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MULTI-CRITERIA SPATIAL ANALYSIS OF LAND ACCESSIBILITY FOR SEISMIC OPERATIONS

WIELOKRYTERYJNA ANALIZA DOSTĘPNOŚCI TERENU NA POTRZEBY SEJSMICZNYCH PRAC POSZUKIWAWCZYCH

Jan Burdziej

Institute of Geography, Faculty of Biology and Earth Sciences, Nicolaus Copernicus University
Geofizyka Toruń Sp. z o.o., Survey Department

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Introduction

One of the main spatial aspects of a given location is its accessibility. Accessibility can be defined as a travel cost to a location of interest. This cost can be expressed in different units, such as distance units (kilometers, miles), time units (minutes, hours, days), financial cost (dollars, Euros), fuel consumption (in liters) etc. In fact, accessibility is hardly ever measured using simple "as the crow flies" distance, as there are many factors that influence accessibility and most of them have complex spatial patterns. Nowadays, there are hardly any physically inaccessible areas on the Earth. Mount Everest can be easily reached by helicopter and deep sea can be explored using advanced submarines. But the accessibility still plays a crucial role in a simple economy: it is easier and cheaper to access some places than others. Therefore, it is a vital task to assess the accessibility in order to minimize efforts and costs related to a particular activity.

The land accessibility of a given location depends on many spatial and non-spatial factors, which modify the accessibility measured using "as the crow flies" distance. They are strongly interrelated and can have different influence in different circumstances. Some of the main factors are road network, land cover, elevation, existing barriers (e.g. rivers, borders), existing connections (flight connections, ferry routes, bus lines), actual weather conditions (wind, ice, snow), mean of transport and its characteristics (e.g. vehicle type), economical environment (costs, supply and demand), law regulations (ownership, access restrictions).

Spatial aspect in seismic explorations

Seismic explorations are commonly used by energy sector for discovering new oil and gas fields. One of the main exploration methods, called “3D”, requires a dense and regular grid of source and receiver points placed regularly along separate lines. Seismic waves are generated on all source points and, after being reflected from underground structures, they are recorded at receiver points. A typical seismic survey may have an area of a few hundred square kilometers or more.

Space and location are key components of all kinds of geophysical exploration and seismic exploration in particular. It is assumed that more than 80% of data in the Exploration and Production (E & P) upstream business has a direct spatial component and can be mapped using GIS (Jepps, 2007). Moreover, nearly all other data in the industry can be indirectly linked to these spatial objects. Taking into account the two main factors, the scale of seismic projects and their dependence on the terrain, it is clear that computer-based systems equipped with spatial data and analytical tools can significantly support decision-makers involved in the seismic enterprise. These systems are generally referred to as spatial decision support systems (SDSS). According to Malczewski (1999) “SDSS can be defined as an interactive, computer-based system designed to support a user or group of users in achieving a higher effectiveness of decision making while solving a semi-structured spatial decision problems”.

One of the main spatial factors that impacts seismic operations, is land accessibility, which influences nearly all stages of seismic survey. The whole enterprise requires access to every shot and receiver point location for a number of people, equipment and vehicles. The time and cost needed to access the survey area can significantly influence the overall project costs. Moreover, the accessibility influences the methodology of a particular survey (e.g. source of seismic waves or seismic profile design). In the desert, the amount of sand dunes, as well as their height and direction (especially in relation to the direction of seismic profiles), determines the amount of equipment (e.g. bulldozers) required for the project. This, as a result, determines the time needed for the project and generates an important share of the total costs. Accessibility is regarded as the cost of travel from a source point to a given destination. In seismic operations, a source point is usually a base camp, where the seismic crew (all the personnel and vehicles) are located. The destination is the whole project area, defined by source and receiver points. Every day a destination point can change, as the production (recording) progresses.

Research areas

Study areas were chosen on the basis of land cover and elevation characteristics. Research areas are located in Poland, Turkey and India.

Polygon A

The first research area, referred to in this paper as the Polygon A, is located in the western part of Poland, approximately 100 km North-West of Poznań (Fig. 1, 2). It represents a typical flat and agricultural area. Although crop lands are dominant (nearly 68% of the total area), there are also four larger forest complexes in the northern and southern part of the polygon (14%) and several post-glacial lakes (3%). Since elevation has nearly no influence on terrain accessibility, it can be assumed that both the road network and land cover will have the most significant influence on accessibility and cost distance analysis. Only dense urban areas and water bodies may pose certain problems for seismic acquisition.

Polygon B

The second test area, Polygon B, is located in the eastern Anatolian region of Turkey, near the city of Erzincan (Fig. 3, 4). It is a typical mountainous region with elevations ranging from 1100 to 2500 meters. Bare ground is the dominant land cover, which covers nearly 80% of the total polygon area. Approximately 14% of the total area is occupied by croplands and nearly 1% by build-up areas (small villages). The western part is highly mountainous, with the highest peak reaching 2500 meters.

