CREATING A SPATIAL ANALYSIS MODEL FOR GENERATING COMPOSITE COST SURFACES TO DEPICT CROSS COUNTRY MOBILITY IN NATURAL TERRAIN

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ABSTRACT

Understanding and visualizing terrain is fundamentally important to military operations. The dynamic nature of spatiotemporal effects in complex natural systems creates unique and ever changing terrain characteristics. For units operating in natural terrain environments, understanding how these conditions will affect Cross Country Mobility (CCM) in vehicles is critical for real world decision making. This project developed a spatial analysis model in a geographical information system for generating composite cost surfaces to depict vehicle mobility in natural terrain based on key thematic terrain layers. The model classifies thematic data for slope, vegetation, soils and hydrological features based on the CCM criteria defined in the US Army Field Manual 5-33. The result modernizes the traditional Army method of using mylar overlay techniques to create composite CCM maps and allows continuously varying parameters. The user can incorporate important temporal and seasonal variables such as wet versus dry conditions to modify mobility costs based on current operational parameters. The thematic data layers will then be optimized using smoothing algorithms and combined to create weighted composite CCM cost surface data. The cost surfaces provide a basis for applied spatial analysis to create cost distances to determine least cost paths and for generating semantic data which depict avenues of approach, key terrain, barriers/obstacles, and chokepoints. The model provides a standardized, yet flexible, application which can be applied to any area of interest and customized to suit the user's intended application. The output cost surface data will provide military units with a clear depiction of mobility within their operational area and can be combined with ancillary vector data to produce hard copy cartographic outputs for field dissemination. Non-military users can apply the model to provide base data regarding vehicle mobility for search and rescue operations, public land management, and environmental impact assessment.

Key words: Military, Terrain Analysis, Cross Country Mobility.

INTRODUCTION

Terrain analysis for military purposes is vital to providing the forces on the ground with much needed geospatial intelligence regarding their ability to maneuver across an area, as safely as possible, to reach their objective. Janlov et al. (2004) have shown that the military situation picture can be developed through spatial analysis and visualizations. The geographical conditions which effect mobility can be analyzed to produce data results which can serve as a decision making aid. Tactical and strategic terrain analysis is one of the five main categories of focus for military geologists (Guth, 1998). Terrain analysis is used to map the characteristics in an area of interest (AOI) which will impact vehicle mobility. Mobility is one of five characteristics to be considered in the tactical assessment of terrain (Parry, 1984). Spatial analysis, performed in a geographic information system, can be employed to use thematic map layers depicting terrain elevation, slope, soil characteristics, vegetation, and hydrological features to derive Cross Country Mobility cost data. This data helps define the relationships between these physical characteristics and provides a resource to aid in analyzing, mapping and visualizing vehicle mobility in natural terrain.

The United States Army has established guidelines regarding the classification of terrain types and characteristics found in the Field Manual 5-33 *Terrain Analysis* (US Army, 1990). The Army's traditional process for creating CCM maps involved the generation of individual thematic map layers using sheets of mylar which were then overlaid on top of one another to derive a composite. The spatial analysis model described in this paper will modernize this process in an automated manner which will produce composite mobility cost data derived from the individual thematic terrain layers, to depict ease or difficulty of vehicle mobility over natural terrain.

The model's output data produces a smoothed continuous mobility cost surface which improves upon the original composite CCM maps that contain sharp data transitions between mobility classifications. The model implements the Army's standardized CCM classification scheme while providing flexibility for the user to customize dynamic terrain conditions, using unique input terrain data. Army terrain analysts or civilian users can modify the variables and parameters in the CCM model to customize the data inputs while choosing to incorporate or exclude conditional environmental factors such as wet versus dry conditions. This provides flexibility for the user to adjust to current environmental conditions within an AOI while maintaining the framework of the Army defined mobility classifications.

The final result is a composite cost surface which has been aggregated from the individual thematic input layers. The CCM cost surface provides a consistent data output for use in spatial analysis to determine cost distances and least cost paths. Aggregate data values can also be reclassified into a simplified "go-slow go-no go" scheme to reduce the complexity of the values. Additional vector data can be overlaid with the CCM cost surfaces and incorporated into map outputs for visualization and reference for decision making.

MODEL DESIGN

This CCM spatial analysis model was developed using ESRI's Model Builder application (ESRI, 2009). The overall model consists of multiple sub-model components which perform data preparation or spatial analysis functions. Figures 1 & 2 provide a conceptual workflow which shows the process, by which the model prepares, modifies, combines, calculates, and produces the final CCM cost surface data using multi-format input data for the five individual terrain analysis thematic layers (Slope, Vegetation, Hydrological Areas, Hydrological Lines and Soils).

