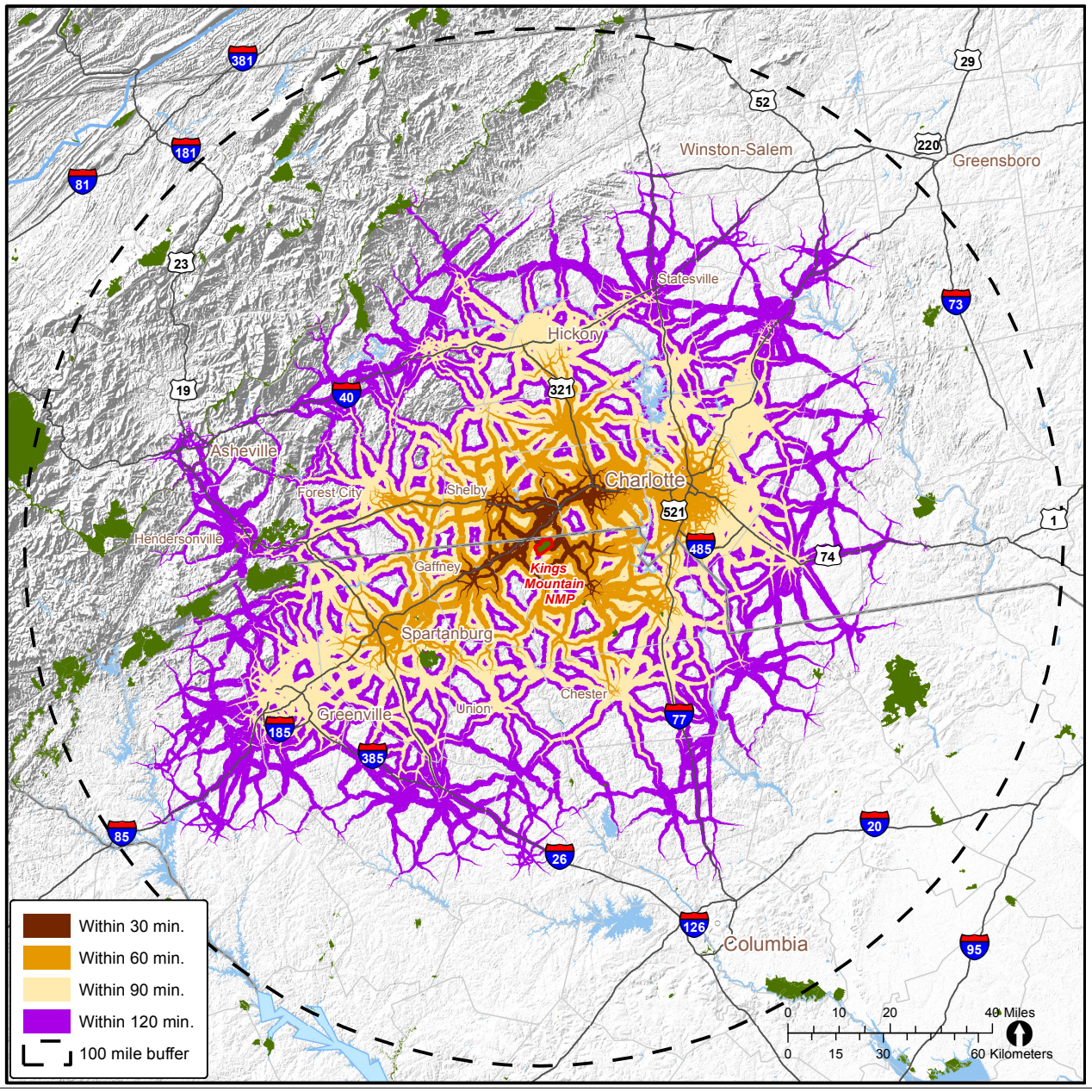
National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

National Park Service Travel Time Cost Surface Model (TTCSM)

March 2015

Natural Resource Report NPS/NRSS/NRR—2015/933



ON THE COVER

A regional view of the travel time model for Kings Mountain National Military Park, highlighting the 4 areas of analysis considered in a population analysis: 30, 60, 90, and 120 minute travel times.

National Park Service Travel Time Cost Surface Model (TTCSM)

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Natural Resource Report NPS/NRSS/NRR—2015/933

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March 2015
U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

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Abstract

This document presents a travel time cost surface model (TTCSM), which calculates travel time from defined point and/or linear locations to other locations within a user-defined area of interest. The TTCSM is designed to model travel time in national park units using readily available geospatial products such as road, trail, and stream networks, digital elevation models and land cover data. Outputs from the TTCSM are point-to-point specific travel time least cost paths (i.e. the modeled fastest path(s)) and raster maps in which each cell value is the modeled time required to reach the given cell from the specified starting point(s).

In order to derive accurate travel time estimates, the TTCSM is intended to be dynamic in nature with the ability to accommodate user (e.g., hiker, backpacker), temporal (e.g., winter / summer data collection) and park specific conditions. The essence of the TTCSM is deriving a meaningful travel cost surface. Travel cost is a function of the user-defined and derived cost and speed surfaces. The cost surface defines the weight or impedance of traveling through a cell, while the speed surface defines the speed at which movement within the cell occurs. Speed is a function of the user-defined average walking speed and slope, except on the road network where speed is equal to the defined road speed limit. Using the derived travel cost surface, travel time calculations are performed using either traditional cost distance or more robust path distance modeling methods.

The TTCSM is intended to be used as a tool to facilitate more efficient field data sampling design and planning.

Acknowledgements

The TTCSM described herein has been a result of iterative model development and refinement from the cumulative efforts of numerous individuals. In addition to the authors listed on this document we would like to acknowledge the contributions of Courtney Hurst, David Pillmore, Billy Schweiger, Colin Talbert, Stephani Schupbach, and Paul Martin.

1. Introduction

The purpose of the Travel Time Cost Surface Model (TTCSM) is to use readily available, or easily obtainable, geospatial products in conjunction with cost distance modeling techniques in a geographic information system for the purpose of modeling expected travel time from a desired location(s) to other location(s) within the defined area of interest. The TTCSM is intended to be used as a tool to help NPS staff be more efficient and effective at travel planning efforts. An essential component of this model is the ability for the user to optimize the model in order to accurately represent their user-specific needs and environments at a localized park unit scale.

