Optimizing Wilderness Search and Rescue: A Bayesian GIS Analysis

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Abstract

Wilderness search and rescue operations function under critical time pressures and resource constraints. For optimal deployment, personnel must be assigned to prioritized search areas following some form of probability map. Incident commanders often have to generate such maps from different sources of information, some of which may be incomplete or imperfect. Here, we use a case study of the search for a lost person in Joshua Tree National Park in Southern California to illustrate how various types of evidence – previous search tracks and a cell phone tower ping – can be integrated, using Bayes' theorem, into an optimal probability search map.

KEY WORDS: *Wilderness Search and Rescue, Lost Persons, Bayesian Analysis, Resource Optimization*

Introduction

Wilderness search and rescue efforts regularly operate under critical time pressures and resource constraints. The risk of death due to exposure or thirst makes it vital to find the lost person as quickly as possible. It is therefore essential that personnel be deployed in the most effective and efficient manner possible. To prioritize search areas, incident commanders must generate probability maps from various sources of information, some of which may be incomplete or imperfect.

Here, we use a cold case study involving the search for a lost person in Joshua Tree National Park in Southern California to illustrate how various types of evidence can be combined into an optimal probability assessment. Prior search tracks, the location of a cell phone tower pinged by the subject's mobile phone, the distance range of that ping, and a viewshed analysis based on terrain altitude were geocoded using a geographic information system (GIS). These various data sources were then integrated in a Bayesian analysis to create a probability map for follow-up search efforts.

Literature Review

Wilderness search and rescue (WiSAR) operations often have to function in large areas with limited resources. An incident commander must therefore rely on a distribution map showing the most likely locations in which to find the missing person in order to efficiently allocate resources, direct search efforts, and coordinate rescue workers (Lin & Goodrich, 2010). Bayes' theorem provides a means for generating such probability maps (Eddy, 2004). Thomas Bayes was an 18th-century English statistician and minister who formulated a theorem describing how to update beliefs when new evidence arises (Iversen, 1984). The equation is:

$$P(A|B) = \frac{P(B|A)\,P(A)}{P(B)}$$

where: $P(A|B)$ is the conditional probability of event *A* given event *B*;
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$P(A)$ is the probability of event *A*; and
$P(B)$ is the probability of event *B*.

Bayesian models are well suited for prioritization analyses. A search region can be divided up into thousands of grid cells, each of which is assigned a probability based on how likely the missing person will be in that location. This *prior* probability, while initially equal over the entire search area, is then adjusted up or down depending on the presence of various attributes ("new evidence") in the grid cell, to create the *posterior*. Some examples of such evidence include proximity from origin or destination, slope incline, density of vegetation, and the location of a discarded water bottle. GIS programs and modern laptop computing power allow for the rapid calculation of updated probabilities even in remote field settings.

Bayes' theorem has been applied in a number of search optimization tasks, including strategies to rescue lost ships (Richardson & Discenza, 1980), locate submarines (McGrayne, 2011; Richardson & Stone, 1971), and find lost treasure (Stone, 1992). Lin and Goodrich (2010) modeled lost-person behavior in wilderness areas with a Bayesian approach using data on terrain features – topography type, vegetation, and local slope. Here, we use the locations of prior search tracks and radius data for a tower ping from the subject's mobile phone to prioritize areas for follow-up search efforts.

Case Study

William Ewasko was a 65-year-old businessman from Marietta, Georgia, who regularly hiked Joshua Tree National Park (JTNP) in Southern California (see Figure 1). On June 24, 2010, he went on a day hike in JTNP, planning to be finished around 5:00 pm. The first location on the planned itinerary he left with his fiancée was Carey's Castle, an ambitious hike for that time of year because of the heat (Mahood, 2012). While arguably not wild or remote, the 1,240 square mile (3,213 km^2) park can still be dangerous, with large rocks, deep canyons, and abandoned mine shafts (Manaugh, 2018). Ewasko was a strong hiker who navigated by map and compass rather than by GPS (global positioning system).

Figure 1: Joshua Tree National Park.

Ewasko failed to call his fiancée that evening; the next morning, park rangers checked the trailhead for Cary's Castle but found no sign of his rented car. They then checked the other locations on Ewasko's itinerary. On the afternoon of June 26th, a California Highway Patrol helicopter spotted his vehicle at the Juniper Flats Trailhead parking area, a common jumping off point for hikers heading to Quail Mountain, also listed on the itinerary.