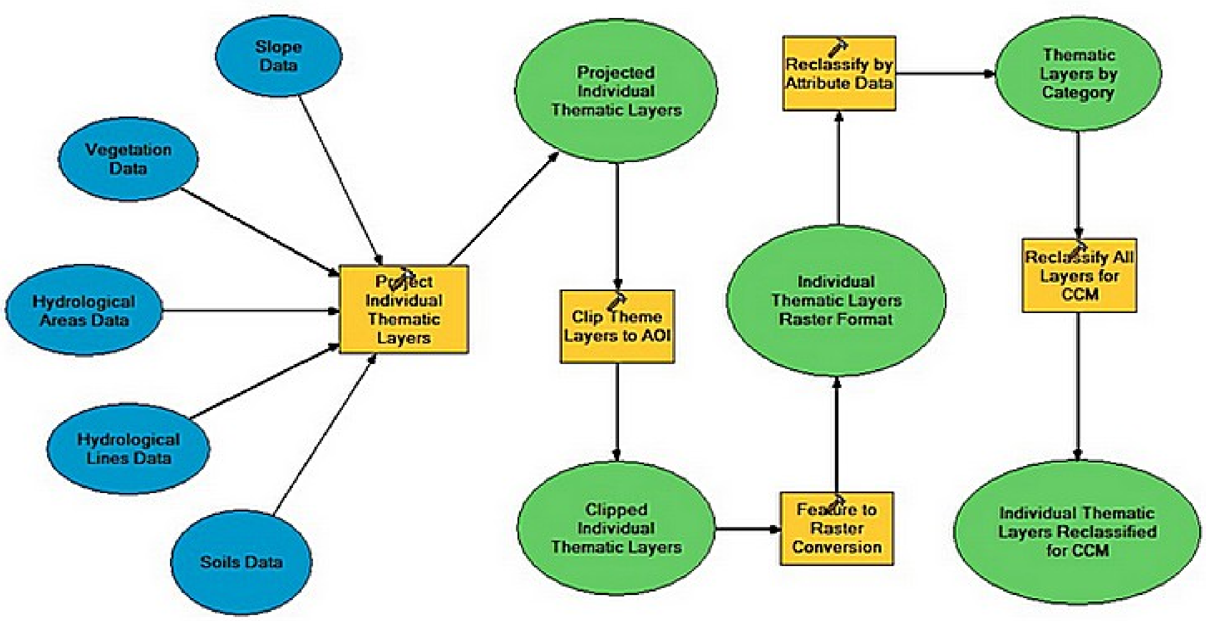

Figure 1. Conceptual Flow Chart of the CCM model process to create individual CCM data for each thematic layer.

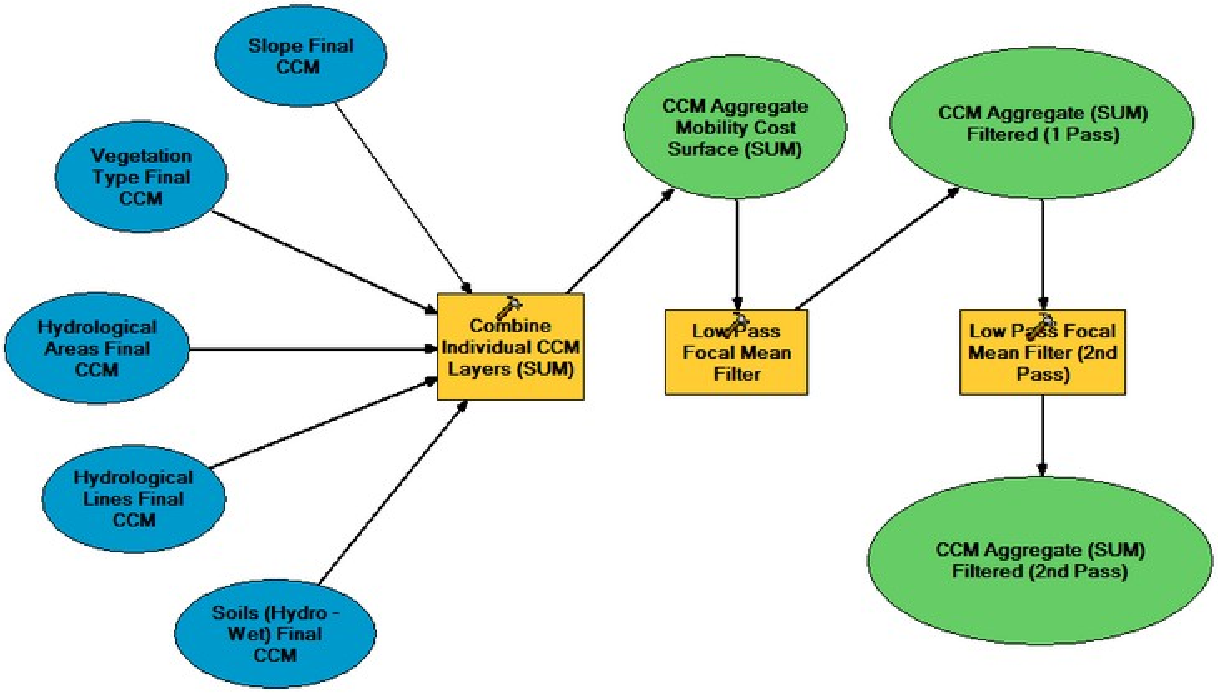

Figure 2. Conceptual Flow Chart of the CCM model process to create final aggregate CCM cost surface data.