Polygon C

Polygon C is located in India, in the state of Rajasthan, 80 km North of the city of Jaisalmer (Fig. 5, 6). This area is a part of the Thar desert, which is the most densely populated desert in the world. The dominant land cover within the polygon is sand dune. Both sand dunes and sandy plains covers over 92% of the area. Dunes have a clearly visible SW-NE direction. Some dunes may have a height of up to 50 meters. They pose a significant obstacle for transportation and therefore they have been modeled as barriers with different barrier factors, depending on their height.

Approximately 9% of the area is occupied by croplands. Fields are randomly distributed over the whole area, although they tend to group near main roads, especially in the South. There is an underground and surface irrigation system that supplies water to fields and houses. There are also a few small villages and single settlements, usually located in the vicinity of croplands.

Data

For this project data has been gathered from several different sources. As a result the data had to be unified in terms of file formats, coordinate systems, spatial extent, resolution etc. The following data was acquired:

- satellite images – obtained as RGB natural color compositions from the Google Earth viewer with a resolution of about 2.5 meters,
- topographic maps – scanned paper maps (scale 1:50,000) for Polygon A and maps created by the Russian Military Topographic Directorate in scale 1:100,000 (Polygon B) and 1:200,000 (Polygon C).
- digital terrain models – SRTM ver. 4 (Jarvis et al., 2008).

Despite these datasets, for each research area the following vector datasets were created: land cover (polygon layer), three possible camp locations (point layer), regular grid of 81 sample destination points (point layer), road network (line layer), barriers (line layer for Polygon C).

Methodology

The Land Accessibility Analysis Model (LAAM) was designed in the Model Builder environment, which is provided with the ESRI ArcGIS package. The initial model was build up of the following components:

- Data Preparation (DP) – this part of the model involved generating a slope model from a digital terrain model and several data conversion and reclassification operations;
- Cost Surface (CS) – in this module a map algebra expression is used to overlay all input layers influencing the accessibility. The result of this module is a cost surface.
- Cost Distance (CD) – final part of the model, which calculates cost distance for a given camp location, generates cost paths to all destination points and creates summary statistics.

The model was exported to a Python script, where several modifications were introduced. The LAAM model was designed to evaluate different camp locations. For this reason the Cost Distance (CD) module was encapsulated within a loop to be performed for all input camp locations. The most important part is Cost Surface (CS), which creates a cost (friction) surface. It uses a map algebra expression, which defines how each input layer will be overlaid. For this paper, the following expression was used:

```
0.06 / (CON(ISNULL(Roads_Reclass),(CON(ISNULL(Barriers_Raster),
((Land_cover_Reclass) * POW(2.71828182845, TAN(Slope / 57.296)
* (-3))),(0.06 / (Barriers_Raster)))),(Roads_Reclass)))
```

The map algebra formula presented here (Fig. 7) is based on the assumption that the time friction surface will represent the time (in minutes) needed to move 1 meter across each pixel. This time effort is calculated by overlaying four input layers: roads, barriers, land cover and slope. The road network is considered to have the highest priority and is regarded as “slope-independent” (meaning that slope has no effect on travel speed on roads). This is based on the assumption that a road type (e.g. highway versus local path) is, in a sense, a derivative of slope and a slope effect is reflected in a road type. This approach was also chosen in order to underline the priority of roads over travelling off road. Therefore, a road network is placed on top of all other layers.

Next, priority is given to the barrier layer. This layer was introduced for Polygon C only to model sand dunes, as the resolution of the digital terrain model was too coarse to represent these land features. Barriers are also regarded as “slope-independent”, as they represent a general time friction, regardless its origins. The land cover layer is given the lowest priority and is placed below other layers. Its values are adjusted using slope values to show the effect of slope on travel speed. This is based on the modified approach of van Wagtendonk and Benedict (1980; after Nelson, 2008) and is computed as follows:

$$v = v_0 e^{-ks}$$

Where:

v – off road speed over the sloping terrain,
v_0 – the base speed of travel over flat terrain, depending on land cover type,
k – a factor which defines the effect of slope on travel speed ,
s – slope in gradient (metres per metre).

The base speed is acquired from the reclassified land cover dataset and *k* factor is assumed to be 3.0 for both uphill and downhill travel. Users can adjust *k* factor to change the effect of slope on travel speed by simply modifying the map algebra expression (Fig. 8).

Finally, a Graphical User Interface (GUI) was created within the ArcCatalog environment (Fig. 9). A tool in the ArcToolbox was created based on the Python file. The GUI helps the user to add input datasets and modify model parameters. Additionally, each part of the GUI was supplied with the help documentation to instruct the user on how to use the tool properly.

Results

The research and development of the LAAM model is currently in progress. Different parameters are being evaluated and results are still being validated. This paper presents the initial results and outcomes of the LAAM, which include:

- cost (friction) surface,
- cost distance surface for each source point,
- least-cost paths for all source and destination points,
- summary statistics (cost distance and distance for each path).

Cost surface

The first outcome of the LAAM model is a cost surface. It can be regarded as a map showing the level of difficulty of travelling over the given area (Fig. 10, 12, 14). Each pixel represents a time value (in minutes) needed to cross one meter within this pixel. The total time of crossing the whole pixel can be calculated by multiplying pixel size and its value. A yellow color on the cost surface maps indicates terrain which allows for relatively fast travel (low friction), while a blue color indicates difficult terrain (high friction). The Table 1 summarizes minimum, average and maximum friction values for each polygon in both time friction units (minutes) and speed units (km/h).

