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Cost Distance Analysis in an Alpine Environment: Comparison of Different Cost Surface Modules

Abstract: The paper aims to present a comparative application of different cost-surface analysis modules in a high alpine environment. Cost analysis is a very controversially discussed subject in archaeology, and for that reason a methodological comparison of weaknesses and strengths of some popular Geographic Information Systems could be a necessary contribution to basic research. Performing the same operations under the same preconditions with three different GIS packages (IDRISI, GRASS, ArcGIS), we were able to compare their ability, handling, performance, and results and to work out their strengths and weaknesses.

Introduction

In August 2004 a project was started by the Austrian Academy of Sciences and the Department for Prehistoric and Medieval Archaeology of the University of Vienna. The aim of the project was to investigate the possibility to apply non-destructive archaeological methods for investigating prehistoric and antique roads crossing the eastern Austrian Alps. The main methods applied were aerial archaeology and GIS-based analyses using various sources of social and environmental data.

From the beginning it was clear that especially in the alpine environment non-destructive methods would never be able to replace conventional methods of archaeological research. Therefore, the idea was that non-destructive methods should function as a filter to narrow down and identify those areas, which could be archaeologically relevant and could become a prime target for a more detailed archaeological investigation using e.g. field surveys and excavation.

To be able to evaluate the applicability of non-destructive methods in the high alpine environment, the area around the Dachstein plateau *(Fig. 1)*, which is archaeologically well investigated, was chosen for the pilot part of the project. The area has been surveyed systematically by ANISA (www.anisa.at), which has produced a remarkable number of archaeological sites and finds[1].

The study area contains a very heterogeneous overall appearance of geomorphology: from the highest peaks slightly below 3000 m, which are covered with glaciers, to high plateaus between 1400 and 2000 m, and plane river valleys. Movement in these areas is dependent on different determining factors. The vegetation differs from bare rock above the tree line, alpine meadows, shrubs, and trees underneath it, to dense woodlands on the flanks of the mountains and agricultural land on the bottoms of the river valleys.

Since the early 1990s, cost weight and cost distance analysis have been a controversially discussed approach in landscape archaeology with several important case studies and different approaches[2]. Instead of adding another attempt to that list, we decided to focus on a single example, the pathways between the Knallwand (a hillfort settlement from late antiquity in the river valley south of the Dachsteinplateau) and the Grafenbergalm, an alpine pasture with small finds from the Roman Age[3]. Here we performed a careful examination and methodological comparison of the weaknesses and strengths of some of the most commonly used GIS cost-surface modules in archaeology: ArcGIS, IDRISI and as Free & Open Source alternative GRASS (http://grass.itc.it).

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[1] E.g. Mandl 1996; Windholz-Konrad 2003. Most recently Mandl 2006, 190 ff.

[2] Van Leusen 2002, 6-1 ff.; Conolly / Lake 2006; Bell / Wilson / Wickham 2002, 169–186; Madry / Rakos 1996, 104–126; Bell / Lock 2000, 85–100; Silva / Pizziolo 2001, 279–286.

[3] Steinklauber 1997, 3–5; Hebert / Schaichinger / Steinklauber 1999, 29; Hebert / Mandl / Steinklauber 2002.