The model contains two primary sections which run in a linear fashion; the preparation and CCM classification of the individual thematic terrain layers and the aggregation of the individual CCM layers into the final composite CCM cost surface. The model utilizes parameters and variables defined within the sub-model functions to ensure that the user sets the key elements of the models process, which are specific to any unique input data and the conditions of their AOI. For example, the user can select whether to use wet or dry hydrological soil conditions which will generate CCM values for each of the different soil group types within the soil layer depending on the effect that moisture has on soil trafficability characteristics. These options reside within the sub-model operators and can incorporate or exclude different functions to adjust the outcome of the aggregate composite CCM cost surface based on changing environmental conditions within the users AOI.

The initial version of the model requires the user to project and clip each input data source individually, rather than by using an environmental parameter, to enhance awareness regarding the disparate projection systems of the input data sources while allowing the user to select specific geographic transformations which are best suited to the re-projection process. The clipping sub-model process runs on the individual input layers once they are re-projected to ensure the appropriate data are included in the AOI after the transformations are complete and to allow the overall extents of multi-format input data to remain the same for all layers.

The next sub-model function performs the data manipulation processes required to prepare vector data inputs for feature to raster conversion. This step primarily involves preprocessing on vector data resources prior to conversion to a raster format. For the hydrological water areas a dissolve function creates a single multi-part feature where water is present so the layer can be converted to a raster format which contains the presence of water as a binary value. All individual thematic terrain layers are output into a raster format in a cell size specified by the user as a variable in the model. The attribute field which will be the basis for the CCM classification is reclassified into bins in preparation for the final CCM value conversion. Following this preparation the model generates the individual CCM layers by reclassifying the prepared attribute values to the individual CCM costs. These individual layers are then aggregated using map algebra to SUM the weighted CCM cost values into a final aggregate cost surface. The composite CCM cost surface is then smoothed with two subsequent passes using a focal mean filter using a 3 x 3 neighborhood area. The user can alter the number of passes for optimizations, but testing found that two sufficiently smoothes the data, drawing out subtle transitions between mobility cost values.

DATA RESOURCES

In order to develop the CCM spatial analysis model a representative area of interest was selected along with corresponding geospatial data for each of the individual thematic terrain layers. The designated AOI (see **Figure 3**) constitutes approximately 6,600 km^2 of Pima County, located in southern Arizona. This area is characterized by horst and graben terrain which ranges from semi-arid desert valleys up to temperate coniferous sky islands on mountain ranges of approximately 2,800 meters in elevation.

The AOI contains a wide variety of elevation changes, diverse vegetation, riparian zones, streams, washes and soil groups that have dynamic hydrological trafficability characteristics depending on wet versus dry conditions. The AOI is subjected to seasonal monsoon climate patterns which bring heavy precipitation and cause flash flooding during the summer months that swell the streams and washes to high flow capacities. This area of interest provided a suitable study area to test and develop the CCM spatial analysis model specifically within the application of mobility in arid or semi-arid terrain environments. Using the desert terrain characterization methods described by Bacon et al. (2008) the comparisons could be made to establish the similarity of the desert terrain in this area of interest to those found world wide or in specific active combat zones.

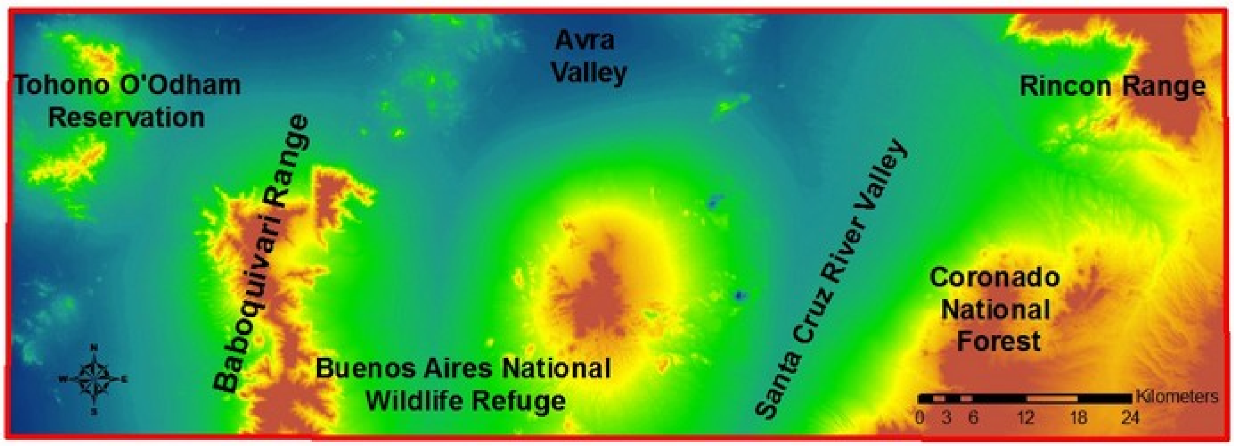

Figure 3. AOI used for the CCM model development with SRTM 1 Arc Second Elevation Data.