This document is divided into a number of sections. Section 2 provides a safety disclaimer which is mandatory to read prior to using this model. Section 3 describes the model logic while Section 4 describes how to run the model in ArcMap. Section 5 provides additional information on each of the model configurations. Section 6 includes a working example that demonstrates analysis of the data included with this model.

2. Safety and Disclaimer

Be aware that TTCSM is a very simplified model of reality. There are many factors that contribute to the realized travel speed which are not accounted for in this model. Furthermore, the model makes numerous assumptions which may not necessarily apply to each situation. Additionally, if the user does not appropriately assign Percent of Maximum Travel Speed (PMTS) values the TTCSM model can potentially provide a route that would put travel party members in danger. Use common sense and local knowledge to evaluate safety risks within the area of interest and adjust the model inputs accordingly to eliminate or mitigate potentially dangerous areas.

3. Model Logic

The foundation of the TTCSM is the assumption that a person will optimize their means and rate of travel to arrive at a destination in the shortest possible time. When possible, a person will favor motorized travel (e.g, cars on roads) over walking. Additionally, a person will drive at the maximum allowable velocity (i.e, at the defined speed limit) and walk at the maximum rate physically possible, indefinitely.

Motorized speed is defined solely by the speed limits of the respective road network. In contrast, foot travel depends both on the physical condition of the person and on the slope over which they are walking. Longer legs, optimal fitness, and a good set of shoes will all increase average walking speed. In areas relatively flat, velocity will match the average walking speed. However, as the slope increases, walking velocity decreases nonlinearly, following the defined equation:

$$6 * EXP\left(-3.5 * ABS\left(TAN\left(\frac{Slope}{57.29578}\right) + 0.05\right)\right).$$

where slope is in degrees (Theobald, 2010; Tobler 1993). Walking rate can further be influenced by the quality of the walking surface and the relative resistance it presents. For instance, a person may walk 80% of normal speed along a rough trail. Likewise, in densely vegetated areas, walking rate may be reduced to an even smaller fraction of normal walking speed.

From this foundation the model is set up to define four factors which influence a person traveling. These factors are listed in order of preference, which accounts both for travel means and rate.

The first factor is motorized travel, which will most frequently be, although is not limited to, the automobile. Motorized travel is preferable because velocity is unaffected by the slope of the landscape; motorized travel up a hill is the same as motorized travel down. The second assumption is that motorized travel is faster than a person walking. While not the case in extremely congested areas over small extents, this assumption generally holds.

When not using motorized assistance, people will follow defined trails and paths. These paths are generally easier to navigate because the surface is smoother than the surrounding geography and paths often traverse steep slopes at angles which make foot travel easier. Paths crossing rivers will have bridges or the water will be shallow enough to permit safe navigation. In summary, travel along a trail is determined by the slope of the trail and any further resistance

provided by the trail where it is rough or muddy.

If a trail is not present, a person will walk cross-country and travel will be impeded. Travel is determined by the slope of the surface and any resistance provided by surface characteristics, including the type of landcover and vegetation density.

Finally, a person will completely avoid some areas because they are barriers to travel. Lakes and rivers are often too unsafe or impossible to cross. Likewise, steep slopes are either too physically demanding and/or too dangerous for travel.

Over an entire area of analysis, each of the four components may contribute to the rate of travel. From the starting point(s), travel time aggregates based on the speed of the traveler.

The next section discusses the required information to adequately model each component in the TTCSM.

4. Using the TTCSM Model

This section provides a quick overview of how to use the model. Further information on each of the model arguments is provided in section three.

The following are mandatory requirements for running TTCSM:

- You must have ArcGIS 10.2 with the Spatial Analyst license checked out and enabled.
- All data must be in the same projection (preferably UTM); the projection type must not be geographic.
- All of the DEM dimensions must be in the same units. In other words, X, Y, and Z dimensions should be the same (preferably meters).

To run successfully, TTCSM requires the specification of seven items. The first three are inputs, the fourth is the grid to create, and the last three are defaults:

- **Workspace – This is where all of the calculations and temporary files will be created. It is recommended that this be a folder which is preferably empty to begin with and does not contain any other critical information that should not be overwritten or removed.**
- **Start Locations – One or more start locations must be specified, either as points or polylines.**
- **DEM – The digital elevation model (DEM) is a grid that defines the extent and resolution of the analysis. Therefore, the extent of the DEM should be equal to or greater than all other layers used and ideally be high enough resolution (i.e., small grid size) to adequately represent the underlying terrain.**
- **Cost Distance Grid to Create – This is the name of the cost distance grid you wish to create. This grid shows the total travel time (in seconds) to every location with the area defined by the DEM.**
- **Normal Walking Speed (mph) – The normal walking velocity of the person on a flat, smooth surface. If the person is wearing gear, the speed should be reduced accordingly. The default is 3.1 mph.**
- **Maximum Travel Time (seconds) – This sets a travel cap to where times greater than this value will be displayed as No Value. The default is 28800 seconds, or six hours.**