Table 1. Statistics of cost surfaces

	Minimum friction		Average friction		Maximum friction	
	Time [min / 1 m]	Speed [km/h]	Time [min / 1 m]	Speed [km/h]	Time [min / 1 m]	Speed [km/h]
Polygon A	0.00075	80.00	0.01271	4.72	0.10358	0.58
Polygon B	0.00100	60.00	0.01443	4.16	1.29897	0.05
Polygon C	0.00120	50.00	0.17127	0.35	8.00000	0.01
Polygon C*	0.00120	50.00	0.00511	11.74	0.08391	0.72

* Calculations excluding barriers, which significantly change average and maximum cost surface friction values.

Cost distance and cost paths

The generated cost (time friction) surface is used by the LAAM model to calculate cost distance surfaces (Fig. 11, 13, 15). They are calculated for each source (camp) location separately. Therefore, for each test polygon three different cost distance surfaces were created. Each pixel on this surface represents a time of travel (in minutes) from a given source to this pixel. Finally, the cost distance surface is used to create the least-cost paths (i.e. the fastest routes) from the given camp to all destination points. Sample cost distances and least-cost paths for Camp 1 on Polygon A, B and C are depicted in Figure 11, 13 and 15.

Summary statistics

The length and the cost of all paths were calculated. The length (distance) is given in kilometers, while the cost (time) is calculated in minutes. For each polygon and all camp locations the minimum, maximum, average and total time and distance statistics were generated. Additionally, minimum, maximum and average speed values were calculated.

Table 2. Summary statistics for Polygon A

Camp	Time (min)				Distance (km)				Speed (km/h)		
	Min	Max	Avg	Total	Min	Max	Avg	Total	Min	Max	Avg
1	1.75	20.48	11.03	849.04	0.19	15.14	8.71	670.46	6.68	66.97	47.38
2	2.59	15.38	8.89	684.61	0.77	11.95	5.59	430.31	12.55	59.31	37.71
3	1.97	21.33	11.85	912.56	0.51	17.24	8.16	628.19	6.67	59.77	41.30

Table 3. Summary statistics for Polygon B

Camp	Time (min)				Distance (km)				Speed (km/h)		
	Min	Max	Avg	Total	Min	Max	Avg	Total	Min	Max	Avg
1	1.72	58.26	17.64	1429.24	0.71	15.20	8.25	667.89	14.75	55.32	28.04
2	2.04	57.23	17.42	1410.65	1.36	14.06	8.14	659.26	14.74	52.99	28.04
3	1.38	54.35	15.30	1239.02	1.15	12.79	6.94	562.05	14.12	55.87	27.22

Table 4. Summary statistics for Polygon C

Camp	Time (min)				Distance (km)				Speed (km/h)		
	Min	Max	Avg	Total	Min	Max	Avg	Total	Min	Max	Avg
1	1.89	27.22	14.94	1210.48	0.47	14.42	6.92	560.51	14.13	42.18	27.78
2	2.58	21.61	11.70	947.50	1.15	9.71	4.94	400.53	13.01	43.64	25.36
3	0.65	27.67	12.69	1027.61	0.17	11.65	5.95	482.14	14.92	49.29	28.15

Each statistic provides an insight to some aspects of the accessibility. The time values can be used to assess how long it will take to travel to the field and how this will influence operating hours. This information can be combined with sunrise and sunset hours to calculate daily maximum time of operation, which can be translated into the level of productivity (e.g. number of points recorded per day). By comparing the total travel time the assessment can be made of how much time can be saved by choosing more optimal camp location.

The total distance can be used to estimate fuel consumption. The difference between distances from different camps indicates possible fuel savings, which contribute to higher revenues and smaller environmental impact.

Discussion

A general analysis of the results indicates that even a slightly different location of the source point can significantly influence the general accessibility of the given area. In case of Polygon A the biggest difference in time travels can be observed between location of camp 2 and 3. The difference is approximately 230 minutes in one way trips, which makes it a total difference of 460 minutes for round trips. This equals to 7.6 hours, which is nearly one working day. The average cost of maintaining a seismic crew in the field can be roughly priced at the level of 15 000 EUR per day. It is interesting to investigate a total travel distance values. The difference between camp 1 and camp 2 is approximately 240 km in one way travels and 480 km for round trips. This means, that only by changing the location from camp 1 to 2 (which are 4.4 km apart) every vehicle will have to travel 480 km (36%) less during the whole project.

In the case of Polygon B, the total travel time varies from 1239 (camp 3) to 1429 minutes (camp 1). The difference is 190 minutes in one way trips, 380 minutes in round trips, which equals to 6.3 hours. This means that travel from camp 1 will take approximately 15% more time than from camp 3. Additionally, the total distance in one direction from camp 1 will be approximately 105 km (19%) longer than from camp 3.