For each of the five individual thematic terrain layers used to assess CCM a representative data layer was acquired from free public domain GIS data resources. The data selected is intended to represent data equivalencies which are commonly available to users in both military and non-military organizations. All of the data resources contain attribute information which provide a basis for CCM cost classification as defined in the FM 5-33. Table 1 describes each data layer used in the model development process while Figure 4 shows the data structure.

Table 1. Thematic Cross Country Mobility terrain layer data resources.

CCM Thematic Layer	Original Format	Resolution/Source Scale	Data Source
Elevation (Slope %)	Raster	30m	Shuttle Radar Tomography Mission (SRTM 1") - NED
Vegetation (Type)	Raster	30m	LANDFIRE Data - Vegetation Type - National Map Server
Hydrological Lines (Streams)	Shapefile	1:12,000	Pima County Geographic Data Library
Hydrological Areas (Water Bodies)	Shapefile	1:12,000	Arizona Atlas
Soils (Hydrological Characteristics)	Shapefile	1:24,000	Soil Mart Data/Pima County Geographic Data Library

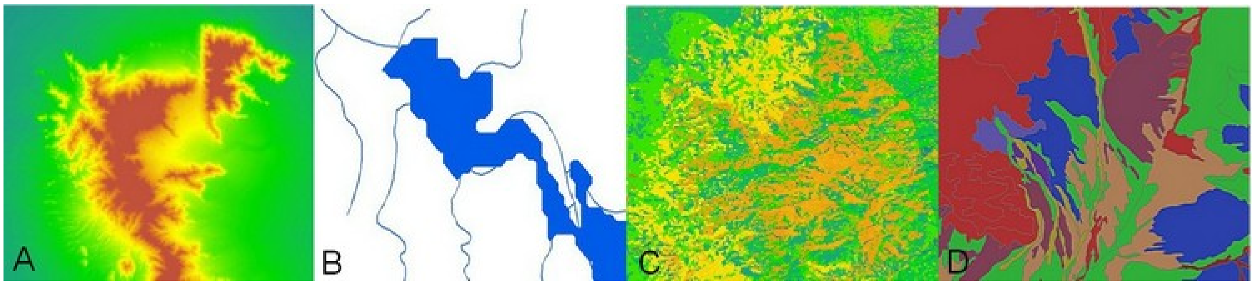

Figure 4. Terrain thematic input layers for CCM model: slope (A), hydrological lines and areas (B), vegetation (C) and hydrological soils (D). Maps cover different regions at different scales.

Based on the potentially unique characteristics of the input data that could be used within the CCM model some data preparation may be necessary prior to ingestion. This means that the attribute field which will be used to classify the individual terrain data layer needs to be properly grouped, valued and defined in the appropriate data type prior to use in the model. In the development of this model the LANDFIRE Vegetation type terrain data layer required that each of the over forty vegetation type areas be assigned a unique numeric value prior to ingestion so the that these values could then be grouped into vegetation type classes based on mobility characteristics which were then reclassified in CCM cost values. Once the data has been properly prepared for ingestion it can be classified into single values or bins which will be reclassified for CCM cost values for the final individual CCM terrain layer.

METHODS

In order to create the aggregate composite CCM cost surface each of the individual thematic terrain data layers must be prepared, projected, clipped, and converted to raster format data. The model performs these tasks as model sub-functions, based on user defined variable and parameter inputs for each of the terrain layers which are then ready for the process of CCM classification and CCM cost value re-classification. Each of the five thematic terrain layers requires separate data preparation, classification and CCM cost value reclassification based on the relationship of the terrain characteristics to vehicle mobility as defined in FM 5-33. The individual data input layer runs through its own linear set of model sub-functions to produce the final CCM cost surface for that theme.

Two of the layers (slope and soils) required the development of non-linear ratios based on the relationship of the terrain attributes, (slope % and hydrological soil groups) to vehicle mobility characteristics such as vehicle speed and hydrological soil trafficability under wet versus dry conditions. These ratios were developed to accurately assign scaled CCM cost values which reflected the impact of these terrain characteristics on vehicle mobility. A sub-function in the model performs the reclassification of the slope bins and soil hydrological groups to CCM cost values. These can be edited by the user to adjust for the unique aspects of the input data and to modify the output CCM cost values, making them more narrowly or broadly defined.