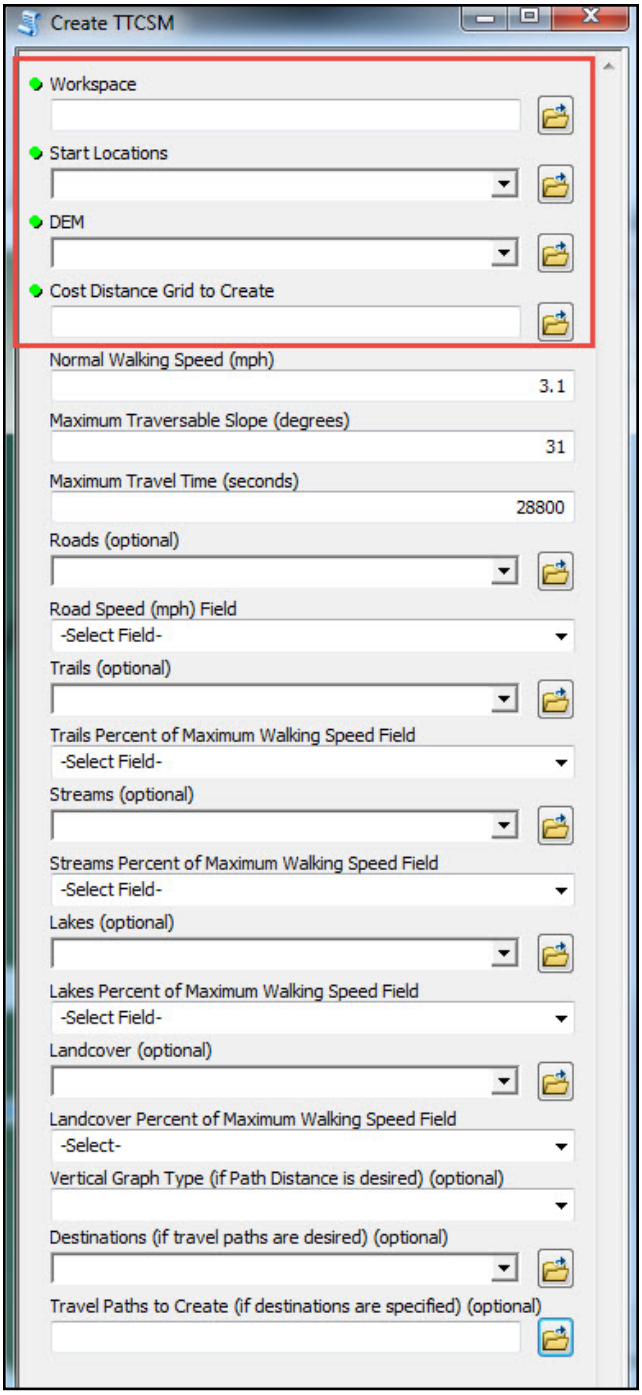


Figure 1. Screen shot showing TTCSM user interface

- **Maximum Traversable Slope (degrees) – Defines when slope becomes an absolute barrier to travel. The default is 31 degrees.**

TTCSM can further be refined by adding additional layers of information or requesting variations in the analysis. If used for the model; trails, streams, lakes, and land cover should have a float field within their attribute table designating PMTS values (decimal values between 0.00 and 1.00). A value of 0.00 indicates a complete barrier, or 0% of normal walking speed. Likewise, a value 1.00 indicates no barrier, or 100% of normal walking speed.

One or more of the following data layers can optionally be added:

- **Roads - Roads should be a polyline feature with each segment defining the travel speed in miles per hour (mph) designated within a specific float field such as "Speedmph". In general, the specified speed will be the speed limit although this speed could be modified to account for rough roads, bad driving conditions, or overloaded vehicles.**
- **Trails – Trails should be a polyline feature with a field defining feature segment PMTS.**
- **Streams – Streams should be a polyline feature with a field defining feature segment PMTS.**
- **Lakes – Lakes should be a polygon feature with a field defining polygon PMTS.**
- **Landcover - Landcover should be a polygon feature with a field defining polygon PMTS.**

For more advanced users, the following may also be specified:

- **Vertical Graph Type – These are advanced algorithms to accommodate differences in travel speed between upslope and downslope. If a vertical graph type is not selected, model assumes the same slope-derived velocity.**
- **Destinations – If you want to define a set of optimized travel paths, you will need to provide a set of destinations. Destinations can be one or more points defined in a feature class.**
- **Travel Paths to Create - If you want to define a set of optimized travel paths, you will also need to specify the name of the file to create.**

Do not rely on the PMTS in cases where safety may be compromised. Values should be carefully evaluated for each situation, tailored to your needs, and confirmed in the field.

5. Further Guidance and Information for Each of the Model Arguments

Workspace

It is best to pick an empty folder on your local computer since a number of temporary files will be created and files will be over-written as needed.

After running the model you may delete the scratch folder.

Start Locations

If you are using a roads layer, start locations should be located at the roads. If not, when the model encounters a road, it will assume the person can immediately hitch-hike and travel at the specified road speed limit.

Digital Elevation Model

DEMs should be in either feet or meters. Any other unit will fail. Meters are preferable to feet because there are fewer required calculations, which will increase performance.

You will need to strike a balance between DEM resolution and performance. Certainly, the higher resolution the DEM, the more detail it provides of the landscape. However, processing time will increase exponentially as a result.

If the DEM is unimportant to the analysis, which is the case if the only means of travel is motorized, a flat gridded surface may be substituted; analysis will occur at the dimensions of the flat grid cells.

Percent of Maximum Travel Speed

Percent of maximum travel time (PMTS) is defined as the percentage of maximum speed when compared to a travel time while walking on a level, hard and extremely smooth path. As Table 1 shows, travel time increases exponentially as the relative PMTS approaches zero (Table 1).

Table 1. PMTS versus travel time

PMTS	Travel Time Units (e.g., Minutes)
100	1.0
95	1.1
90	1.1
80	1.3
50	2.0
20	5.0
10	10.0
5	20.0
0	Infinite

Perhaps the most difficult step in preparing the data is deciding what relative speed to assign. We recommend that you start with relative speeds and hone the precision through time. For example, trails will have a relatively high PMTS compared to dense shrubs; Tundra is certainly easier to walk on that wetlands. As you refine the values, the key to successful assignment is to utilize the cumulative knowledge and experience available from you and other staff members within your park. Keep in mind that PMTS values for the model must be represented as a decimal (simply divide PMTS by 100).

Cost Distance Grid to Create

By default, TTCSM uses the ESRI Cost Distance method to calculate travel time (http://resources.arcgis.com/en/help/main/10.2/index.html#//009z00000018000000). From each starting point, cost distance calculates the least accumulated cost to move. Cost in this case is defined as the time, measured in total seconds, required to walk across a unit of area (i.e., single grid cell of the DEM). Thus, as one moves away from the starting points, the total time required aggregates by the value of each respective cell.

Maximum Walking Speed

The average walking speed of a person is approximately 3.1 mph (http://en.wikipedia.org/wiki/Walking). Walking rate, however, may vary greatly depending on the physical condition of the person, including their height and fitness level. Furthermore, what clothes they are wearing and what gear they are carrying should also be factored in.