The results of the accessibility analysis for Polygon C need to be carefully assessed, since the barrier layer was additionally used to model dunes as obstacles. Each dune ridge was assigned a friction between 4 and 9 minutes, depending on the height, in order to enforce bypass routes. Therefore, the friction value of dunes was over exaggerated. This can be clearly seen in the cost surface statistics presented in Table 1. In this way most of the cost paths go around dunes and their friction is not added to the path cost. It only modifies the shape of the route. Total travel time in Polygon C varies from 947 minutes (camp 2) to 1210 minutes (camp 1). This indicates, that travel time is 28% longer for camp 1 in comparison with camp 2. Also the total distance vary significantly. For the camp 2 total travel distance is 400 km, while for the camp 1 it is 560 km (40% more), although they are only 3.3 km apart.

The absolute values obtained from the LAAM model shall be used very carefully. They depend heavily on the parameters used (speed values assigned to land cover and road types, k factor for incorporating slope effect, barrier friction etc.). The model still needs to be calibrated and further research will focus on finding optimal parameters for different scenarios and landscape types. At this stage it is particularly useful to compare the results of cost-distance analysis for the same area and different camp locations, i.e. examine the relative differences. In such case all parameters (such as land cover, speed values and k factor) are constant and the comparison is more reliable.

Conclusions

The initial results of this research lead to the following general conclusions:

- The accessibility significantly influences seismic operations. It is a vital task to assess it and describe using a quantitative approach.
- Multiple criteria and factors need to be evaluated in order to assess the accessibility. These criteria depends on the purpose of the analysis and the terrain being evaluated. Further research needs to be carried out in order to examine the effect of different environmental criteria on land accessibility.
- The road network is one of the main factors that influences accessibility. During seismic operations, however, the road network can be also regarded as a hindering factor, as roads introduce noise during seismic acquisition and become barriers for laying out the equipment.
- Resolution of the SRTM model is not good enough to represent small and medium size obstacles, such as dunes. The effect of DTM's resolution on final results shall always be considered.
- Further research is needed on cost surface creation algorithms. New criteria shall be evaluated and new relations between all parameters shall be examined (e.g. the effect of slope on road travel, different effect for uphill and downhill travels).

All models are wrong, some are useful. This rule of thumb, generally attributed to the statistician George Box, is particularly true for spatial data and spatial models. This is because space and our environment are infinitely complex, thus difficult to model. It is not possible to model all factors and criteria. However, modeling is justified as long as it can produce useful results. Spatial decision support systems are not intended to take decisions on their own. They are designed to provide useful information that can be combined with the expertise and knowledge of users to support decision makers in taking more optimal decisions.

This research shows that modeling a complex environment for very specific applications, such as seismic industry, can provide valuable and useful information. This information cannot be easily retrieved without GIS and multi-criteria spatial analysis.

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Streszczenie

Głównymi metodami, które wykorzystuje się obecnie do odkrywania nowych złóż ropy naftowej i gazu ziemnego, są metody sejsmiczne. Lądowe badania sejsmiczne wymagają olbrzymiej ilości sprzętu i siły roboczej. Jednocześnie są one w bardzo dużym stopniu uzależnione od warunków terenowych, takich jak pokrycie i ukształtowanie terenu czy obecność obiektów antropogenicznych, np. dróg i zabudowań.

Dostępność terenu jest jednym z głównych czynników o charakterze przestrzennym, który ma wpływ na przebieg badań sejsmicznych. Może być ona zdefiniowana jako koszt dotarcia do określonego miejsca, przy czym koszt ten może być wyrażony w różnych jednostkach, np. jako czas dojazdu, zużycie paliwa lub koszt wyrażony w pieniądzach. Głównym celem niniejszej pracy jest opracowanie metodyki szacowania dostępności terenu na potrzeby prowadzenia prac sejsmicznych. W tym celu wykonano Model Szacowania Dostępności Terenu (ang. Land Accessibility Assessment Model – LAAM), który uwzględnia pokrycie i ukształtowanie terenu, istniejącą sieć dróg oraz ewentualne przeszkody. Model został zaprojektowany w środowisku ArcGIS Model Builder. Następnie model ten został wykorzystany do oszacowania dostępności terenu dla trzech poligonów testowych. Poligony zostały tak dobrane, aby reprezentowały różne typy terenu: rolniczy, górski oraz pustynny. Każdy z trzech obszarów został uznany za hipotetyczny rejon prac sejsmicznych metodą 3D. Na podstawie wysokorozdzielczych zdjęć satelitarnych i map topograficznych pozyskano dane o pokryciu terenu, sieci dróg oraz informacje o ewentualnych przeszkodach terenowych (barierach). Ukształtowanie terenu zostało opracowane na podstawie numerycznego modelu terenu SRTM (wersja 4). Dla każdego obszaru stworzono 81 punktów docelowych oraz zaproponowano 3 różne lokalizacje bazy, które zostały poddane ocenie z punktu widzenia dostępności terenu.