The remaining three thematic layers (vegetation, hydrological lines and areas) were converted within the model to values which reflected general mobility classes based on their terrain characteristics. The mobility classes were then reclassified to CCM cost values which reflected the impact of the classes' terrain characteristics on vehicle mobility.

Non-Linear CCM Cost Ratios

The slope thematic terrain layer that was generated within the CCM model for the development process utilized SRTM 1-arc second Digital Elevation Model (DEM) data. The slope layer consists of a raster which contains values reflecting the percent of slope for each grid cell (30m) in the AOI. The user can employ DEM data of differing resolution but should be aware that the effect that the data spacing has on slope calculations and its distribution within the AOI of interest. Guth (1995) showed that there is a consistent drop in the average percent of slope value the greater the data's spacing. For the purposes of CCM larger data sizes increases the slope averaging and is well suited for showing ease or difficulty of vehicle movement.

In the development of the CCM model a slope raster layer was generated using NED 1/3-arc second data with a cell size 7m. The resulting output slope layer showed indications of contour line "ghosts" which contained anomalous elevation distributions which demonstrated inordinately high numbers of point data values located along a specific contour interval, reflecting the DEMs derivation from USGS topographic source maps (Guth, 1999). This underscores the importance of data input selection utilized within model.

A model sub-function runs the slope calculation on the DEM data using Spatial Analyst, to produce values of slope as a percentage. FM 5-33 provides data showing the non-linear relationship of certain percent slope bin values to overall top speed with any slope being greater than 45% considered a "no go" area or impassable by a tracked vehicle. Table 2 shows the percent of slope bin values and the corresponding non-linear ratio which was calculated based on the effect of percent of slope on vehicle top speed. The speed difference ratio reflects the percent of the highest possible speed a slope bin value can have. This ratio was then used to calculate a whole integer CCM cost value which the CCM model sub-function would assign to the slope bin categories found in the original slope thematic terrain layer.

Table 2. CCM cost value classification based on non-linear ratio of slope to speed (mph) as defined in FM 5-33.

Percent Slope	Speed Ratio Difference	Speed (mph)	% of Highest Speed	CCM Cost
0-3 %	1.00	34.50	100.00%	10
3-6%	1.06	32.65	94.64%	11
6-10 %	1.12	30.80	89.28%	12
10-15%	1.19	27.40	83.92%	13
15-20%	1.44	24.00	69.57%	14
20-25%	1.63	20.00	61.26%	16
25-30%	2.16	16.00	46.38%	22
31%	2.16	15.33	44.45%	23
32%	2.25	14.67	42.52%	24
33%	2.35	14.00	40.59%	25
34%	2.46	13.34	38.66%	26
35%	2.59	12.67	36.72%	27
36%	2.88	12.00	34.79%	29
37%	3.04	11.33	32.85%	30
38%	3.24	10.67	30.92%	32
39%	3.45	10.00	28.98%	35
40%	3.70	9.33	27.04%	37
41%	3.99	8.66	25.11%	40
42%	4.31	8.00	23.18%	43
43%	4.71	7.33	21.25%	47
44%	5.18	6.67	19.32%	52
45%	5.75	6.00	17.39%	57
>45%	No Go	0	0.00%	5000

The percent of slope values were grouped into bins for the lower slope areas, as these have a lesser impact on mobility, while the high percent of slope values began to be individually assigned CCM cost values which reflect subtle impact of percent of slope on mobility cost. The final slope CCM cost layer contains a raster where every grid cell is assigned a CCM cost value which characterizes the relationship of percent of slope to vehicle mobility. All of the slope bin values have been assigned an integer CCM cost value with a weighted penalty value (5000) added to reflect these areas as "no go". Once this sub-function of the model is complete the slope CCM layer is prepared for aggregation with other individual CCM thematic data layers.

The soils thematic terrain layer used to develop the CCM model is a raster data layer which has a single attribute field that contains data values for each cell that express the composition of the hydrological soil group defined as a floating point value. This attribute field was prepared by creating a ratio of the dominant soil group characteristic found within a cell combined with the minority soil group characteristic. This allows for a more precise evaluation of soil characteristics and to create a non-linear ratio to associate the hydrological soil group composition to its effect on the soil trafficability for CCM.

Field Manual 5-430-00-1 defines the soil CCM characteristic as the capacity of soils to support military vehicles (US Army, 1994). Soil hydrological conditions affect the soils ability to support weight and provide traction for vehicle movement including the number of vehicles which can pass over the same terrain. This is because the trafficability of fine-grained soils, which include silts and clays, changes when they are wet and hamper vehicle movement due to increased slipperiness, stickiness, and decreased strength. The opposite is true during dry weather. Temporal weather conditions and the presence or absence of moisture can have severe impacts on CCM for different hydrological soil group types. The hydrological soil group assignment was based on the classification system developed by Neilsen and Hjelmfelt Jr. (1998).

