Applying Least Cost Path Analysis to Search and Rescue Data: A Case Study in Yosemite National Park

by

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List of Abbreviations

AGOL	ArcGIS Online
BLM	Bureau of Land Management
DEM	Digital elevation model
FEMA	Federal Emergency Management Agency
GIS	Geographic information system
GPS	Global positioning systems
IC	Incident command
IGT4SAR	Integrated Geospatial Tools for Search and Rescue
IPP	Incident planning point
IRMA	Integrated Resource Management Applications portal
ISRID	International search and rescue incident database
LKP	Last known point
MRLC	Multi-Resolution Land Characteristics Consortium
NAD	North American Datum
NLCD	National Land Cover Database
NPS	National Park Service
PCS	Projected coordinate system
PLS	Point last seen
POA	Probability of area
POD	Probability of detection
PsWD	Persons with dementia
SAR	Search and Rescue

TTCSM	Travel time cost surface model
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
WISAR	Wilderness search and rescue
YNP	Yosemite National Park

Abstract

There were around 65,000 search and rescue (SAR) incidents from 1992 to 2009 throughout national parks in the United States. Of those incidents, around 2,500 were fatal. Studies surrounding SAR incident data typically revolve around the subject rescue and recovery process. The study of lost person behavior and psychology can also affect this field of work in a way that is beneficial to the lost subject. Search and rescue incident commanders (IC) must exhaust all possible indications of where the subject may be and which direction they may have traveled. The objective of this study was to apply least cost path analysis to search and rescue data in Yosemite National Park. For this study to be successful, the cost paths will indicate possible evidence of deviation from designated park trails. The least cost path analysis required an incident planning point (IPP) and a subject found or recovery point for each case investigated. An overland travel cost surface was constructed using impedance tables from Integrated Geospatial Tools for Search and Rescue (IGT4SAR). One hundred seventeen SAR cases were subject to least cost path analysis in this study. Resulting paths were traced manually from beginning to end to find points of divergence from trails or roads. Thirty-six paths contained likely divergence points. Thirty-one were from trails and five were from roads. This confirmed the least cost path analysis and trail divergence studies were successful. There were also clusters of divergence points in some park locations, suggesting possible problematic areas. While it is not implied that the paths are exactly those chosen by lost individuals, the methodology can be reproduced with different data to assist with park trail construction or maintenance.

Chapter 1 Introduction

The field of search and rescue (SAR) is one that relies heavily on the expertise and cooperation of several disciplines and branches of emergency services and personnel. Searchers assigned to SAR tasks must be familiar with lost person behavior as well as local geography to be most effective on SAR missions (Koester, 2008). Often what causes a person to become lost or disoriented on a hike or camping trip may be simply a matter of improper planning before the trip commenced (Doke 2012). Or, the subject may have also been taken against their will, leading to their absence and related search. This uncertainty over cause can often leave searchers with a sense of confusion due to the lack of clues that the subject may have left behind. Because of this, searchers need as much information pertaining to the search subject's potential whereabouts as possible.

Search and rescue volunteers or personnel understand that finding the subject is a time-consuming feat. Many search scenarios are completed using grid-pattern searches. However, some terrain cannot be traversed in such a pattern, so clues are necessary to identify the best locations to which teams should be assigned (Doherty 2013). Because of this, searchers rely heavily on data that are crucial to the proper planning of SAR missions. Those data include the point last seen (PLS) or the last known point (LKP) of the search subject and any behavioral patterns that the subject may have exuded. The PLS is the location where the subject was last seen by a witness. The LKP is consistent with the tracks or clues that the subject has recently left behind (Abi-Zeid and Frost 2005). Searchers often designate positional clues like the PLS or the LKP of the subject as the initial planning point (IPP) of the search (Koester 2008). This information, when combined with a geographic information system (GIS) and GIS analytical techniques can greatly assist search teams with SAR missions.

SAR team members focus on finding subjects as quickly as possible. Timesaving techniques as well as predictive analytics have become common for use in many missions (Johnson 2016). Many of the predictive analyses utilize terrain, elevation, and time that the subject has been missing to paint a picture of how far the subject could have traveled as well as the likelihood that the subject is still alive. Some of these tools use statistics that have been derived over the years and accepted as proper theoretical values. These values are based on the type of search that is being conducted as well as the physical fitness of the subject and many other determining factors (Syrotuck 2000).