The search focused on Quail Mountain and other areas reachable from this trailhead. Then, at 6:50 am, Sunday, June 27th, Ewasko's mobile phone registered ("pinged") with a cell phone tower on Serin Drive, Yucca Valley, just to the northwest of JTNP. This contact suggested he had traveled well beyond Quail Mountain. Searchers redeployed in response but were unable to find any trace of Ewasko.

The official search continued until July 5th and involved hundreds of personnel, search and rescue teams from all over Southern California, dogs, horses, helicopters, and a fixed-wing aircraft. A number of additional searches were later conducted by experienced volunteers with substantial training in search and rescue techniques and backcountry travel. While the first group of searchers focused on a common area, these later efforts covered several additional locations. JTNP management was supplied with electronic copies of the GPS tracks so the search file would contain a complete record. To date, there is a reported total of 1,772 person-miles (2,852 km) of search tracks.

The failure to find Ewasko was unexpected. JTNP is lightly forested and the terrain is fairly easy to survey. There are no remaining viable theories as to his whereabouts. People follow certain travel patterns and rarely move in a truly random manner (Koester, 2008; Robbins, 1977; Rossmo, 2000). What they do and where they go makes sense to them at the time (this is why people generally follow the easier option of walking downhill). Subjects who are not quickly found by search and rescue personnel have usually done something unanticipated, such as traveling further than estimated and leaving the designated search area. They may also head in an unexpected direction for reasons that, while logical to them, are not known to searchers. It is likely that something like this happened in the Ewasko case (Mahood, 2016).

Method

Bayes' theorem provides a method for combining different types of evidence to produce an optimal search strategy for WiSAR operations. The sources of available information employed in the Ewasko analysis include the areas that had already been searched, the location of the Serin Drive tower, the radius of the mobile phone ping, and terrain features that would have blocked cell phone coverage (Mahood, 2018). The mathematical details of our Bayesian analysis are provided in the Appendix.

The boundaries for the analysis are shown in Figure 2. This region was determined by such factors as the location where Ewasko's vehicle was recovered, park borders, roads and trails, maximum possible distance hiked, major terrain discontinuities, and other relevant features. The assumption here is that the region covers the entire area (within reason) where Ewasko might be located.