This CCM model utilized a non-linear ratio which reflected the relationship of soil hydrological group characteristics under wet conditions to Rating Cone Index values (RCI_1). RCI indicates the soil strength for vehicle mobility which has been corrected for remolding (US Army, 1994). Field Manual 5-33 provides RCI_1 data which defines the relationship between soil types and RCI Values. Table 3 shows the CCM cost values which were calculated based on the non-linear ratio that defines the difference from the best possible RCI_1 value (165). The CCM cost values for this layer do not contain a weighted penalty as the AOI does not contain any soil types which are considered "no go" during wet conditions.

Table 3. CCM cost values based on non-linear ratio of soil group trafficability characteristics (wet) to RCI_1.

Soil Group Values	**Soil Group**	**RCI_1 (Wet)**	**% of Best RCI_1**	**RCI_1 Ratio Difference**	**CCM Score**
1.00	**D**	165.00	100.00%	1.00	10
1.25		144.25	87.42%	1.14	11
1.32		138.79	84.11%	1.19	11
1.37		134.42	81.47%	1.23	12
1.38		133.88	81.14%	1.23	12
1.47		126.27	76.53%	1.31	13
1.53		120.73	73.17%	1.37	13
1.56		118.31	71.70%	1.39	14
1.57		117.57	71.26%	1.40	14
1.67		109.67	66.46%	1.50	15
1.68		108.21	65.58%	1.52	15
1.73		104.13	63.11%	1.58	16
1.74		103.84	62.93%	1.59	16
1.89		91.22	55.29%	1.81	18
2.00	**C**	82.00	49.70%	2.01	20
2.24		70.24	42.57%	2.35	23
2.31		66.38	40.23%	2.49	24
2.33		65.33	39.60%	2.53	25
2.40		62.00	37.58%	2.66	26
2.44		59.78	36.23%	2.76	27
2.47		58.67	35.56%	2.81	28
2.47		58.47	35.44%	2.82	28
2.50		57.00	34.55%	2.89	29
2.56		54.22	32.86%	3.04	30
2.63		50.75	30.76%	3.25	32
2.67		48.67	29.49%	3.39	34
2.72		45.89	27.81%	3.60	36
2.82		40.82	24.74%	4.04	40
3.00	**B**	32.00	19.39%	5.16	47
3.17		30.83	18.69%	5.35	54
3.53		28.29	17.15%	5.83	58
3.72		26.94	16.33%	6.12	61
>= 4	**A**	25.00	15.15%	6.60	66

Mobility Classes

For the vegetation (type), hydrological lines (streams/washes) and hydrological areas (lakes/reservoirs) mobility classes were created based on the attribute information present in each input data layer. Since the relationships between these terrain features and CCM is more direct, mobility classes were created to categorize the terrain attributes into groups which are assigned CCM cost values with weighted penalties.

The vegetation terrain layer originally contained attribute information that included over forty different individual vegetation types. These types were grouped into generalized classes based on CCM impacts defined in FM 5-33 which uses "stem diameter" and "stem spacing" as constraints on vehicle mobility. The vegetation mobility classes were then assigned CCM cost values within the model sub-function based on density estimates and the descriptive characteristics of the vegetation terrain classes. Areas characterized by grasslands and desert scrub were given lower CCM costs while areas with larger tree types were given higher costs with coniferous pine forest being penalized. Table 4 shows the mobility classes and cost values for vegetation, hydrological lines and areas.

Table 4. CCM cost values based vegetation type, presence of water areas, and CFS flow rates

Generalized Vegetation Type Classes	**CCM Cost Value**
Herbaceous/Nonvascular-dominated, Grasslands, Agriculture, Savanna	10
Desert Scrub, Pinyon-Juniper, Chaparral	20
Oak, Riparian, Mesquite Woodland	100
Conifer Forest, Ponderosa Pine Woodland	2500
Water Area Present (Yes/No)	**CCM Cost Value**
Yes	5000
No	0
CMS Values (m^3/s)	**CCM Cost Value**
No Data	0
< 14.16 - 28.31	10
28.32 - 56.63	20
56.63 - 141.58	30
141.58- 283.16	40
> 283.16	1500

The hydrological water areas were assigned CCM costs in a binary fashion to reflect the presence or absence of water features. Areas where water was present were given a weighted penalty value to designate these areas as off limits to vehicle traffic. All other areas we reclassified within the model to a value of zero so as not impact the values of the other four thematic terrain layers during the map algebra aggregation process.

The hydrological line features were grouped into mobility classes based on the original attribute field for the streams/washes layer which contained data indicating the cubic meter per second (m^3/s) flow rates of the streams at full capacity. The model was run using the parameters of wet conditions to assess mobility if heavy seasonal rains had flooded the drainage networks within the AOI, impacting mobility. The CCM values were assigned in a progressively costly manner but only streams over 283 CMS (m^3/s) were given a weighted penalty. This penalty value affects the cost of movement in relation to stream and wash features in that bisects the area of interest. A least cost path analysis will move a certain number of pixels in another direction to avoid the high cost but if it is evenly distributed across the AOI it will have an equal penalty to cross.