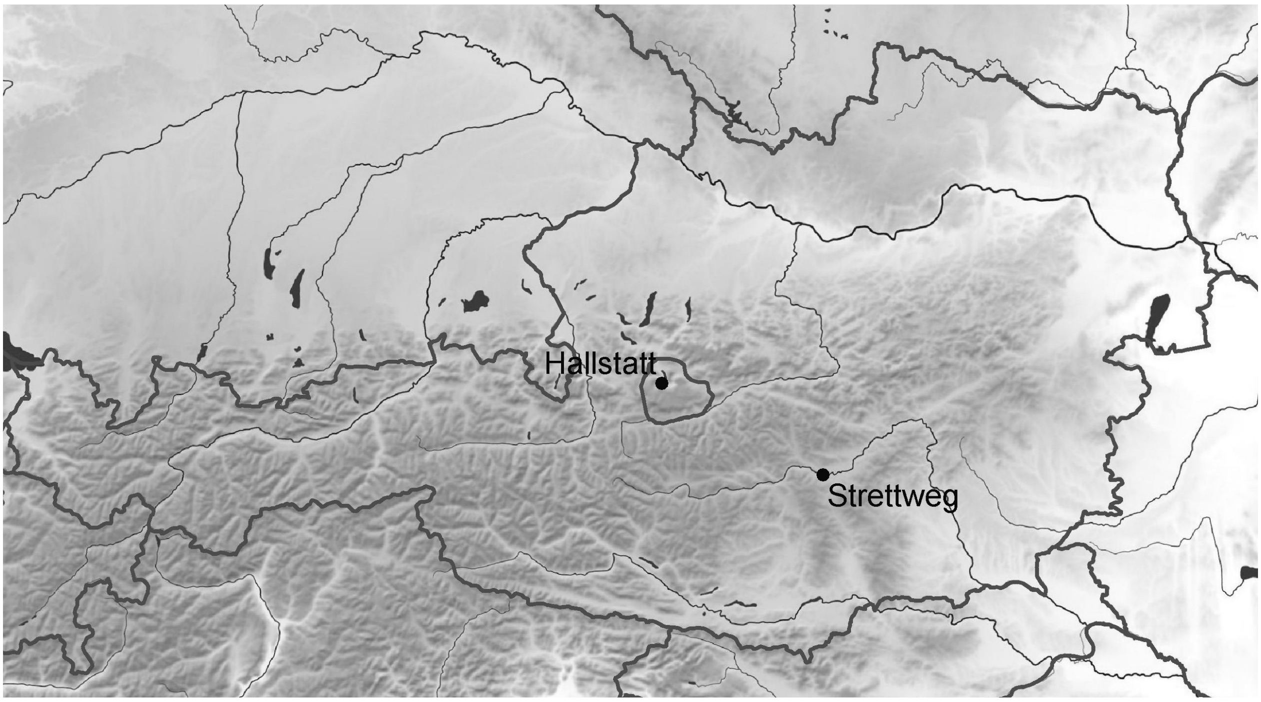


Fig. 1. The study area in the Austrian Alps between Hallstatt and Strettweg.

Data Collection

For the cost-surface analysis terrain models, hydrological and geological maps, climate-change-studies, as well as bio-diversity and vegetation databases were investigated in order to reflect their influence on a deductive predictive model[4].

High alpine scenery offers a limited number of resources and issued some special challenges to ancient men. This happenstance helped us to bring into focus just a few factors which regulate humans' moving and settling in the regions around the tree line: Management of pasture first of all requires extensive meadows and assured water supply. Moving in high mountains mainly depends on environmental factors, such as slope and condition of the soil. By contrast cultural or religious factors like territorial boundaries, sanctuaries or taboo areas were impossible to be determined for the study area.

The bedrock of the Dachstein-Plateau is karst. This porous form of limestone enabled the formation of pastures in enclosed basins where material from glacial erosion was deposited[5]. In these areas, marshy meadows and small lakes can therefore be found. Karst impedes easy movement for animals and human beings, another reason for moving preferably over the grass covered meadows. Although water is an attractive factor on the dry elevated plain, it becomes a barrier on its flanks, forming canyons and river valleys.

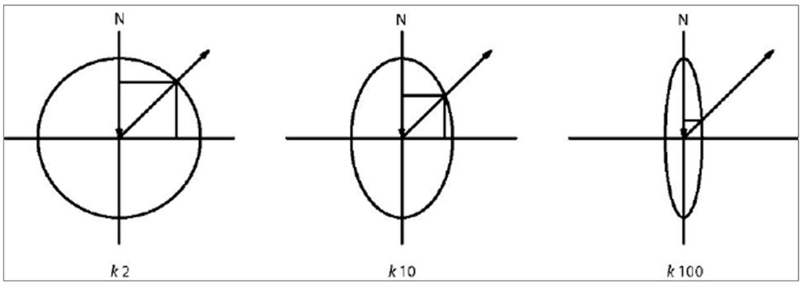
No matter which GIS software one uses, the most crucial point during the process of creating a cumulative cost surface is the selection, combination, and weighting of these environmental factors. It is an individual decision of the single researcher and therefore a completely subjective process.

We focused on three central factors: slope, type of terrain and hydrology, assigning them different weights after discussion with locals, herdsmen, and climbers. The resultant cost raster is the combination of these factors.