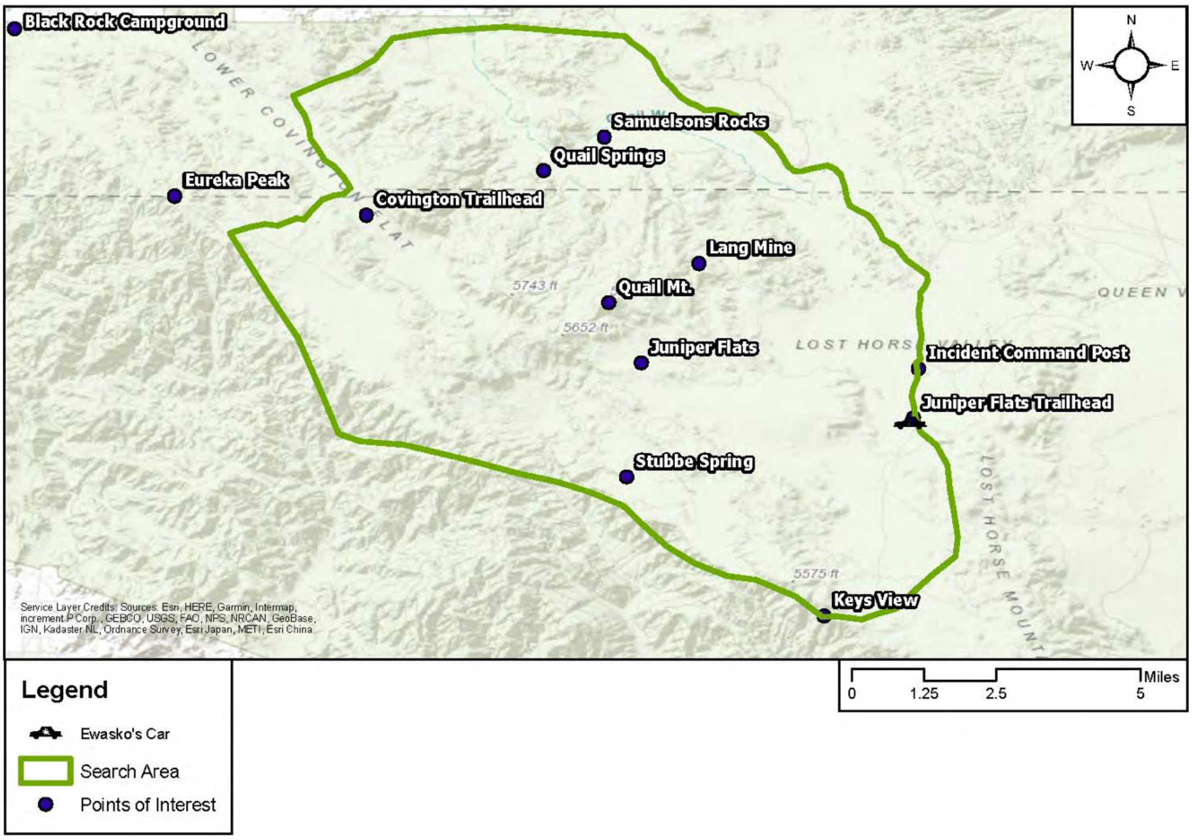

Figure 2: Search Area Boundaries for Bayesian Analysis

This region encompassed 184,857 grid cells, each 100 feet (30.5 m) by 100 feet, or 10,000 square feet (929 m^2), for a total area of approximately 66 square miles (172 km^2). The probability of each grid cell was adjusted based on the following evidence:

1. Search tracks: The JTNP master file contains electronic GPS tracks for the official and volunteer searches for Ewasko (see Figure 3). These were downloaded into ArcGIS so the length of any search track(s) in a given grid cell could be determined. The tracks were given a 50-foot (15.2 m) buffer radius, representing a conservative estimate of the range of a searcher's field of vision. The total length of the tracks was multiplied by 100 (the total buffer width, 50 feet + 50 feet) and divided by 10,000 (the grid cell area size, 100 feet x 100 feet) to give an estimate of the proportion of the grid cell area covered by the search. This value was then subtracted from 1 to calculate the grid cell probability. A search track through the exact middle of a grid cell would result in a probability of 0, while a search track through only a corner would produce a proportionately higher probability. If a grid cell contained multiple search tracks, all were considered in the probability calculation. JTNP is close to both Los Angeles and Palm Springs, with millions of visitors annually, so areas immediately next to commonly used trails and roads were considered "cleared."