The final result of the first phase of the CCM model is five separate thematic terrain layers which have been individually assigned CCM cost impact values which have been tailored to express the relationship between the terrain characteristics and their impact on vehicle mobility as defined by the Army's criteria.

CCM Composite Cost Surface

The final set of sub-functions to be performed within the CCM spatial analysis model execute the aggregation of the five individual CCM terrain layers into a single composite cost surface with values that reflect the spatially coincidental mobility costs of each terrain layer's characteristics. This is executed using map algebra SUM function which adds each of layers values together to produce the composite CCM cost surface. Once the aggregate CCM composite cost surface is produced the model runs two passes of focal mean filters, using a neighborhood of 3 x 3 cells, to smooth the continuous surface and produce more subtle transitions between CCM cost impact values.

RESULTS

The result of running the CCM spatial analysis model with the appropriate input thematic terrain layers is an aggregated CCM composite cost surface which is produced in a standardized manner, but based on the customization of data made by the user and utilization of the appropriate model sub-functions and parameters. The final CCM composite cost surface is generated from the five individual thematic CCM cost layers (Figure 5). These individual layers provide CCM cost surfaces by terrain theme, which can be used for additional CCM spatial analysis applications.

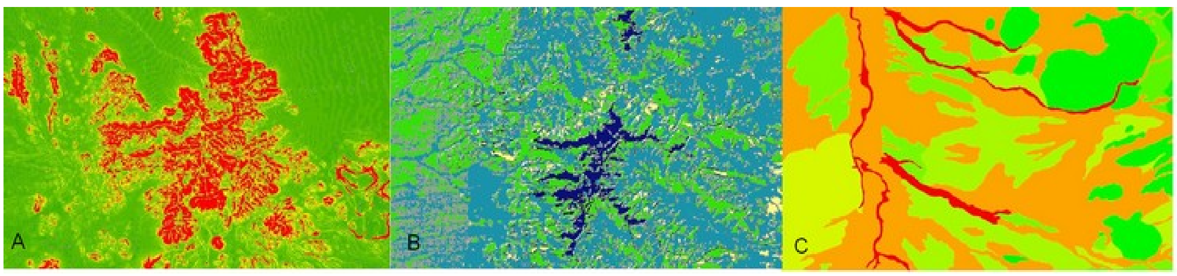

Figure 5. Individual thematic CCM cost classified layers: slope (A), vegetation (B) and hydrological soils (C). Maps cover different regions at different scales.

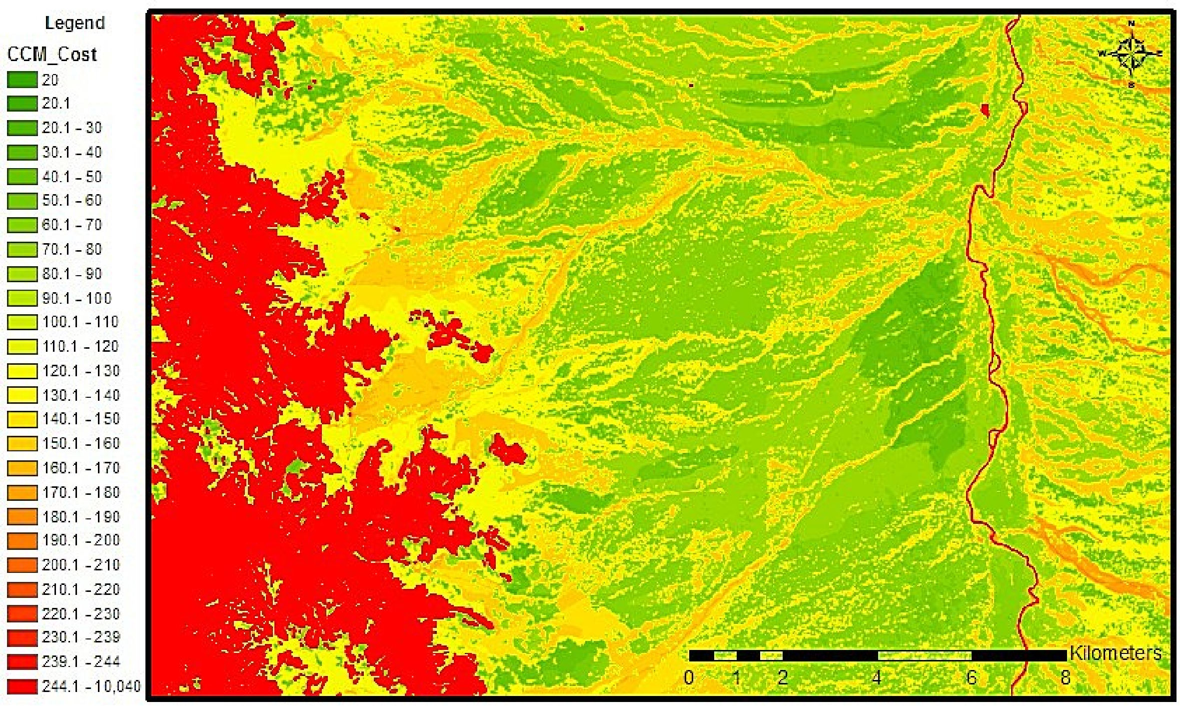

Figure 6. The aggregated CCM composite raster cost surface generated by the spatial analysis model.