Model Szacowania Dostępności Terenu został wykorzystany do obliczania tzw. powierzchni kosztowej (ang. cost surface) oraz tzw. powierzchni odległości kosztowej (ang. cost distance surface) dla każdej lokalizacji bazy. Na podstawie tej analizy można dokonać wyboru optymalnej lokalizacji bazy. Model MSDT został również wykorzystany do obliczenia najkrótszych tras dojazdu do poszczególnych części projektu sejsmicznego oraz oszacowania całkowitych czasów potrzebnych na dojazdy oraz ich długości. Wyniki uzyskane przy pomocy modelu MSDT mogą zostać wykorzystane przez osoby zarządzające projektami sejsmicznymi, np. w celu optymalizacji decyzji związanych z lokalizacją bazy, z której wykonywany będzie dany projekt. Pozwalają one również obliczyć długości dojazdów i w ten sposób oszacować zużycie paliwa. Wyniki te mogą zostać również wykorzystane do oszacowania trudności prowadzenia prac sejsmicznych w danym terenie.

mgr Jan Burdziej
jan.burdziej@umk.pl
+4856 611 2565

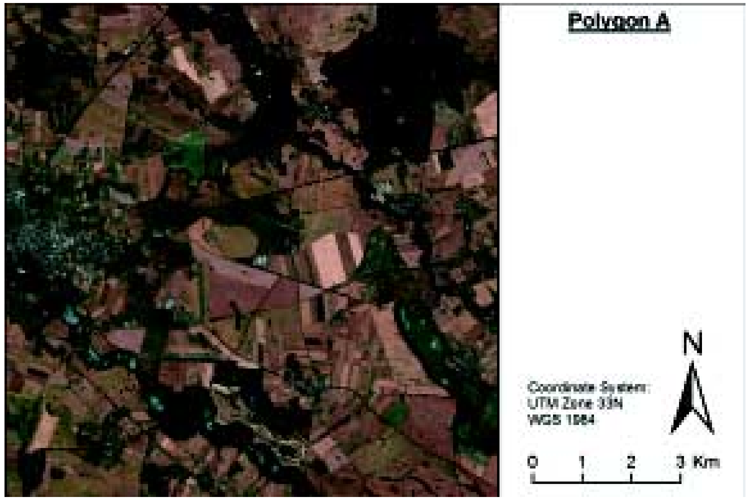

Figure 1. Satellite image of Polygon A
(Source of imagery: Google Earth / Digital Globe)

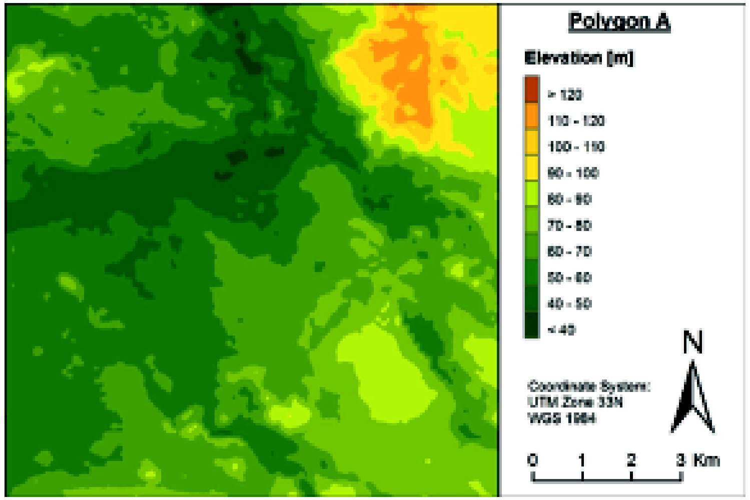

Figure 2. Elevation map of Polygon A

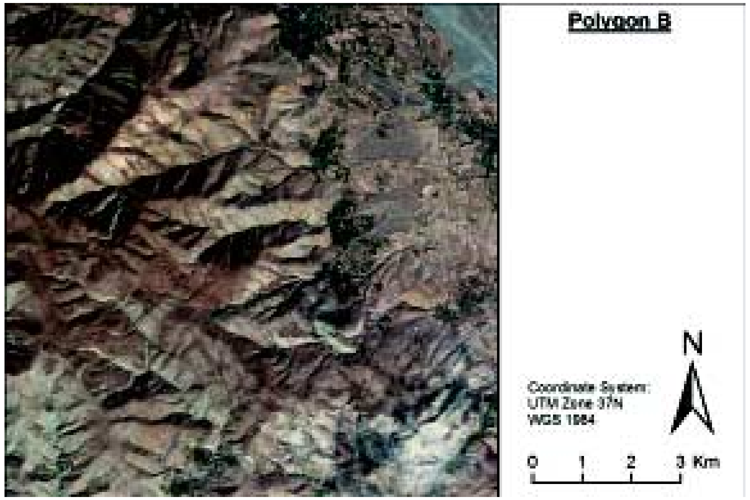

Figure 3. Satellite image of Polygon B
(Source of imagery: Google Earth / Digital Globe)