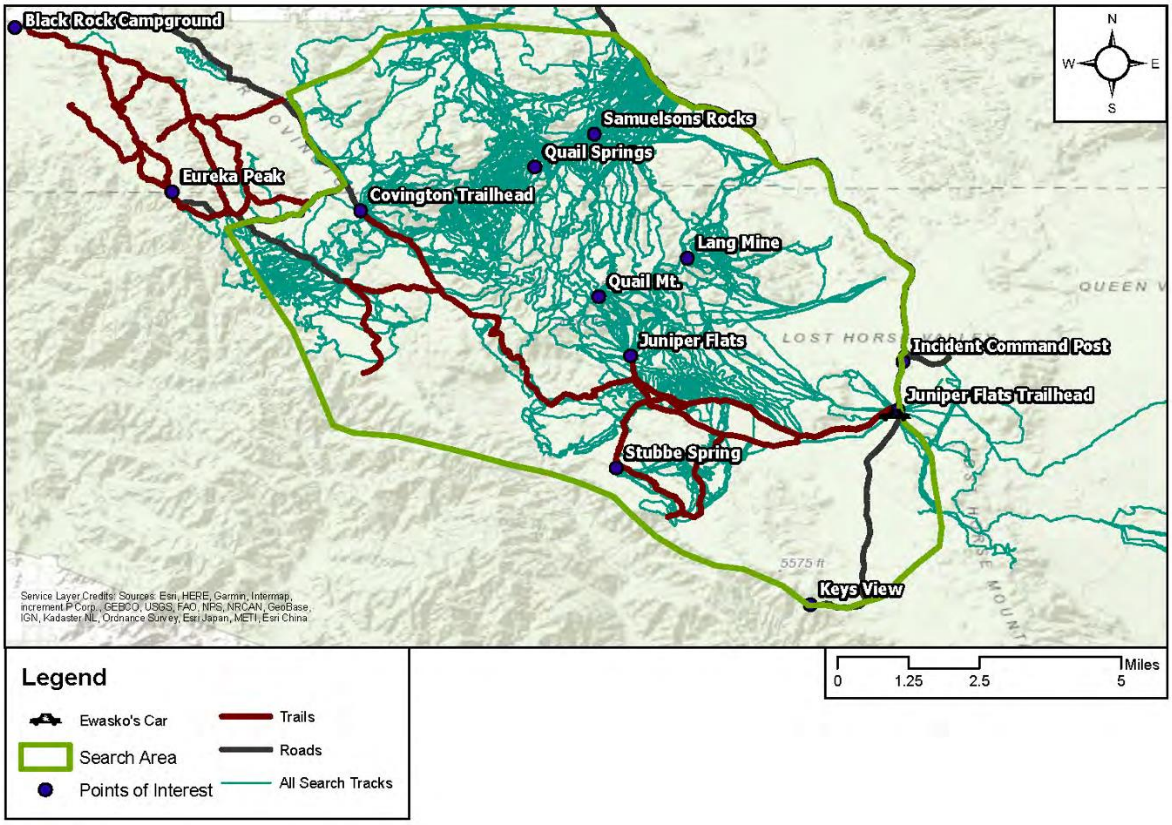

Figure 3: Search Tracks, Trails, and Roads

2. Distance from Serin Drive cell phone tower: The radial distance from Ewasko's Verizon mobile phone to the tower when it pinged was estimated to be 10.6 miles (17.1 km). As the exact position of the Serin Drive tower is known, the distance to a given grid cell can be readily calculated and the probability estimated from a Gaussian (normal) distribution. Bayes' model can handle "error rates" and analyze a band of possibilities (Blair & Rossmo, 2010). This tower was omnidirectional and not equipped to provide bearing data; however, based on the known facts of the case, the direction was almost certainly to the southeast. Figure 4 illustrates the range of the ping distance estimate. Figure 5 displays the southeast arc of the 10.6-mile probable distance radius from the Serin Drive cell phone tower (located off the map to the northwest).