Software Comparisons

A limited special case for a cost surface analysis with quite easily predictable results in a well known archaeological landscape gave us the possibility to compare the capabilities and results of some of the

[4] Inductive vs. deductive approach: Van Leusen 2002, 5–4.
[5] Graf 1990, 170–171.



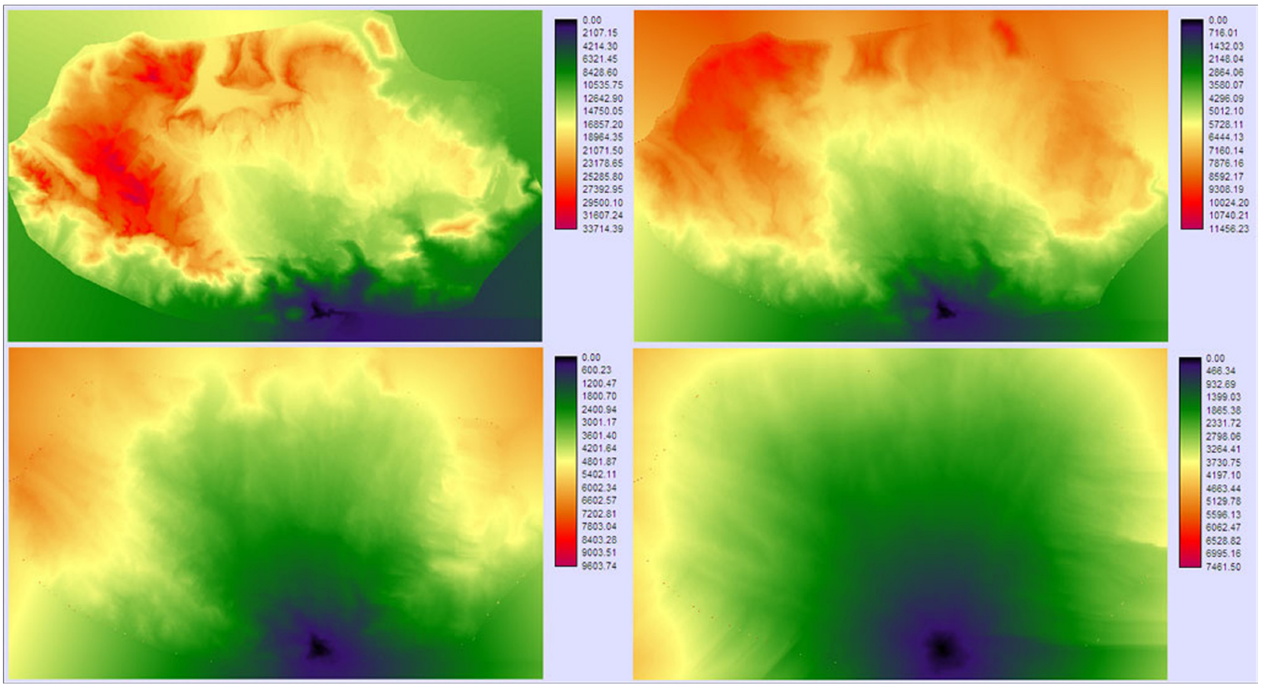


Fig. 2. Different "k" coefficient in VARCOST : 0.1 (u.l.), 1 (u.r.), 2 (l.l.), 10 (l.r.). Starting Point: Knallwand hillfort. Increasing "k", costs are more and more limited around the direction of maximal friction, paths become more linear.

most used GIS-Systems: ArcGIS 9.1, IDRISI 15 and as a Free & Open Source alternative GRASS 6.1[6].

To model the cost of human movement, a tool is needed which has the possibility to distinguish between isotropic and anisotropic cost. Isotropic means that the cost of crossing a single cell is equal independently of the direction in which you cross it. In the case of walking slopes, cost will be anisotropic, since the energy needed will depend on the direction of one's movement (uphill, downhill, or parallel to the slope). Another typical example for terrain anisotropy is when crossing raster cells representing a river: Costs act differently depending on whether the movement is down-river or up-river and again differently if one wants to cross it[7].