Be aware that the model does not account for changes in speed due to fatigue. Thus, walking speed is the same regardless of whether someone has been walking 10 minutes or 10 hours.

Maximum Slope

A maximum slope can be defined in order to specify a value above which a hillside is considered a cliff and functions as an absolute barrier to travel. The model default is 31 degrees, the maximum generally considered safe for roofers (http://roofgenius.com/Roof-Info/WalkRoofPitch.asp) and is further supported by Kinsella-Shaw, Shaw and Turvey (1992). Of course, what can be traversed safely will also depend on the type of land cover, the hiking experience and physi-

cal condition of the person, and the amount of gear they are carrying.

Maximum Travel Time (seconds)

Setting a maximum travel time is useful when presenting/viewing the cost surface grid. If you have exceptionally long travel times, they can skew the color mapping. Furthermore, analyses will not take as long since they will terminate at the maximum specified travel time.

Areas above the maximum travel time are set to Null/NoData.

Roads

Be aware that the model does not have a concept of parking lots or parking tickets. Thus, travel can switch from roads to walking at any location.

Roads are never masked if the slope of the surrounding hillside exceeds the maximum slope value.

There is currently no ability to discern differences in travel time due to one-way roads. In other words, one-way roads are treated as two-way.

Trails

Where a trail exists, the slope and resulting travel speed is calculated to follow the contour of the trail, which is typically less than the slope of the underlying hillside.

The model assumes that trails are always walkable (unless a PMTS of zero is specified!). Therefore, in cases where the trail slope is calculated to be unusually steep, which is often a result of the resolution of the DEM, the model will cap it to the maximum allowable slope specified when running the model. For example, if the model is run using the default maximum slope of 31 degrees, trail slopes will be capped to never be more than 31 degrees.

Adding PMTS field and values can accommodate walking resistance factors such as mud, rocks, loose gravel and snags which can slow walking if detailed trail data or knowledge is available.

Streams

For streams (and rivers), the Strahler (or Shreves) stream order provides a consistent and simple means of assigning PMTS. Table 2 gives an example Strahler stream order and the assigned PMTS. Local stream/river conditions should be accounted for in the assigned PMTS, such as high water because of spring runoff and large weather events. The mobility of travel party should also be accounted for by the user. Stream/river segments too dangerous to be safely crossed should be assigned a PMTS model input value of 0.0.

Table 2. Stream order and corresponding PMTS.

Strahler Order	PMTS (% of normal)	PMTS model input value
1	70	0.7
2	60	0.6
3	50	0.5
4	30	0.3
5	20	0.2
6	10	0.1

Lakes

Unless boats or other watercraft are available to transport field crew across lakes, it is recommended to assign lakes as an absolute barrier to travel (i.e., PMTS = 0).

Land Cover

There are a number of potential land cover data sets that can be used, including the National Land Cover Dataset (NLCD 1992), GAP data (GAP 2006), or a local park vegetation map.

The land cover data will need to be attributed with an appropriate PMTS for each land cover class. Table 3 provides an example NLCD PMTS assignment. If land cover data is in raster format, convert it to a

Table 3. Example PMTS (% of normal) for NLCD cover classes

NLCD Cover Class	PMTS (% of normal)	PMTS model input value
Open Water	0	0.0
Perennial Ice/Snow	15	0.15
Developed, Open Space	90	0.9
Developed, Medium Intensity	90	0.9
Developed, High Intensity	95	0.95
Barren Land	10	0.1
Deciduous Forest	70	0.7
Evergreen Forest	65	0.65
Mixed Forest	75	0.75
Dwarf/Scrub	75	0.75
Shrub/Scrub	75	0.75
Grassland/Herbaceous	80	0.8
Pasture/Hay	80	0.8
Cultivated Crops	80	0.8
Woody Wetlands	20	0.2
Emergent Herbaceous Wetlands	25	0.25

polygon with "Raster to Polygon", choosing the land cover class name as the field, do not simplify polygons. Add a float field named "PMTS" to the resulting land cover polygon attribute table and populate the PMTS field for each land cover class with an appropriate value of 0.00 to 1.00. (Where 0.00 indicates a complete barrier or 0% of normal walking speed and a value 1.00 indicates no barrier, or 100% of normal walking speed.) If the land cover also represents water bodies, it will be important to understand how it overlaps with the any other water layers being provided. In cases where there is not overlap (i.e. the same water body is represented in two different locations), water may be over-represented.

Vertical Graph Type

By selecting a vertical graph type, you are opting to use the ESRI Path Distance method, a more complex and potentially more realistic method of calculating travel time distance (http://resources.arcgis.com/en/help/main/10.2/index.html#//009z0000001q000000). Path distance approximates the surface distance that must be traveled in the vertical and horizontal[1] directions.

The TTCSM tool has nine predefined VFGs. These include:

- Binary
- Linear
- Symmetrical Linear
- Inverse Linear
- Symmetrical Inverse Linear
- Cosine
- Secant
- Cosine-Secant
- Secant-Cosine

See ESRI overview for more background on these VGFs.

Once you are comfortable with TTCSM, we recommend you use this option since it should provide more realistic estimates of walking speed based on direction.

Destinations

Travel time least cost paths can be derived from the start point to each specified location in the "destinations" data layer.

If your destinations are unreachable, TTCSM will fail. Destinations may be unreachable if:

- They are beyond the maximum travel time cap
- There is an impassible barrier between the starting points and destinations (e.g., water bodies, steep mountains, etc.)
- Your destinations are outside the extent of the DEM

Travel Paths to Create

The least cost path spatially shows the optimal modeled path (least cost) to each destination from the closest starting point.

[1] Note: while Path Distance can calculate the horizontal factor as well, currently, TTCSM only calculates the vertical factor using the DEM as the vertical factor raster.