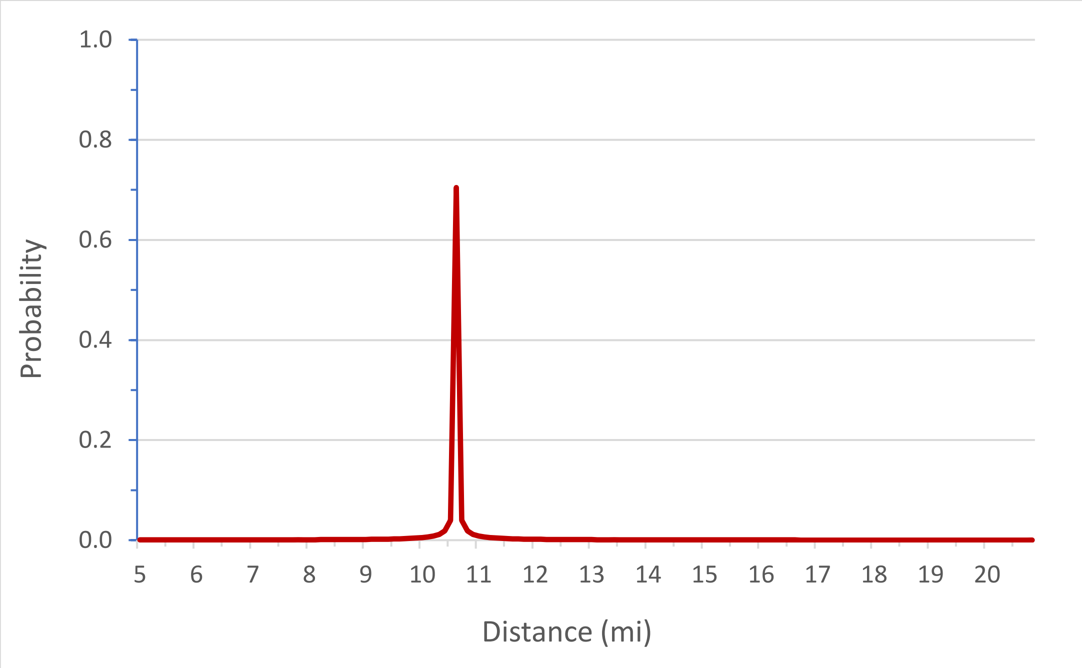

Figure 4: Probability of Distance from Serin Drive Cell Phone Tower

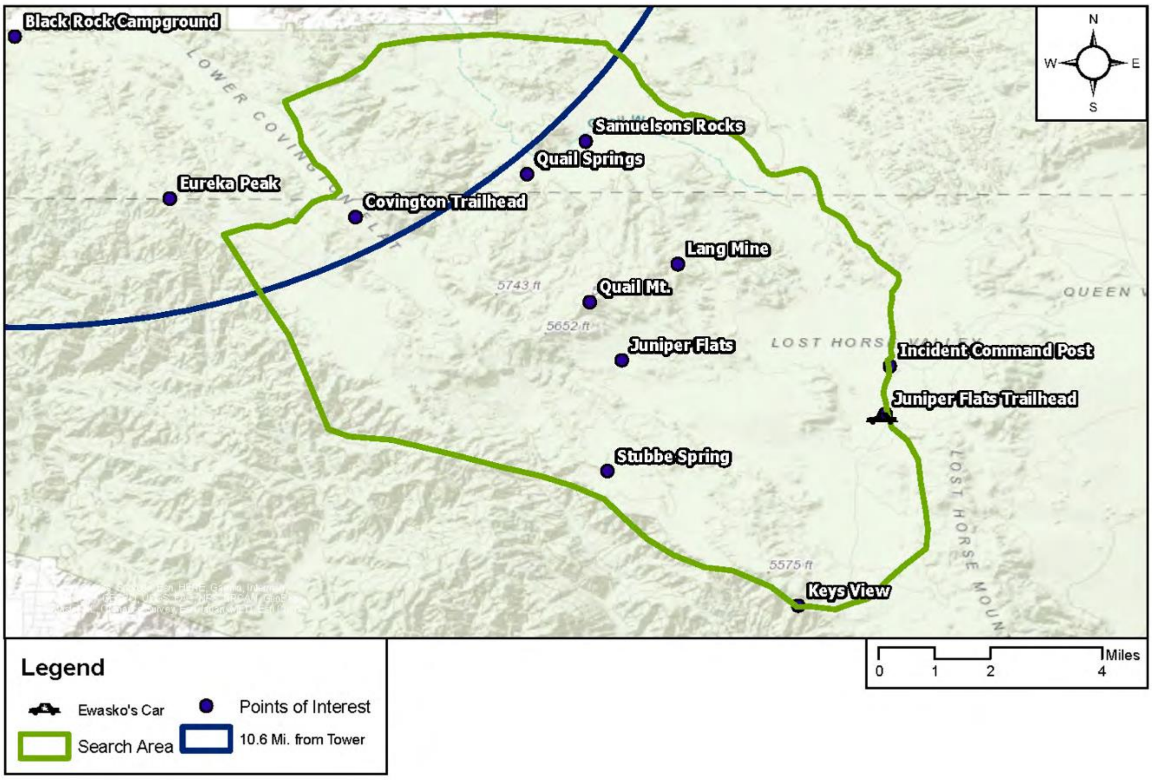

Figure 5: Southeast Arc of Serin Drive Cell Phone Tower 10.6-Mile Ping Radius

3. Viewshed: A viewshed analysis was calculated in ArcGIS against a digital elevation model (DEM) based on the U.S. Geological Survey National Elevation Dataset (NED). The resolution

for JTNP was one third arc-second (~10 meters). Locations from which the line of sight to the Serin Drive cell phone tower was blocked due to other terrain (i.e., impeding areas of higher altitude) were identified, and grid cell probabilities reduced accordingly. To be conservative, the height of the tower (100 feet, 30.5 m) was doubled in the analysis. Geodesic and planar methods produced similar results. Figure 6 shows the areas in the search region with cell phone coverage.