Figure 6 shows the final CCM composite cost surface for a portion of the area of interest, which is visualized using a color ramp to draw out the transitions of mobility areas which depicts the ease or difficulty of vehicle movement. The cost surface data has values which range upward to a possible aggregate score of 10,040. Based on the CCM classification values any score over 244 is deemed to hold at least one penalty or "no go" area and is therefore visualized in the output CCM cost surface as such. This composite raster is well suited for visualizing Cross Country Mobility and provides a data resource from which further spatial analysis processes can be run including generating cost distances, performing least cost path analysis, and for use in predicting potential environmental impact of vehicle use.

Using qualitative analysis to assess the results it shows steep high mountain terrain areas, where coniferous pine stands are found to be "no go" areas. Further, since the "wet" hydrological soil condition values were used to simulate the rainy monsoon season conditions the drainage areas show high mobility costs which increase to a "no-go" penalty area for the larger stream which has a high volume flow. A large amount of mobility cost variation occurs in the mid range values from approximately 50–140. This reflects the complex dynamic of increasingly steep terrain and the presence of denser, more substantial vegetation. Most of the flat low lying areas which are not in drainages appear to have low mobility costs.

Looking deeper at the effect that the focal mean filter had on smoothing the transitions between CCM cost value areas the result becomes apparent (see Figure 7). The transition from the initial output raster, through multiple passes of the filter, shows the effect of the smoothing can have on emphasizing or minimizing subtle transitions which may impact least cost path analysis. The final surface can be smoothed using the number of iterations preferred by the user to suit their analytical needs.

Figure 7. CCM cost surfaces from no smoothing filter (1), filtered with one pass (2), filtered with two passes (3).

DISCUSSION AND CONCLUSIONS

The development of the Cross Country Mobility Spatial Analysis Model has demonstrated that mobility cost surface data can be generated in an automated fashion using geographic information. The output individual and composite CCM cost surfaces provide a data resource for further spatial analysis processes that are based on standardized Army classifications. The model provides flexibility to the user to modify, add, exclude or alter the variables, parameters and classification values to suit the unique spatiotemporal conditions found in the designated AOI. The final output CCM composite cost surface contains smoothed data transitions which enhance the data as a resource for visualization and spatial analysis functions.

The model can produce results at resolutions and quality levels which match the input data. This is the primary limitation of the model. Horttanainen and Virrantaus (2004) used non-spatial stochastic simulation and expert knowledge to evaluate the uncertainty of military terrain analysis results and found that the absence of quality information about the input source data increases uncertainty in the terrain analysis results. Their spatial uncertainty model approach could be utilized to assess the data reliability.

The amount of reliable well documented data available would constrain the reliability of the output of the CCM spatial analysis model. This may be of less concern for users focusing on the domestic operations within the United States where more reliable and well documented data exists, but this could prove problematic for AOIs where data of the appropriate type might be scarce or unavailable for certain thematic terrain layers. Consideration could be given to the value of producing standardized thematic input data sets which would allow for CCM cost surface generation.

Future iterations of the model could include additional geoprocessing functions to produce a greater number of hydrological soil cost surfaces which calculates RCI based surfaces for a greater number of passes (RCI_{50} and RCI_{100}). These RCI cost surfaces could show the impact that increased vehicle traffic has on vehicle mobility and its relationship to Vehicle Cone Index (VCI) values, which defines whether a vehicle can negotiate a given soil condition for a given number of passes (US Army, 1994). Areas which can support different vehicle types could be assessed to estimate environmental impacts. Wu et al. (2008) discuss creating mission impact profiles for specific areas based on the vehicle number of passes associated with live training events. Shoop et al. (2005) has shown that this type of terrain data can be used to calculate the maneuverable acreage within an operable AOI. Therefore more robust RCI based hydrological soil cost surfaces produced by this model would provide data for additional spatial analysis functions that could assess vehicle impacts and delineate "no-go" areas for specific vehicle types.

The Cross Country Mobility model that was developed is a tool which can be used by military or non-military users alike to produce valuable cost surface data using a straightforward linear series of geoprocessing functions. The model is not intended to be an all encompassing system for producing highly complex mobility data results but to be used to create consistent CCM cost surface data which serves as the basis for further spatial analysis functions where mobility and terrain impacts need to be assessed.

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Please contact the author directly to acquire a copy of this spatial analysis model.

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