6. Vector to Raster Conversion Priority Logic

TTCSM allows for several input layers to be provided as a vector data type (roads, trails, streams, land cover, and lakes). However all of the calculations that the TTCSM has to complete occur within raster data types. Therefore all of the input vector data layers must be converted from vector to raster. Depending upon the DEM resolution and the cell alignment with vector features, it is possible to have more than one unique feature within a single cell. This presents a problem with our linear input layers (roads, trails, streams) that can cause significant effects to the resulting travel time model. For example if you have a single cell that is dominated with 25 mph road features but also contains a highway at 55 mph, its raster representation would be a 25 mph cell. This is not optimal because it will truncate travel times at that cell to 25 mph when it would realistically be an artery of travel because of the presence of the highway. To control for this effect we use the polyline to raster tool in ArcGIS with a priority field. Priority logic for each linear layer is broken down below:

1. Roads: priority is given to higher speed roads to prevent lower speed roads from truncating higher speed roads.
2. Trails: priority is given to higher PMTS (less resistant) trails to prevent lower PMTS (more resistant) trails from creating barriers to travel and trail junctions.
3. Streams: priority is given to lower PMTS (more resistant) streams to prevent higher PMTS (less resistant) streams from creating artificial less resistant points at stream confluence points.

7. Working Example

Included with this model is some sample data to ensure TTCSM is working correctly, become acquainted with the model, and understand how the source information needs to be set up.

For this example, we will follow a scenario frequently encountered in national parks. You need to dispatch a park ranger to access four remotes site but are unsure of:

1. What is the optimal starting location? There are currently two ranger stations (A and B) on each side of the park; which station should you dispatch from?
2. Where should the ranger park their vehicle and begin hiking?
3. What is the preferable walking path to take to keep to trails, when possible, and avoid steep areas and other difficult terrain? Is it faster to walk directly to the site by wading over the stream or is it faster to drive a vehicle and then hike?
4. What is the estimated time it will take to reach the site?

Figure 2 shows a map of the hypothetical area. Vegetation cover has been shaded to reflect the density of vegetation where darker areas represent denser, and therefore more difficult to travel through, vegetation.

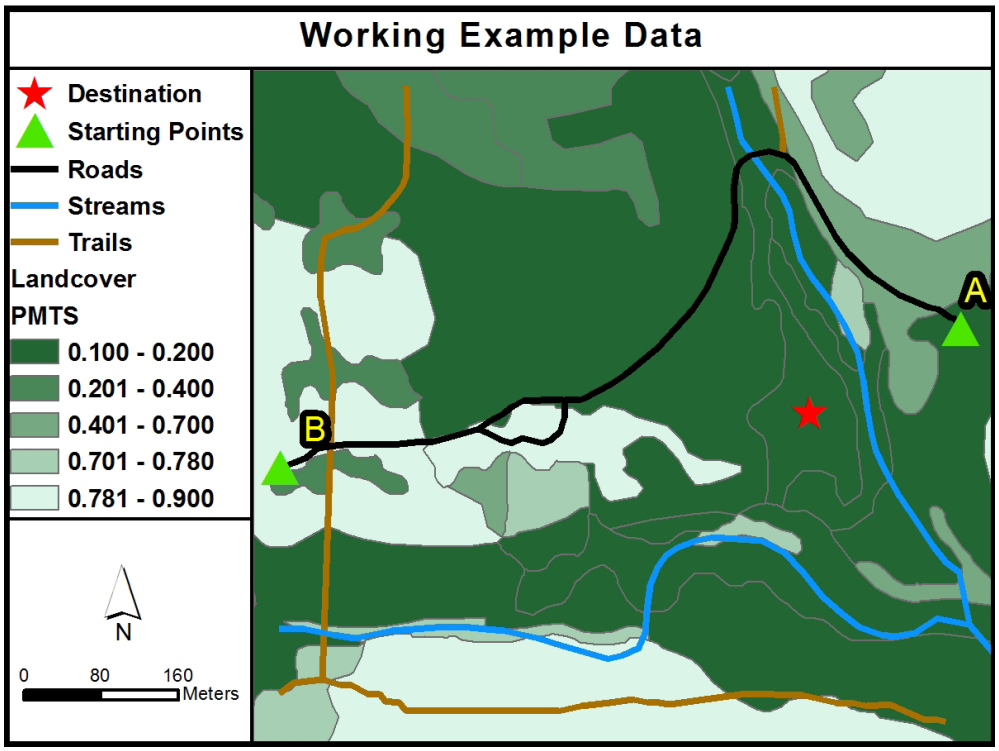


Figure 2. Working example data layers

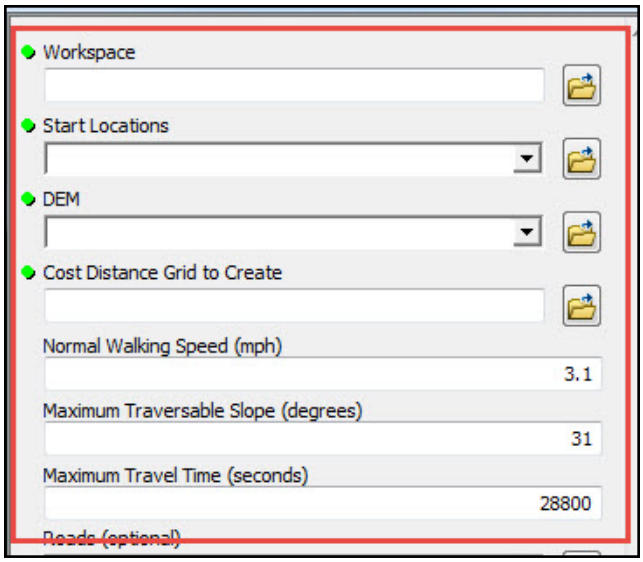


Figure 3. Close up screen shot showing TTCSM user interface

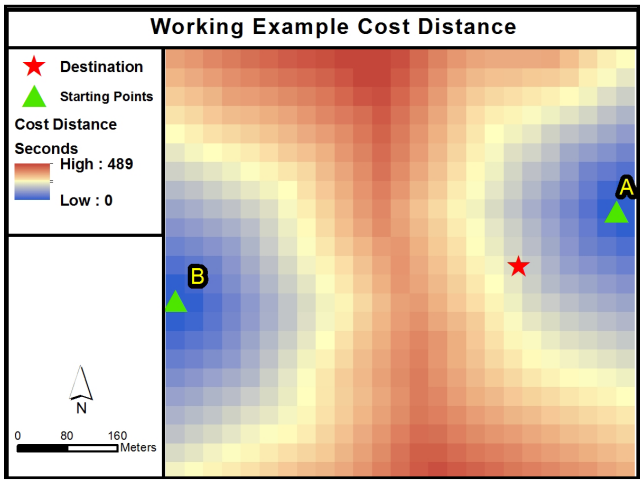


Figure 4. Cost distance result for DEM input.