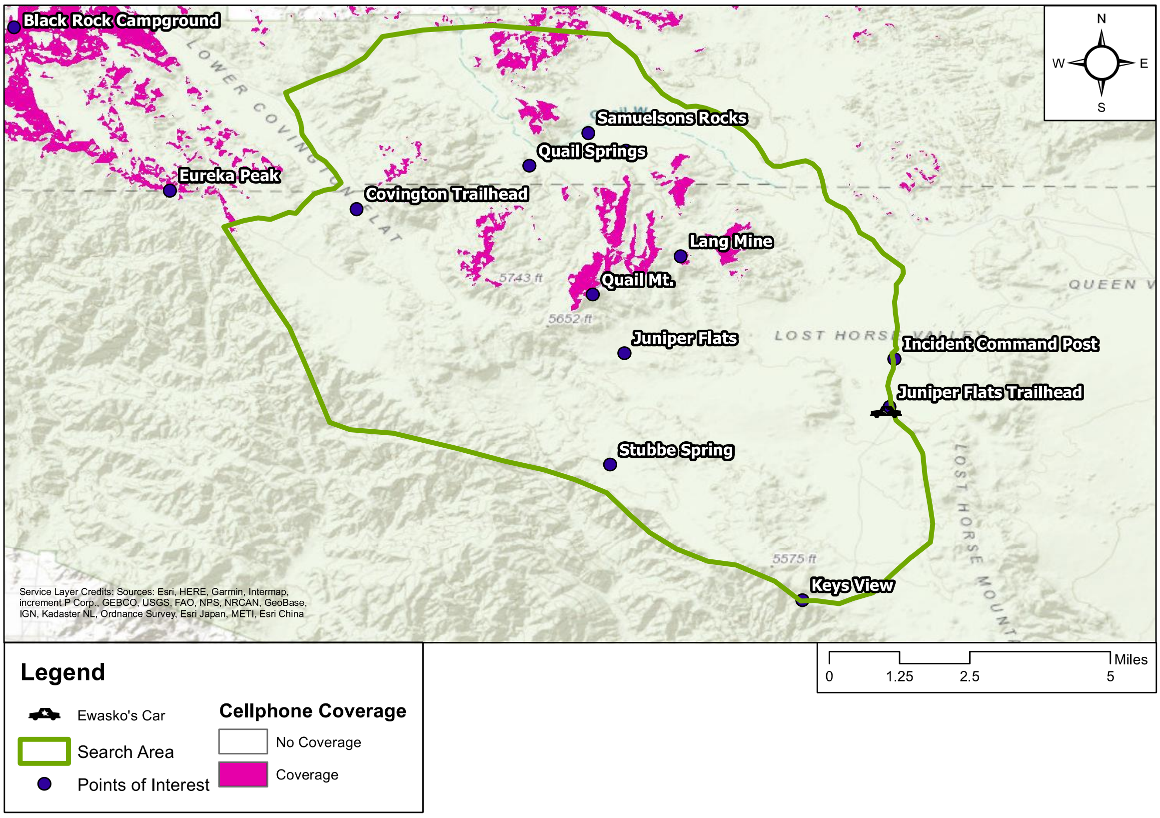

Figure 6: Areas with Cell Phone Coverage

Results

The optimal search map generated by our analysis is shown in Figure 7. Colors, ranging from blue to red, represent the various probabilities for finding Ewasko (the probability color scale in the legend lists relative numbers, not specific probabilities). The peak areas are all to the north of Quail Mountain and generally fall within a two-mile (3-km) radius of the now dry Quail Springs. These areas are not coterminous, but rather group roughly into seven different zones. The inset map depicts the zone of highest probability. These results could be further modified by such factors as a particular location's physical inaccessibility.