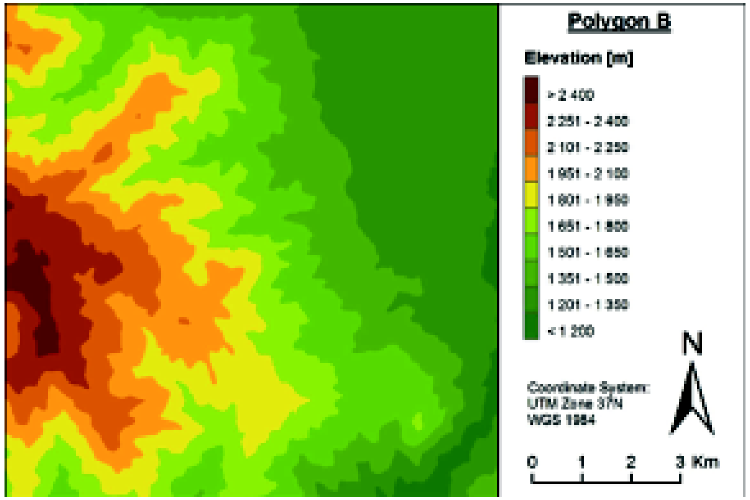

Figure 4. Elevation map of Polygon B

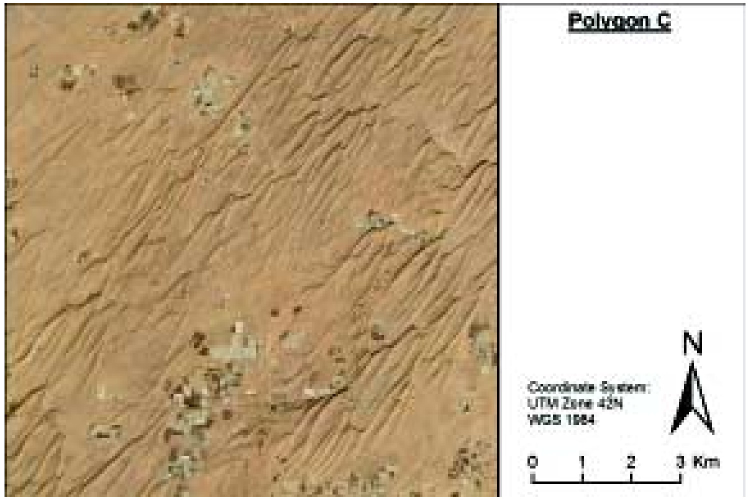

Figure 5. Satellite image of Polygon C
(Source of imagery: Google Earth / Digital Globe)