Surprisingly, the capability to model anisotropic costs is only a recent feature of GIS and the developers themselves still have to encourage their users to incorporate interchanging experiences and difficulties[8].

IDRISI 15 Andes

In IDRISI 15 Andes the COST and VARCOST modules model isotropic and anisotropic costs. Movement impeding or facilitating factors are defined as relative *frictions* and *forces*[9]. If a hiker needs 350 calories/h to walk along flat ground (base friction of 1) and 700 calories/h to go uphill with the same speed, we can assign to the slope a friction of

[6] The selection is based on the mostly used packages. Worth to mention also: SAGA GIS's cost surface modules: Olaya 2004, 159 ff.

[7] Van Leusen 2002, 6-5.

[8] Eastman 2006, 255.

[9] Eastman 2006, 256.

2. Going downhill consuming 175 calories/h is equal to a friction of 0.5. Frictions less than 1 are called *forces*. Following this schema, users have to reclassify their data in order to obtain an image describing the magnitude of costs/frictions. In the case of walking this image will usually be dominated by the factor slope.

The second factor of anisotropic cost modelling in IDRISI is the *direction of friction* image, which represents the direction from which the maximum frictional effect occurs. In case of a person walking across a landscape, the *direction of friction image* is an uphill pointing aspect-image *(Fig. 2)*.

Having both datasets, the user can calculate a cost raster for one or more starting points which reflects the effective costs depending on the angle of crossing a cell. The output can be manipulated by reclassifying the *magnitude of friction* raster and by changing the user-defined coefficient "k": With "k" it is possible to control the increase of the resistance or friction between the angles 90°–0° in relation to the direction being considered as maximal friction.

A slower increasing of friction facilitates the calculation of straighter paths[10]. The pathway function finally calculates the least cost path.

GRASS 6.1

GRASS 6.1 also has two modules to calculate isotropic and anisotropic cost maps: *r.cost* and *r.walk*[11]. While *r.cost* models isotropic cost surfaces, *r.walk* calculates a raster map representing the anisotropic cumulative cost of moving from one geographic location to another.

The input is an elevation raster together with another raster, whose cells represent friction cost. The friction cost map is again a combination of reclassified and weighted environmental/cultural factors. In addition to the friction map, *r.walk* considers an anisotropic travel time depending on different walking speed associated with downhill and uphill movements following the formulas of Aitken and Langmuir[12]. With a user-defined parameter of the linear equation combining movement and friction costs, one can modify the output *(Fig. 3)*.

The least cost path module *r.drain*, created for hydrological applications, traces a flow through an elevation model on a raster map layer. The main weakness of *r.drain* is that it calculates the path by choosing the lower value between adjacent cells and terminates like water when the lowest value is reached, even if it is not the destination point chosen by the user. For that reason we had to export GRASS cost raster maps in IDRISI to calculate the least-cost path.

ArcGIS 9.1

ESRI's ArcGIS 9.x has a large number of cost-modules incorporated in its Spatial Analyst extension. *Cost-distance* and *path-distance* are the equivalents to the isotropic and anisotropic modules of IDRISI and GRASS[13].

In addition, it offers a module for *corridor analysis*, which calculates the sum of accumulative costs for two input accumulative cost rasters *(Fig. 4)*.

ESRI's cost distance tools calculate for each cell of a raster map the least accumulative cost to a predefined starting point. Both source point and cost raster are needed, optionally composed from datasets reclassified to a common scale.

With the *path distance* tools, one can add more cost complexity adding horizontal and vertical factors that influence the total cost of moving from one location to another.

Unfortunately, the modules had problems handling a raster larger than 7000 × 4500 pixels (our DTM with a resolution of 10 m). Problems also occurred with the import and export of data generated by IDRISI and GRASS. Comparisons were additionally difficult because ESRI uses a completely different terminology in its documentation.

Discussion

During our tests, we performed various calculations creating paths between the Roman sites on top of the Knallwand and the Grafenbergalm. Surprisingly, it was impossible to reproduce the same or even

10 Eastman 2006, 257.
11 http://grass.itc.it/gdp/html_grass63/r.walk.html [27 May 2007]; Neteler / Mitasova 2004.
12 Aitken 1977; Langmuir 1984.
13 http://webhelp.esri.com/arcgisdesktop/9.2/index.cfm?TopicName=Cost_Distance [27 May 2007].