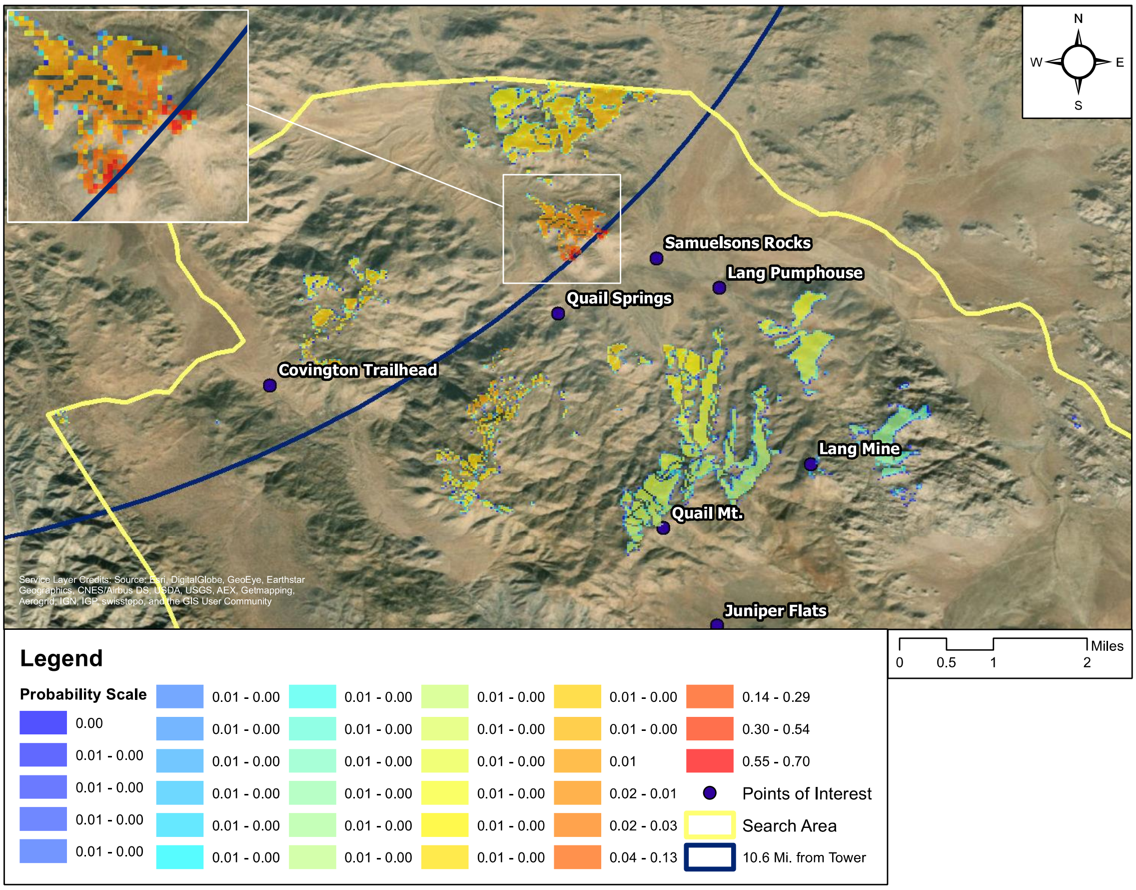

Figure 7: Optimal Probability Search Map

Optimal search areas, ranked by colour scale, shown in relationship to JTNP landmarks and 10.6-mile ping radius from Serin Drive cell phone tower. Inset box at upper left magnifies highest probability region.

Discussion

Incident commanders establish search priorities based on knowledge, experience, and local geography. Resources are reallocated accordingly when new information emerges and as areas are cleared. Here, we discuss how that process can be formalized using a Bayesian approach. Incorporating all available evidence reduces the chance of locations being overlooked even if their initial probability assessment was inaccurate (Lin & Goodrich, 2010).

Bayes' theorem also allows for the encoding of both expertise and uncertainty. Knowledge and experience of lost person behavior and local terrain characteristics should naturally inform a search and rescue mission (see Koester, 2008). However, the ability to handle uncertainty is also needed as missing person cases often involve a number of "maybes" and "possibilities." For example, one searcher found a bandana in JTNP which may, or may not, have belonged to Ewasko. A Bayesian model can appropriately incorporate such findings (e.g., to the degree it is believed the found item belonged to the missing person).

Our analysis was of a cold case with stable information; however, information is dynamic in the early days of a search and rescue mission as new findings and negative search results flow into the incident command center. The probability map requires constant updating, a task this model can quickly accomplish with GIS software and GPS inputs. Responsive functionality is important when time is a pressing concern.

Limitations

All search and rescue efforts involve assumptions, which should be carefully evaluated as they may undermine the conclusions if invalid. The following limitations of this analysis should be noted:

- The boundaries in Figure 2 outline the area within which Ewasko would be found. Even if these borders are not completely accurate, the effect on the outcome is minimal as the goal was to identify and prioritize remaining search areas, most of which were not located near the region's edges.
- Searchers would have seen Ewasko's body if it was within 50 feet of their track. The rocky areas in JTNP contain caves and canyons, however, that are difficult to search (Manaugh, 2018). Additionally, decomposition and animal scavenging quickly disarticulate human bodies, the remains of which may become distributed over large areas (Haglund & Sorg, 1997). This produces smaller body parts (sometimes buried by animals), but also more of them for searchers to discover.
- Signal-propagation physics is reasonably precise, so the distance estimate for the Serin Drive cell phone tower ping is thought to be 90% accurate (given no unusual atmospheric thermal conditions).
- The rate of distance drop-off from the cell phone tower was equal for both nearer and further positions, as shown in the graph in Figure 4. This may not be completely accurate as shorter distances sometimes appear to be longer due to reflection from rock faces. To partially compensate for this, the height of the tower was doubled in our calculations on the grounds that it was better to be more inclusive than exclusive.