To start with, we can run the model using the minimum requirements, giving us the accumulated travel time from the start locations over the surface. We will also choose the default walking speed (3.1 mph), maximum slope (31 degrees), and travel time (28800 seconds = 6 hours) (Figure 3).

Because we are only using a DEM at this point, the surface offers no other barrier to travel except being somewhat steeper in some locations (Figure 4). Thus, the time required to access the trails generally radiates out from each of the two potential starting points (A and B). Certainly, if only topography were considered, Station A would be the logical dispatch point and require only 210 seconds to access.

Now, if we include all of the layers (i.e., roads, trails, stream and landcover) we get a much different surface with a significantly longer travel time (763 seconds) due to the travel resistance of the landscape (Figure 5).

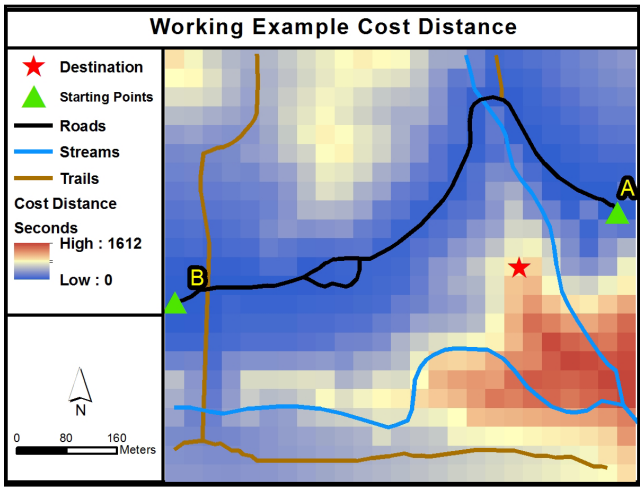


Figure 5. Cost distance result for DEM, roads, streams, and trails inputs.

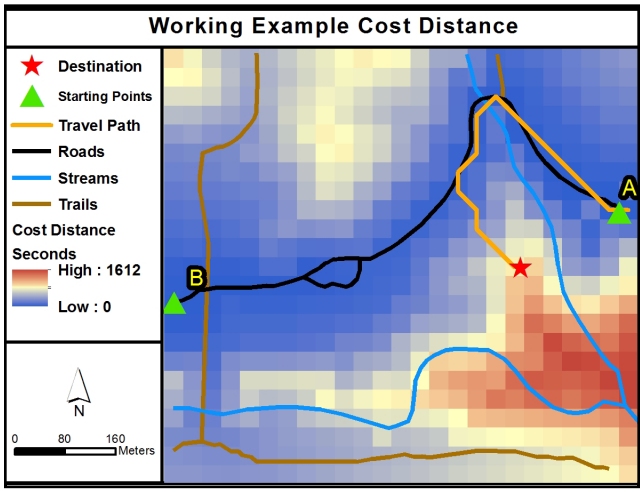


Figure 6. Cost distance and travel path results for DEM, roads, streams, and trails inputs.

If we run the model again and specify the exact destination (red star symbol), TTCSM will provide the optimal path, which in this case is from Ranger District A (Figure 6).

Considering optimal travel time, we can now recommend (*with the understanding that this is modeled information which may not accurately represent actual conditions*) that a ranger should be dispatched from Station A and follow the travel path presented above.

Note: depending on the resolution of the DEM, suggested travel paths may not match the underlying road/trail network precisely.

8. Sensitivity Analysis: Model Consistency

An underlying question with any analysis is how dependent the accuracy/reliability of model is on the resolution of the underlying data layers. For the same geographic extent, TTCSM processing time increases exponentially with improved resolution[2]. Therefore, there is the desire to find the optimal balance.

The resolution of analysis in TTCSM is determined entirely by the digital elevation model (DEM). One of the first steps in the model is to rasterize vector and resample vector layers (when different) to that resolution. Of particular concern is how the linear layers, especially roads and trails that have a direct bearing on all travel, might be affected by a selected resolution.

Thus, the first question we want to answer is:

- Is linear travel time sensitive to the resolution of the analysis?

An additional potential influence of resolution can occur with off trail travel time. Therefore a second question we want to answer is:

- Is off trail travel time sensitive to the resolution of the analysis?

8.1 Data and Analysis

Attempting to understand the effect of resolution on travel time, even when controlling for road travel only, is a challenge. Perhaps most difficult to account for is the road network itself. Except in dense western urban areas, roads are rarely a standard grid. Without an even grid network, road bottlenecks can easily influence overall travel time. These bottle-necks are likely to increase as the road density decreases where travelers have fewer options on how to reach specific destinations.

A second factor is the location of the destination. Additionally, the ultimate destination and where it is located within the road network in relation to the road network is a further complication.

To better understand the effect of resolution on travel time, we had to keep things as consistent as possible yet still be realistic. We decided against using the regular grid road network since it doesn't match the road patterns typically encountered around national parks. Therefore, we used the ESRI 2005 roads, which include highways, county roads, and local roads.

We opted to test for different types of parks that represent various landscapes (Table 4). Eleven NPS park unit travel time outputs were evaluated across three resolutions (30 meters, 90 meters, and 270 meters). The evaluated parks were chosen to represent different topographies and development levels to provide realistic results for users.

Table 4. Selected parks aggregated by landscape type.