Since most hikers and park visitors do not intend on becoming lost, some environmental, physical, or cognitive factor must come into play when they become search subjects. Part of what may cause park visitors to become disoriented may have to do with trail design or maintenance. Taking a wrong turn or starting a trail that does not loop back to the trailhead may cause some individuals with good intentions to become lost. It is often assumed that individuals will turn in the direction of their dominant hand when met with a decision point like a fork or turn (Koester 2008). However, much of what compels an individual to make the decision to turn one way or another while on a route or trail has to do with the terrain (Koester 2008) and trail signage (Bell 2008). A trail or route's difficulty is dependent on the steepness of the terrain or the length of the full trail or route. Since many visitors to parks are not familiar with terrain changes and trail forks, trail information is typically posted at trailheads of popular trails. Way marker signs are usually installed along the trails to guide visitors in safer directions (Bell 2008). Signs are posted as often as possible to help prevent individuals from becoming lost or injured along popular trails while also providing visitors with a sense of comfort and security while exploring (Trapp, Gross, and Zimmerman 1994).

To find where lost hikers and other park visitors may have made a bad judgement call or possibly taken a wrong turn off a trail, this study required past SAR incident data. Search and rescue GIS data typically contains the locations where subjects were found or recovered. However, to obtain a clearer picture of where park trails may be in need of maintenance to keep park visitors from losing their way, locations where lost persons began their journeys was also necessary.

1.1 Motivation

After researching the topic of SAR and the spatial data available from past SAR missions, it was evident that the prevention of lost persons and the avoidance of future SAR missions was not often studied. Even though this study is not focused preventing individuals from becoming lost, the methods and findings from this study could encourage future research into lost person prevention, SAR mission avoidance, or park trail maintenance.

Many of the past SAR studies that have included a GIS or GIS analytical techniques have been fixated on the idea of theoretical search areas or mobility models. Often, the use of GIS in the field of SAR is solely for the creation of assignment areas, clue trackers, terrain, and situational awareness. The more advanced techniques like mobility modeling and theoretical search areas may allow for decreased search times, leading to higher probabilities of subject survival (Johnson 2016).

Of the many SAR organizations contacted for this study, very few participated in GIS data collection. Many organizations employ the use of electronic maps as well as global positioning system (GPS) units to track areas that have already been searched, but often do not track the point last seen (PLS), last known point (LKP) or the incident planning point (IPP) of the subject or the mission. Koester’s International Search and Rescue Incident Database (ISRID) contains one of the most comprehensive lists of search and rescue incident data in the world (Koester 2008) and lists the organizations who are responsible for contributing. This list was key in finding the data used in this study.

Finding the least cost paths of individuals who were lost in a park could provide park staff and future park planners with an idea of how trails can be groomed to accommodate inexperienced individuals. There were around 65,000 SAR incidents from 1992 to 2009 in national parks throughout the United States. Of those incidents, around 2,500 were fatal (Heggie 2009). The National Park Service (NPS) (US National Park Service 2006) and Bureau of Land Management (BLM) (U.S Department of the Interior Bureau of Land Management 2017) employ many agents and rangers who assist other SAR organizations with the search efforts in national parks and national conservation areas.

1.2 Why Least Cost Path?

Least cost path analysis can help to theorize paths between two points over a surface that includes terrain, elevation, and terrain features (Esri 2017a). Least cost paths, or paths of least resistance, are not typically used to carve out hiking trails or scenic routes. Land features, like slope and terrain, are often considered when planning trails but if strictly followed, trails would not emphasize natural points of interest or viewpoints nearly as well (Bell 2008). Since trail locations are important in the consideration of trail sign placement, trail maintenance, and trail planning, they were also priority in this study.