Finally, it should be recognized that this is a simplified model, based on a limited number of factors. In reality, other variables may also be important considerations.

Future Research

Bayes' theorem provides the foundation for incorporating a wide variety of information sources. Here, we used prior search tracks and cell phone data (tower location, ping radius, and viewshed). Lin and Goodrich (2010) analyzed topography, vegetation, and local slope. Other factors that could be integrated into a WiSAR framework include direction of travel, weather conditions, seasonality, recovered clothing/water bottles, and so on – anything of material relevance. Research on missing persons, the development of lost-person-behavior algorithms, and the use of individual profiles can further inform an analysis (Koester, 2008; Lin & Goodrich, 2010; Velarde, Etlinger, & Rossmo, 2019). It may even be possible, with further research, to construct Bayesian networks that model sets of relevant variables and their conditional dependencies, allowing for a more powerful and holistic approach to optimizing WiSAR operations (Taroni, Aitken, Garbolino, & Biedermann, 2006).

Conclusion

"If you haven't found them, then they're someplace you haven't looked yet" (Pete Carlson, Riverside Mountain Rescue Unit, quoted in Manaugh, 2018). This observation raises the issue as to where one should look next. The purpose of our analysis was to answer that question by illustrating how Bayes' theorem can be used to generate prioritized search maps.

The Bayesian analysis for the Ewasko case was completed in August 2018. The results were posted by coauthor Thomas Mahood, who has written about the search over several years, on his blog (OtherHand.org). The prioritized areas have yet to be extensively searched, so the accuracy of the map in Figure 7 cannot yet be evaluated. Obviously, the utility of this analysis would have been greater if it had been done at the start of the search, then regularly updated.

This was a cold case, but the same techniques can be applied in search and rescue operations for missing persons who are hopefully still alive. One of the advantages of the approach is its ability to continually integrate new information (e.g., item recovery, negative searches, etc.) into the search plan in real time in order to optimize resource allocations. The ultimate goal is to improve WiSAR efficiency and effectiveness and help save lives (Lin & Goodrich, 2010).

Appendix

Data inputs

Data inputs for this Bayesian analysis include:

1. estimated distance from cell phone tower (10.6 miles) = *D*
2. cell phone coverage (no buffer) = *C*
3. previous search tracks (50-foot buffer) = *S*

Prior Probability

$P_{\text{prior}} = \frac{A}{10{,}000}$

where *A* = total search area (in square feet)

However, as we are only interested in prioritizing search areas, not in estimating actual probabilities, the prior can be ignored as it is equal for each cell.

Probabilities

Distance

Dx = from Serin Drive cell phone tower

p(*Dx*) = from Gaussian distribution; exponent = 1.2 (see graph in Figure 4)

Coverage Area

$C_x = \frac{ca}{10{,}000}$

$p(Cx) = Cx \,/\, \sum_{i=1}^{N} Ci$

where: *ca* = cell phone coverage area (in square feet) within cell *x*

N = 10,000

Search Tracks

$S_x = 1 - \frac{100P}{10{,}000} = 1 - \frac{P}{100}$

$p(Sx) = Sx \,/\, \sum_{i=1}^{N} Si$

where: *P* = length of search track (in feet) within cell *x*

N = 10,000

Bayesian Probability

$$LR_{Tx} = (LR_{Dx})(LR_{Cx})(LR_{Sx}) = \frac{p(Dx)\,p(Cx)\,p(Sx)}{[1-p(Dx)][1-\mathrm{p}(Cx)][1-\mathrm{p}(Sx)]}$$

where: LR_{Tx} = total likelihood ratio for cell x

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Abbreviations

DEM	digital elevation model
GIS	geographic information system
GPS	global positioning system
JTNP	Joshua Tree National Park
NED	National Elevation Dataset
WiSAR	wilderness search and rescue

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