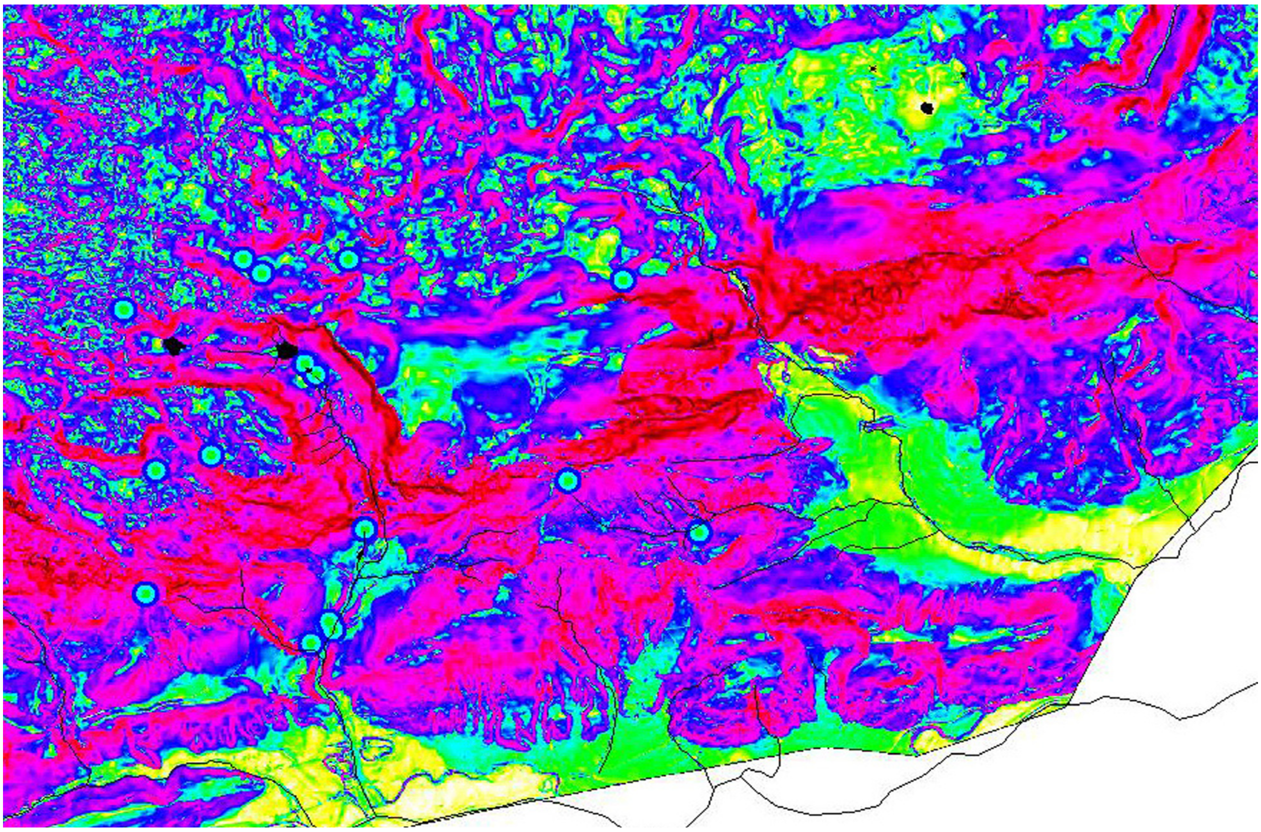


Fig. 3. GRASS – Isotropic Friction Cost Raster + [lambda * Walking Energy (anisotropic)] = Cumulative Costs.