Landscape Type	Selected Parks
Coastal	Acadia National Park, Point Reyes National Seashore
Desert/Canyon	Arches National Park, Badlands National Park, Mojave National Preserve
Suburban	Colonial National Historic Park, Cuyahoga Valley National Park, Prince William Forest Park
Alpine	Glacier National Park, Mount Rainier National Park, Rocky Mountain National Park

To separate out linear travel from off trail travel two travel models were created, one allowing travel along linear layers eliminating the effect of topography on results and one where the entire landscape is processed as "off trail" eliminating the effect of linear travel on results. For the linear travel time destination points, we selected 50 randomly distributed points along roads for each park. For the off trail travel time destination points, we selected 50 randomly distributed points across the landscape. These locations were sampled for travel time results at all three resolutions and 30 meters versus 90 meters and 90 meters versus 270 meters comparisons were made.

[2] Note: We confirm that the model follows the pattern of have an increased process time when the resolution/extent increase (results not presented).

Table 5. Park type percent change for road sampling.

PARK TYPE	MEAN PERCENT CHANGE 30m to 90m	MEAN PERCENT CHANGE 90m to 270m
Alpine	8.7	12.8
Desert/Canyon	3.5	8.0
Coastal	4.6	6.8
Suburban	4.4	7.3

Table 6. Park type percent change for off trail sampling with and without slope barriers.

PARK TYPE	MEAN PERCENT CHANGE NO Slope Barrier		MEAN PERCENT CHANGE 31% Slope Barrier	
	30m to 90m	90m to 270m	30m to 90m	90m to 270m
Alpine	2.0	2.1	3.9	2.1
Desert/Canyon	2.4	2.8	2.6	3.5
Coastal	1.1	2.0	1.1	2.1
Suburban	3.2	3.4	3.2	3.5

8.2 Results

Tables 5 and 6 present the mean percent change by park type for linear travel and off trail travel for the two resolution comparisons. Positive mean percent values report percent change as a decrease in travel time when comparing the finer resolution to the coarser (30m vs. 90m and 90m vs 270m). Linear travel time decreases as resolution becomes coarser for all park types. Off trail travel time also decreases as resolution becomes coarser for all park types, but not as significantly as linear travel.

8.3 Discussion

An explanation for decreased linear travel times is as resolution becomes coarser, roads that do not actually connect, become connected. This can occur if multiple road features exist in a single pixel but are not connected. When these road features are converted to raster the pixel both features occupy can only represent one feature and the two become effectively connected in their raster representation. This is visually presented in Figure 7 which shows a selected area within Mount Rainier National Park where tight switchback roads and near roads become connected at 90 and 270 meters. At 30 meter resolution this is much less likely to occur but still possible depending upon road density. This effect can be controlled choosing a resolution that minimizes this effect where road density is high.

An effect on off trail travel time when resampling a raster to coarser resolutions is the decreased distance traveled to reach a destination because least resistance paths become simpler (less changes of direction). This can be illustrated in Figure 8 where three least resistance paths are displayed with each other over a 270 meter DEM. Notice how the complexity of the path increases as the resolution becomes finer. This is mirrored in the distance each path covers to reach the destination: 30 meter traveled 9,374 meters, 90 meter traveled 8,948 meters, and 270 meter traveled 8,532 meters.

Off trail travel time decreasing as resolution becomes

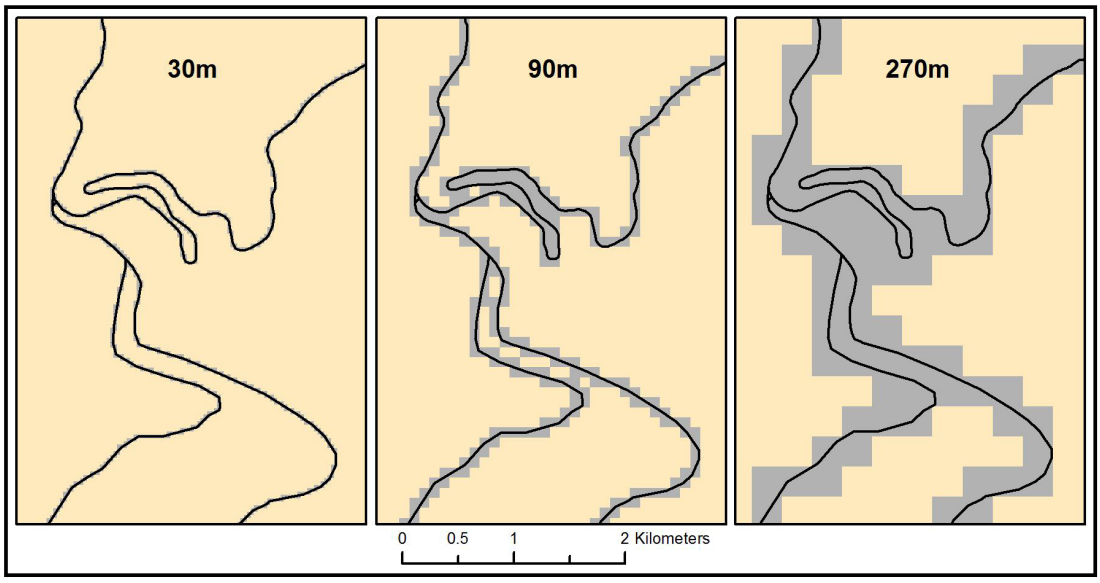


Figure 7. Mount Rainier National Park example of road vector conversion to raster at 30, 90, and 270 meters.