Trails are able to navigate the least cost path when necessary but not to the disadvantage of the natural beauty of the trail or safety of the terrain. Further elaboration of trail design is available in Section 2.4. Since trails do not follow the least cost path, this does not mean that the surrounding features share in that quality. The term *route traveling* is used by SAR team members to indicate routes taken by lost individuals who follow what appear to be trails (Koester 2008) but may not necessarily be designated park trails. This involves traveling on some route, trail, or drainage (Hill 1998). Hill observed that a lost individual who uses the route traveling method will rarely backtrack. When an individual begins route traveling, they may very well be following a park trail. However, they may also be following a drainage that has the same appearance of a park trail that follows the path of least resistance. It is not possible with the data available for this study to process the exact paths traversed by lost individuals. However, hiker intended destinations in the missing persons data, that are described further in Chapter 3, explained that many of the hikers who became lost intended to arrive at points of interest in the park. The major points of interest are the end result or highlight of the trail. Trails are typically groomed to include points of interest during the course of the trail (Bell 2008), so it is assumed that the lost individuals in this study followed designated park trails as much as possible.

Some lost individuals do seek higher ground to enhance their view of the terrain or to view park features that may possibly be familiar from their map (Hill 1998). Others may seek higher ground to obtain a stronger cellular signal. After a lost individual attempts to enhance their view, they will likely descend the mountain to return to the trail upon which they were navigating. Many park trails also ascend in elevation, so those who are route traveling will not always use the path of least resistance if they are strictly route traveling. However, Syrotuck observed that 7% of hunters and hikers traveled uphill when lost and 89% used the path of least resistance (Syrotuck 2000). The path of least resistance will be the likely method chosen as the lost individual seeks familiar infrastructure in the fastest time possible when route traveling becomes ineffective. This study ignores the possibility that lost individuals might climb to higher ground to seek enhanced views of the terrain. Thus, this study assumes that lost individuals began on a trail and, once lost, follow the path of least resistance or the least cost path.

1.3 Study Area

Yosemite National Park consists of 748,436 acres of land mass, of which 704,624 acres are designated wilderness. According to the NPS, there were over 5 million visitors to the area in 2016 (National Park Service 2017). Throughout the park, there are 800 miles of walking paths, 214 miles of paved road, and 20 miles of paved walking and biking paths. In 2016, there were 329 SAR incidents and 16 fatalities in the park. In 2015, there were 239 SAR incidents and 20 fatalities within YNP (National Park Service 2017)[1]. There have been many studies related to SAR in Yosemite National Park and because of the relatively plentiful data, this park was chosen for the study. The boundary of the Yosemite National Park is outlined in Figure 1.

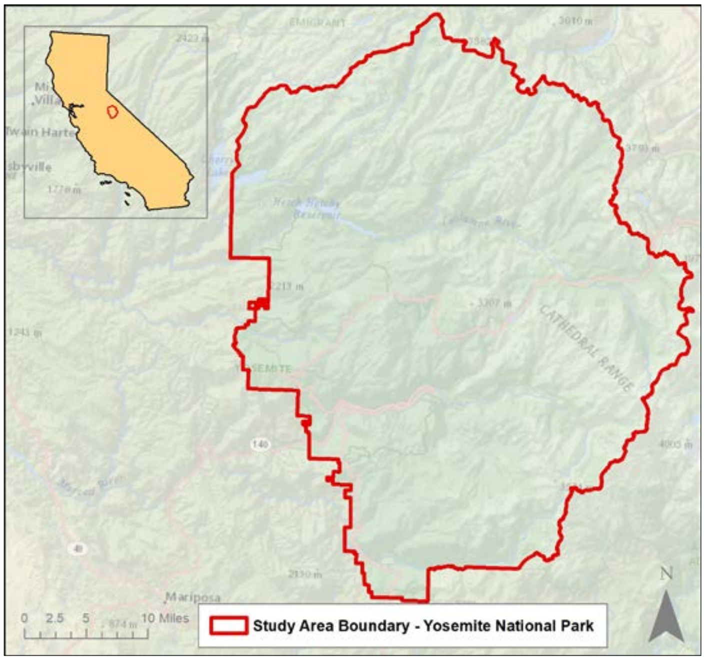

Figure 1 Study area

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[1] The fatalities within the park were not necessarily caused by incidents related to search and rescue events. Current park statistics can be viewed at https://www.nps.gov/yose/learn/management/statistics.htm.