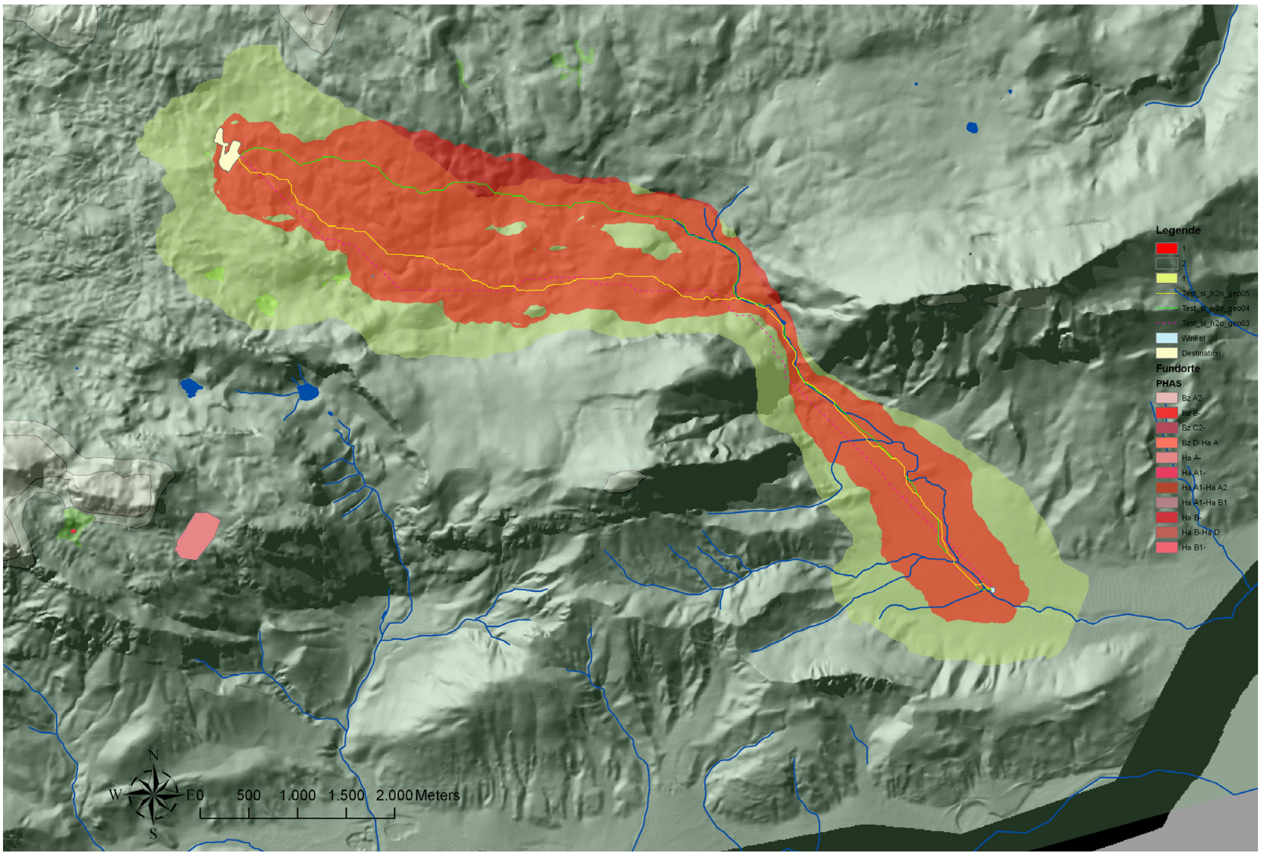


Fig. 4. ArcGIS – Corridor Analysis.