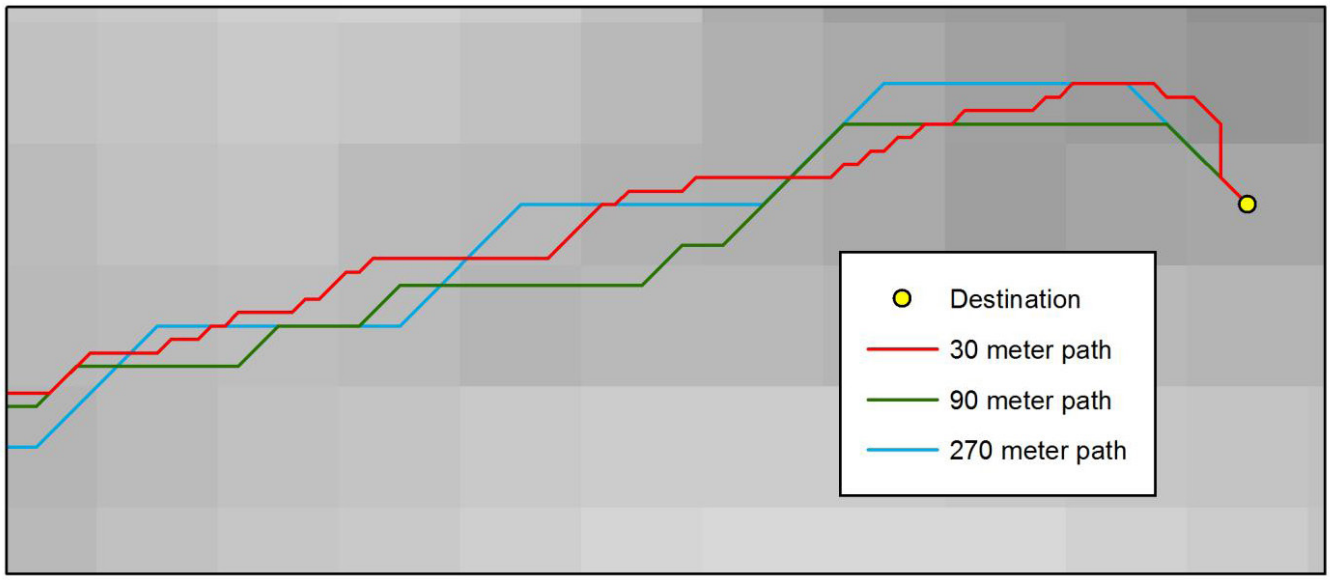


Figure 8. Raster resolution path differences.

coarser can also be potentially explained by several effects of resampling to a coarser resolution. Resampling from 30 meters to 90 meters and 30 meters to 270 meters causes smoothing of the DEM, this is most apparent in diverse or rough topography. Thus off trail travel times would decrease as a result of smoothing in these areas. Smoothing will cause slope barriers created by the "Maximum Traversable Slope" parameter to exist in a model based on 30 meter data but not at coarser resolutions, therefore decreasing off trail travel if less barriers exist. This effect was logically apparent in the results for Alpine parks as well as Arches National Park. Figure 9 shows this effect of smoothing upon slope barriers in Rocky Mountain National Park by comparing travel time outputs where orange represents no data because of slope greater than 31 degrees. There is clear decrease in barriers leading to more connectedness of the landscape. Though not seen in the reported results because they are averages across similar landscape types, there were sample points in Alpine parks that saw up to a 40% decrease in travel time because of slope barrier elimination at coarser resolutions. However it was also observed that slope barriers can exist at coarser resolutions but not at 30 meters because of how raster pixels are oriented on the landscape. This can explain why some sample points resulted in longer travel times in parks with high slope areas at coarser resolutions.

The discussed differences in TTCSM results display the need for the user to make well informed decisions

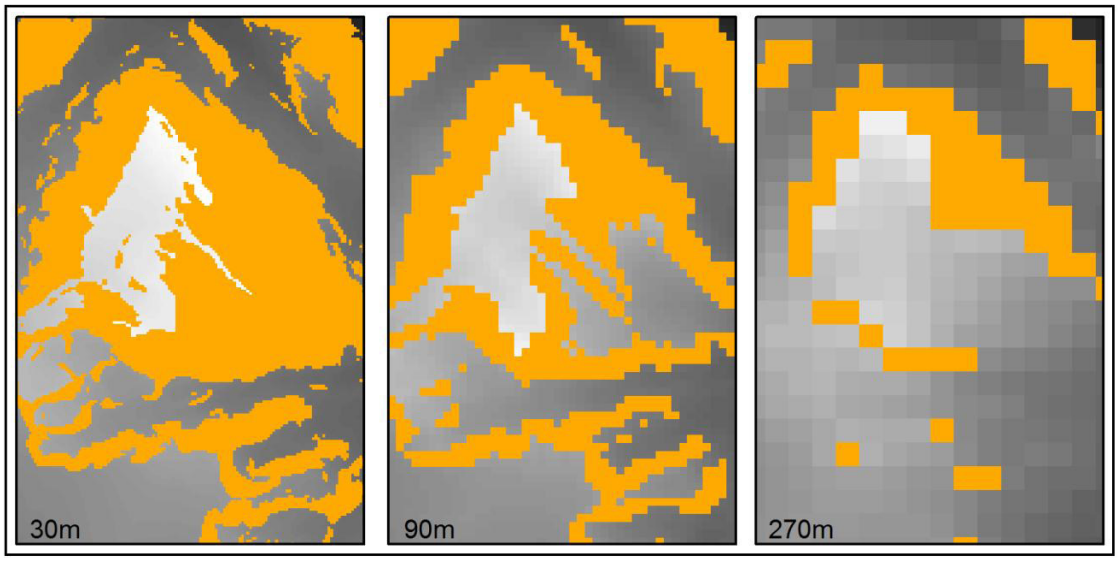


Figure 9. Rocky Mountain National Park example of slope barriers (slope greater than 31 degrees) that result in No Data pixels (orange) in travel time model results.

about what DEM resolution to choose based on their area of interest. Linear vector layers can be significantly affected by coarse resolution representation, creating connectedness that does not exist and decreasing travel time results. This can be controlled by using appropriate resolution data for your road and trail networks that minimizes this effect. If a selected area's topography is the most significant parameter in travel planning and slope barriers are a concern the finest available resolution data should be used. On the contrary if an area of interest is on the majority flat or topographic change is gradual a coarser resolution my yield similar results.

A potential input layer that was not examined for resolution change is land cover. Depending upon a land cover layer's complexity/detail it could experience significant change/loss of detail as resolution becomes coarser and should also be considered when choosing the DEM resolution for the model if it is an input into your travel time model.

All of the test results emphasizes that local knowledge of the area being modeled is paramount when making decisions about DEM resolution. The user must ask themselves how will their vector input layers (roads, trails, streams, and land cover) be represented as a raster at the DEM resolution and how well does the DEM resolution represent the complexity of the topography. If any terminology or statements made about resolution selection are unclear, seek out a GIS expert or contact the authors of this report for guidance.

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