emerging field of glacial archaeology. Here I will discuss the benefits and possible limitations to these methods, as well as the issue of data and software accessibility in GIS.

Visibility analysis has been useful in various archaeological studies (e.g. Gaffney and Stančič 1991; Lock and Harris 1996; Smith and Cochrane 2011) but has been theoretically questioned due to its inability to incorporate human perceptions in space (Llobera 2003). However, researchers have taken this into consideration and have been developing methods for incorporating the influences of perception into visibility analyses (Llobera 2000; 2003; Murrieta-Flores 2010; 2012) making the method stronger and more applicable to archaeological studies. The DEM used in visibility analysis calculations is another source of criticism. It is argued that a modern landscape DEM cannot accurately predict visibility because it does not take the paleoenvironment into account (Wheatley and Gillings 2000). However, in some situations, the landscape has not changed significantly (e.g. in high altitudes) and a modern landscape DEM could be sufficient for calculating visibility. Other unknowns such as vegetation cover, weather, and human visual acuity make it difficult to definitively assess viewsheds or lines of sight (Murrieta-Flores 2012). Nevertheless, visibility analyses can provide valuable information about the study of the visual structure of landscapes and help to explain spatial and social phenomena in relation to movement patterns and archaeological remains (Sorensen and Lanter 1993).

Locational analyses have been useful in the broad archaeological sense (e.g. Howey 2007; Whitley and Burns 2008; Carrer 2013), as well as in glacial archaeology (Dixon, Manley and Lee 2005; Andrews *et al.* 2012). This type of analysis is particularly beneficial for the assembly of multi-spatial, -scale, and -temporal data layers into one comprehensive index so that criteria can be evaluated based on their shared or varying characteristics (Kvamme 1999). Locational analysis effectively allows the user to define the important or relevant factors to their study, thus tailoring the analysis to the needs of the researcher (Howey 2007). However, since methods of selection and weighting are subjective, it is important to be overt about the selection and justification process used. Methods such as Multi-Criteria Decision Analysis (MCDA) provide good opportunities for selection and weighting of criteria in multi-factorial situations (e.g. Ahamed, Rao and Murthy 2000; Joerin, Thériault and Musy 2001; Malczewski 2006; Chen, Yu and Khan 2010).

Until recently, LCP analyses were considered to be an under-utilized GIS method in archaeology (Howey 2007). However, interest in (pre)historic movement patterns has been growing and the applications of least-cost paths have broadened (Herzog and Posluschny 2011; Kondo and Seino 2011). Similarly to visibility analyses, more emphasis is being placed on the integration of social and cultural aspects into modeling (Murrieta-Flores 2010; 2012). In reality, the chosen path of travel across a landscape is not always the shortest, nor the easiest, but may have been chosen based on social and cultural factors that are often unknown (Llobera 2000; Lock and Pouncett 2010; Murrieta-Flores 2010; Verhagen and Jeneson 2012). Despite these unknowns, simulations of optimal paths can be useful for understanding potential travel routes through terrain based on the natural accessibility of the landscape (Egeland, Nicholson and Gasparian 2010; Wheatley *et al.* 2010; Murrieta-Flores 2012). This could be particularly useful in remote areas such as high latitudes/altitudes and mountainous environments.

These three methods could also be used collectively to enhance their GIS performance. For example, the results of visibility analysis have been used as input criteria in locational analysis cost rasters (e.g. Lee and Stucky 1998), and cost rasters created in locational analysis could be slightly adjusted and used as the basis of an LCPA. The integration of multiple criteria from multiple disciplines into multiple methods in GIS could aid in the production of beneficial archaeological results. To date, visibility and LCP analyses have not been used in glacial archaeology but could enhance the level of understanding about how (pre)historic people interacted with their environments based on their visual perceptions (Murrieta-Flores 2010) or movement patterns for revealing potential travel routes across archaeologically unknown terrains (Egeland, Nicholson and Gasparian 2010).

When conducting research using any GIS method, the choice of resolution and scales are vital because they can directly influence outcomes (Lock and Pouncett 2010; Herzog and Posluschny 2011). When conducting glacial archaeological research in remote locations, often spatial data are sparse and difficult to obtain. Now, thanks to platforms like Google Earth (Google 2013) and World Wind (NASA 2011), access to satellite imagery from varying time periods, from anywhere in the world, has increased and has consequently made visual analyses of study sites easier. The MapTiler (Přidal 2012) application allows users to upload aerial images and other map data in a very high resolution to Google Earth. This allows data of varying types and time periods to be overlaid onto each other for visual comparisons outside of a traditional GIS interface. Additionally, a free global 30 m resolution DEM is currently available to download from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) from the NASA Jet Propulsion Laboratory (NASA 2012). This provides free access to a medium resolution DEM which can be used as the basis of GIS investigations. The accuracy of spatial data should also be taken into consideration. For example, Herzog and Posluschny (2011) emphasize the importance of an accurate DEM as it is the basis of most spatial analyses. Knowing the specifications of data will give more insight and knowledge at the primary level of modeling and help to negate the adverse implications of the GIS seen as systematic button-pushing without questioning of the results (Verhagen and Whitley 2012). Arguments for GIS methods in archaeology have been strengthened by the robust dissections of results. In the early stages of GIS-based studies in archaeology, more focus was directed to computer generated models rather than archaeological theory (Wheatley and Gillings 2000), and results were not carefully examined but merely assumed to be accurate. This created debate within the domain of theoretical thinking in archaeology, resulting in the validity of computer generated visibility models and predictions to be doubted (Wheatley and Gillings 2000). To lessen the negative aspects of spatial technologies, researchers have improved spatial methodologies by investigating the results with statistical analyses and rigorous testing (van Leusen 1993; Wheatley 1995; Fisher *et al.* 1997; Lake, Woodman and Mithen 1998; Carleton, Conolly and Ianonne 2012; Carrer 2013).

GIS users should also be aware that different computer softwares use different algorithms in their calculations. With open-source softwares these are outwardly stated however, commercial softwares often do not make this information available (Verhagen and Jeneson 2012). Recently, open-source GIS programs such as the Geographic Resources Analysis Support System (GRASS) (GRASS Development Team 2013), Quantum GIS (QGIS) (QGIS 2013), and the System for Automated Geoscience Analyses (SAGA) (SAGA 2013) have grown in popularity due to their capabilities for information and data sharing, as well as full access to the implementation details, including algorithms of all tools. In order to fully understand and have confidence in GIS methods, the calculation details should be taken into consideration, and recent advancements in open-source softwares are allowing this to happen.

As with any type of spatial analysis or modeling, there are challenges and uncertainties. Unknown variables make it complicated, but not unrealistic nor impossible, to make predictions about how past landscapes were used by (pre)historic people. Incorporation of GIS, specifically visibility, locational, and LCP analyses into archaeological research has proven to provide significant insights into (pre)historic settlements and movement patterns. GIS methods could benefit research endeavors in frozen environments and mountainous terrains by focusing efforts that promote the discovery of vulnerable materials from decomposition once they have been exposed from the ice.

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