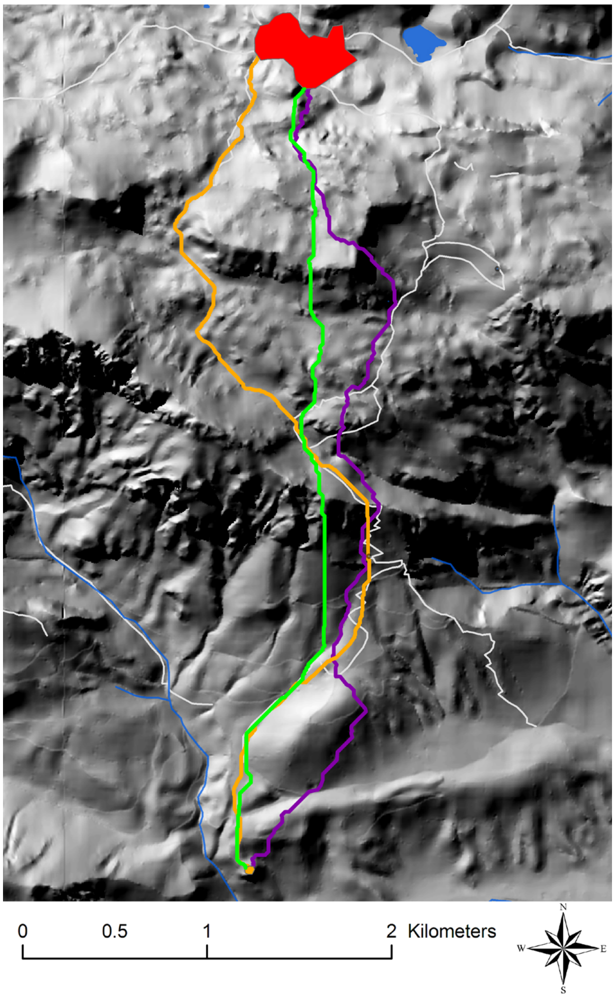


Fig. 5. GRASS (orange), ArcGIS (green), IDRISI (violet). Least cost paths calculated with modules default settings.

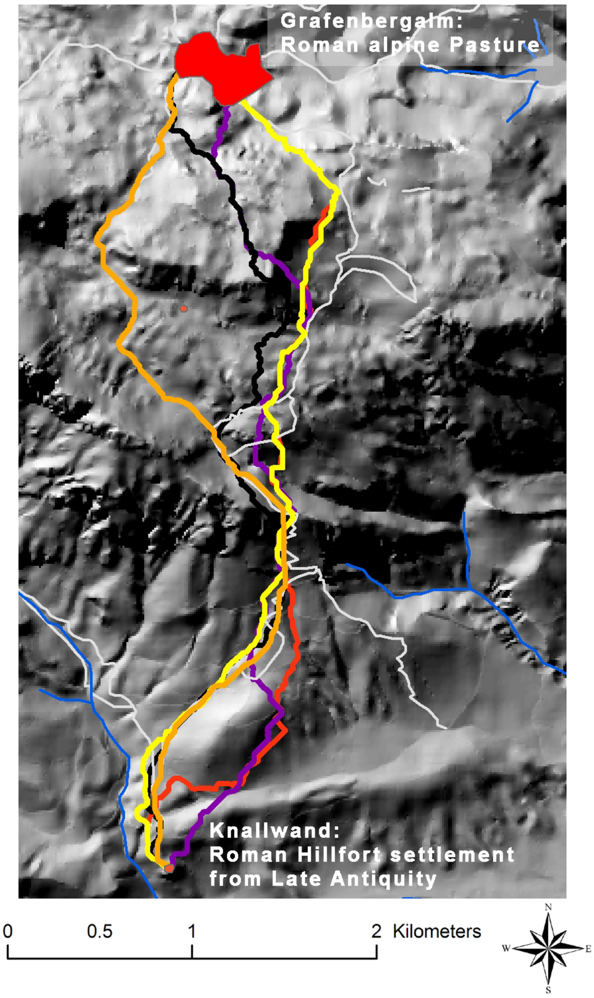


Fig. 6. Different results depending on reclassification and user defined parameters.

very similar results even when using the same data, weighted in the same relation.

Fig. 5 shows three paths, each one calculated by a different GIS package (orange = GRASS, green = ArcGIS, violet = IDRISI). A raster map composed of slope (66%), soil type facilitating movement (22%) and proximity to sources of water (200 m direct line buffer, 11%) serves as the base data. It was processed with default values by all three cost analysis modules.

While the path calculated by ArcGIS ascends in a very straight line following the network of modern hiking paths, the orange path (GRASS), after a common passage north of Knallwand diverges first to the east, then to the west, taking more advantage of the relief than the ArcGIS path. The violet path (IDRISI) also avoids steep slopes and proceeds mainly east of the others. For long distances it also follows modern hiking paths.

The main causes of the deviations may be the different way of requested reclassification, especially between IDRISI (<1 = forces, >1 = frictions) and GRASS/ArcGIS (arbitrary reclassification), different algorithms[14], and the limited possibility of interchanging the cost raster between the three systems. While import end export of data between IDRISI and GRASS seem to function properly, it was not possible to export the same data to ArcGIS. Therefore, it was nearly impossible to reproduce the same process of data preparation in two different GIS packages.