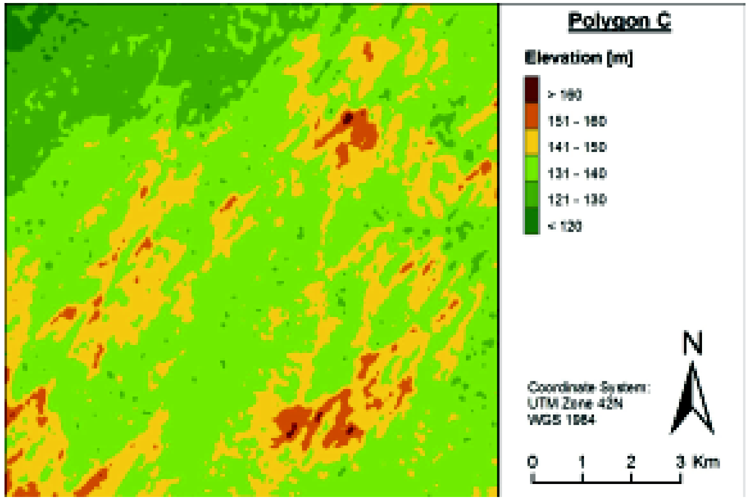

Figure 6. Elevation map of Polygon C

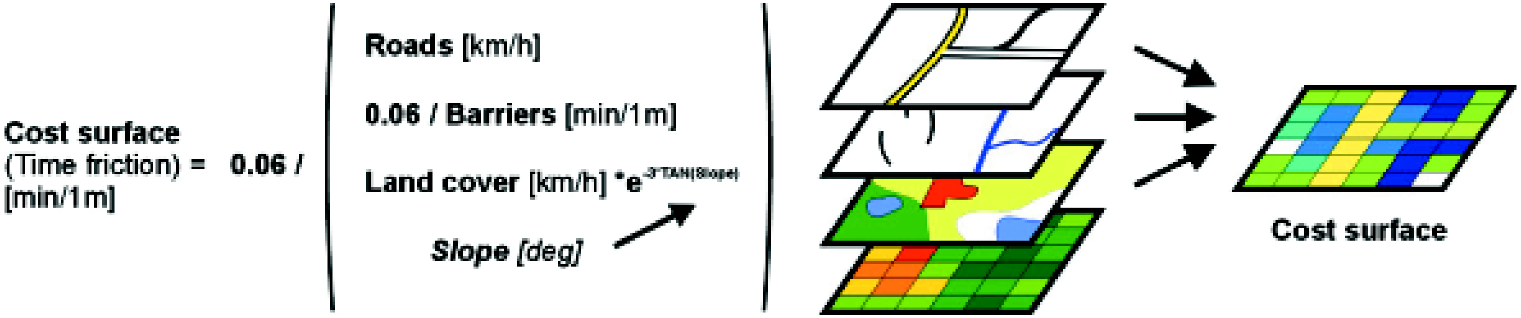

Figure 7. Schematic view of map algebra overlay algorithm

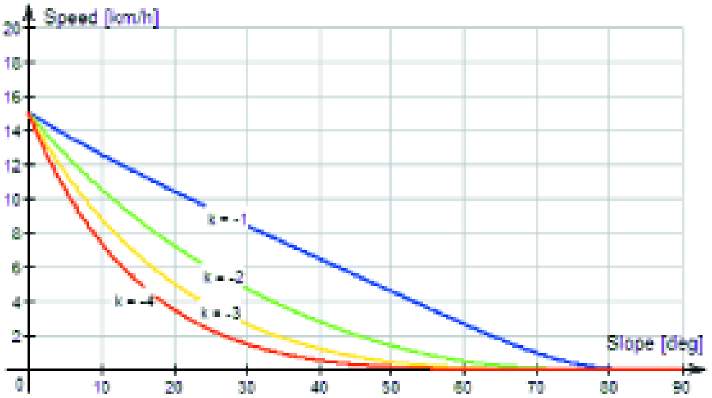

Figure 8. Effect of slope on travel speed [15 km/h]