1.4 Research Objectives

The main objective of this research was to determine if modeled trail divergence locations could reveal any patterns that could indicate where enhanced trail maintenance or strategic trail signage placement could help lead to prevention of lost persons or avoidance of SAR missions. This study could also assist with decision making in the park trail planning process. To complete this task, this study sought to:

1. Evaluate the potential utility of Least Cost Path Analysis to reveal cost path divergence from park trails;
2. Create an overland travel cost surface consistent with Yosemite National Park roads, streams, lakes, land cover, slope, and trails;
3. Utilize SAR GIS analytical techniques as a guide for determining appropriate cost surface model parameters.

The success of this study relied upon the fundamental understanding of lost person behavior and the psychology of lost persons. Search and rescue incident commanders (IC) rely heavily on past lost person behaviors as well as lost person survival statistics (Koester 2008), so including this practice in this study was appropriate.

1.5 Study Expectations

This study was initially undertaken to demonstrate a means by which to prevent individuals from becoming lost. However, after a few preliminary analyses and research into the subject, it was found that a question about how to prevent individuals from becoming lost was not able to be answered with the data at hand. However, the data are able to assist with visualization of the paths that individuals may have taken in accordance with the cost surface created. Thus, the expectation was that the paths presented after the completion of the analyses could show a pattern in areas that are in need of attention. If there is more than one point of trail divergence from any designated trail within the park, this may show park management where hikers may be leaving the trails and where more signage or maintenance may be necessary. Since this study revolved around the notion that lost hikers and other park visitors stay on designated trails or roads before becoming lost, the expectation is that most of the final cost paths will follow roads or trails.

1.6 Thesis Organization

This thesis continues with a detailed background of SAR terms, history, and relation to GIS, as well as trail construction and trail sign placement. Further into this paper, the data sets gathered for this thesis as well as the preliminary analyses to prepare the data for the primary analyses are discussed. The methodologies for the primary analyses are reviewed along with the purposes behind them. Finally, this thesis concludes with a discussion of the study outcomes and any future work recommendations relating to this study.

Chapter 2 Related Research

This study investigates several key characteristics of search and rescue techniques, the underlying psychological behaviors of lost persons, and characteristics of trail systems and the park trail planning process. While taking these themes into consideration, this study considers the mechanics behind the task of finding lost persons in a wooded terrain as well as the technology currently used to assist with that task. Since many field-data gathering tools have transformed from bulky GPS equipment to smart phone applications, more searchers can have the understanding and utility of search and rescue (SAR) tools without time invested in training. Because of the new ease of use, data pertaining to SAR missions and subjects is more easily collected. This large amount of data is used to run several analyses, including least cost path analysis and theoretical search area. These analyses can act as predictive tools when search missions are still in the planning stage.

The large number of visitors to YNP demonstrates the need for all search and rescue techniques to be exhausted. The large visitor volume also calls attention to the need for consistent trail maintenance and sign adjustment. The primary research points that were considered throughout the research process included search and rescue techniques and history, lost person psychology, and behaviors of lost people in wilderness locations. The use of GIS in rescue and recovery efforts, technological advancements in SAR software tools and mobile applications, least cost path analysis, and park trail maintenance and planning are also discussed in this chapter.

2.1 Search and Rescue Techniques and Terminology

Search and rescue efforts consume thousands of hours of labor as well as millions of dollars per year (Sava et al. 2016). Due to the arduous task of finding lost persons, strategic planning is key prior to search efforts. Most searches begin with a broad idea of the last known point (LKP) or the point last seen (PLS) of the search subject (Koester 2008). After the location of the LKP or PLS is identified, the SAR teams commissioned to the task will be assigned areas to search by the incident commander (IC). Search and rescue experts will also research the physical fitness of the subject as well as any other survival training that the subject may have completed (Koester 2008). This research gives rescuers a better idea of how far the subject could have traveled from the time the subject was reported missing to the time the search parties were dispatched (Doherty, Doke, and Ferguson 2008).

Some other factors that rescuers consider when searching includes the age of the subject, possible injury, knowledge of the terrain, emotional stability, and mental health. National Park Service staff take part in most SAR missions within national park boundaries due to their expert knowledge of the terrain (National Park Service 2012). Oddly, the NPS is not legally obligated to take part in the search of missing persons. However, according to NPS management practices, the saving of a human life takes priority over all management practices (US National Park Service 2006).