[14] The *Free & Open Source* GIS GRASS uses Dijkstra's algorithm (http://grass.itc/gdp/html_grass63/r.walk.html), while algorithms of IDRISI and ArcGIS are proprietary and not accessible.

Fig. 7. (l.) Modern road and medieval mountain pass road on the Sölkpass. (r.) Knallwand to Grafenbergalm: Straight computed paths in 3D-view.

In a second step we concentrated our efforts on observing the effect of altering different user defined coefficients and variables. The results from IDRISI are shown in the following *(Fig. 6)*.

The very straight violet line is the least cost path calculation using the base raster with the VARCOST default values. The red line was calculated on the same raster, but using the value "1" for "k" (instead of the default value "2"): As a result the path avoids steeper slopes. Consequently we operated with "k" values under the default value of 2, in order to get paths with gentle ascents.

The yellow line is a least cost path over an anisotropic raster from IDRISI where slopes over 50° become disproportionally higher and unattractive for crossing. A similar strategy, using IDRISI, was applied by Bell, Wilson and Wickham in the Sangro Valley Project[15].

The orange line, which deviates clearly towards west, was calculated in GRASS with default settings and the base anisotropic cost raster exported from IDRISI.

The calculated paths were archaeologically evaluated. A visit to some of the modelled paths showed that those calculated without the 50° slope-limit were by far too steep to drive cattle up and often even to climb. Interestingly, the orange path (GRASS cost raster) corresponds to a channel of supply that the shepherds use today if they want to reach the bottom of the plateau as fast as possible. A result like that is not surprising if we remember that *r.walk*'s speciality is to consider the anisotropic travel time. This is another strong indication that the results of cost surface and least cost path calculations do not only depend on the data, but also on the calculating algorithm. For bringing the cattle up or down, the shepherds today use the modern hiking paths (depicted in light grey), which are close to the modelled red and yellow lines. The yellow and red lines additionally seem to match more or less to a planned but never realized forest road.

Although most of the single paths follow quite different lines, there are some sections where one can observe a striking overlap (e.g. halfway between the Knallwand and the Grafenbergalm *(Fig. 6)*). These are areas, which would be worthy of detailed investigations by aerial archaeology and intensive survey in order to filter out locations for archaeological excavation.

The main problem in archaeological terms is the unrealistic modelling of computed paths in steep terrain. The paths climb uphill in an unrealistic straight line and not in the typical zigzag way one would expect *(Fig. 7)*. The aerial photograph of the Sölkpass[16], which is in the neighbourhood of our study area, shows the medieval roads leading up to the pass. Their zigzag form at the moment cannot be reproduced by a cost surface / least cost path module.

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[15] Bell / Wilson / Wickham 2002, 176 ff.

[16] Mandl 2003.

As a solution to that problem we would like to call attention to a direction dependent least cost path algorithm presented in 2000 by Walter Colischonn and Jorge Victor Pilar[17] which so far has not been implemented in a commercially available GIS package: It can calculate the best route on a steep mountain following a spiral path, using sharp turns like road builders do and have always done in the past.

Conclusions

In this paper, an examination and methodological comparison of weaknesses and strengths of some of the most commonly used GIS cost-surface modules in archaeology was presented. The quality of results from a cost distance analysis depends mainly on the user defined parameters provided by each software solution.

Additionally, the output will also differ to a large degree depending on the software used for calculating cost raster and least cost path. Even when starting from the same pool of data weighted in the same proportion, the results were in parts largely deviating from each other.

Besides these differences, the main problem of calculating least cost paths for archaeological purposes in steep terrain is that due to the algorithms borrowed from hydrology, the calculated paths follow unrealistically straight lines. An algorithm which has the potential to provide better results is already published but still not implemented in commercially available GIS software.

Despite these problems, we are convinced that the currently available cost-surface modules can be usefully applied in archaeology, if the archaeologist allows for their weaknesses. The result therefore will not be the exact location and reconstruction of an individual path. The benefit of cost distance analysis can rather be seen in its ability to narrow down corridors of interest for detailed examination through aerial archaeology, geophysics, or extensive field surveys. In archaeologically unknown regions they can deliver the first indications for possible links between archaeological sites.

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[17] Collischonn / Pilar 2000, 397–406.

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