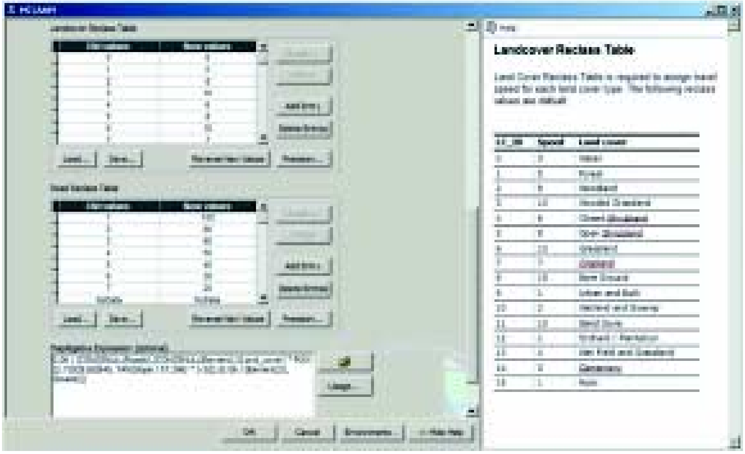

Figure 9. User interface of the LAAM

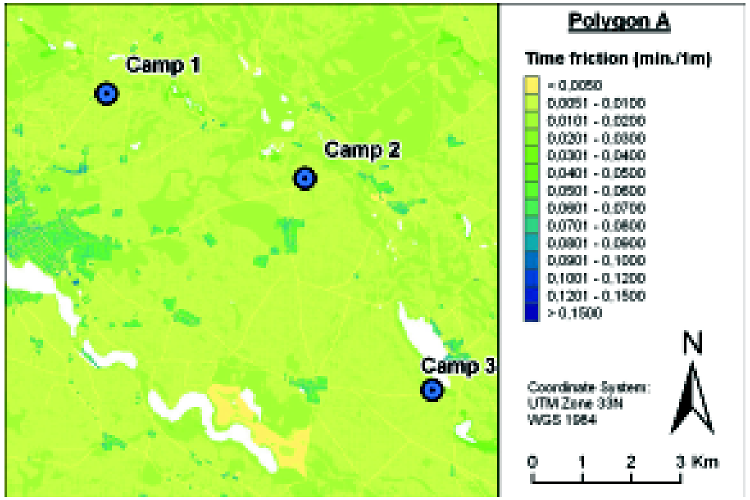

Figure 10. Cost surface – Polygon A

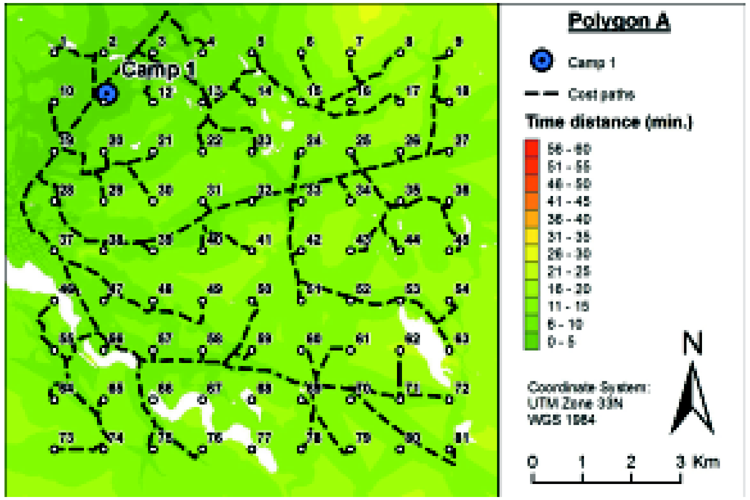

Figure 11. Sample cost distance and cost paths for Camp 1 on Polygon A

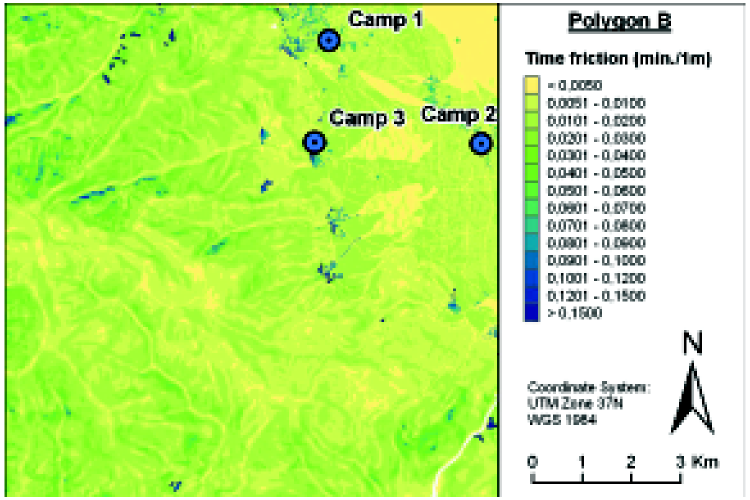

Figure 12. Cost surface – Polygon B

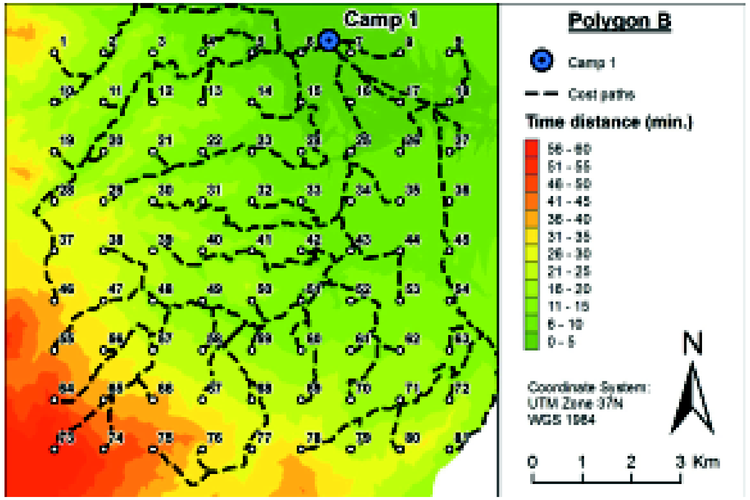

Figure 13. Sample cost distance and cost paths for Camp 1 on Polygon B

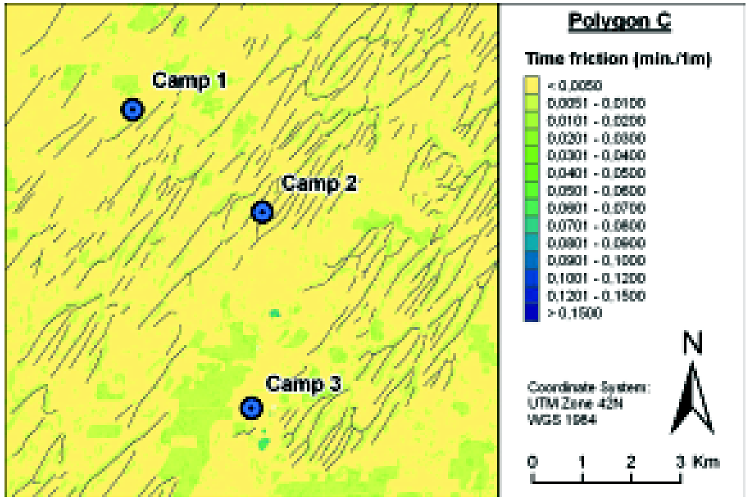

Figure 14. Cost surface – Polygon C

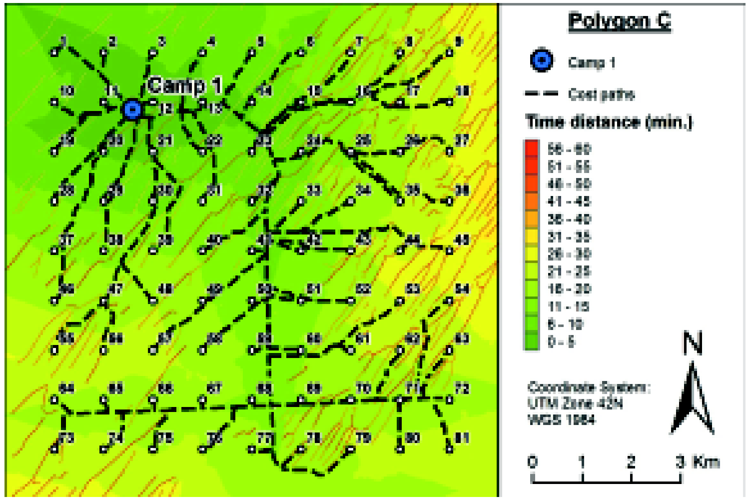

Figure 15. Sample cost distance and cost paths for Camp 1 on Polygon C