Several techniques that rescue personnel practice in the field require the use of maps. Since most searches will require teams to split up, search areas need clarification. This will ensure that the search is as effective as possible and that the searchers do not search the same areas several times (Koester 2008). There are, however, tools that GIS specialists and incident commanders can use to analyze the terrain, assign search areas, and keep record of clues. Those tools can, however, be used differently depending upon the type of search that rescuers are conducting.

Part of what sets search and rescue teams apart from other emergency personnel and organizations is the terminology and language that team members use throughout search efforts. Several different search scenarios such as medical, despondent, lost, evading, or criminal indicate what type of search is being conducted and possible reasons why the subject is missing. The purpose behind naming the search scenarios stems from the resources that are required for a successful search. Search teams and ICs must allocate resources responsibly as SAR efforts are time consuming, labor intensive, and financially draining endeavors (Heggie, Amundson 2009).

It is important to distinguish the difference between a *lost* individual and a *missing* individual. A missing individual may be part of search scenarios including avalanche, criminal, evading, despondent, investigative, overdue, or trauma (medical). The behaviors that are displayed by missing persons may be deliberate. This would possibly cause the individual to actively avoid searchers to retain their absence. A missing person may also have been taken against their will or be incapable of reaching those who are searching for them because of injury or medical issues. On the other hand, a lost person is likely active in seeking for a solution to their problem (Koester 2008). Lost individuals are not capable of finding their way due to unfamiliar surroundings or mental impairments. The common search scenarios that are often discussed in SAR cases are listed in Table 1.

Table 1 Search scenarios. Source: Koester 2008

Search Scenario	**Definition**
Avalanche	Subject who fell victim to an avalanche.
Criminal	This lost person could have been the victim of an abduction or murder. The perpetrator of the crime sets the location of the victim, which may cause problems for searchers.
Despondent	This search scenario involves a person who suffers from depression or may be inclined to suicidal actions. For this reason, these incidents are extremely time-sensitive.
Evading	This scenario involves those who are actively avoiding searchers. This group may include psychotic individuals and children.
Investigative	The search subject may have staged a disappearance, may have been placed in jail, may be hospitalized, or may be unable to communicate. This search scenario is also known as a “bastard search.”
Lost	This person is incapable of finding their way back to their origins. This person may suffer from dementia or another cognitive disorder. If a dementia patient is reported missing, they are automatically classified as lost. May also include persons with dementia (PsWD) or Alzheimer’s or autistic search subjects
Medical	This scenario is apparent often after the subject has already passed away. The subject is missing due to a condition such as stroke, heart attack, or another fatal health ailment.
Near-Drowning	This scenario can include any missing person who was thought to have been in or under water in some sort of anguish. This person could have been a victim of near drowning (survived) or was a victim of drowned.
Overdue	This search typically ensues once a subject has been out for too long. The subject never intended on being lost, nor was ever lost. This subject is typically recovered on their way back and not in distress.
Stranded	This scenario involves a subject who found themselves missing due to external forces, such as a broken-down vehicle, high tide, swollen impassable rivers, etc.
Trauma	Subject was not able to return due to an injury incurred.

Search scenarios are important for search planners because this gives them an idea of how fast the subject was traveling or the likelihood that the subject is still alive (Syrotuck 2000). There are several publications to which many SAR teams refer, but one of the more popular SAR guides is Robert Koester's *Lost Person Behavior: A Search and Rescue Guide on Where to look – for Land, Air, and Water* (Koester 2008). In this guide, Koester describes the statistical probabilities of certain survival rates of different search scenarios of lost individuals. Koester bases his statistics on the data provided to the International Search and Rescue Incident Database (ISRID). Because the accuracy of this data is vital to SAR teams, the data uploaded to ISRID need to be as exact as possible. The International Search and Rescue Incident Database follows a strict schema to retain consistency with terminology and to ensure that data can be used universally for statistics and field analysis for training purposes and SAR missions.

2.2 Psychological Limitations and Behaviors of Lost Persons

Many factors are involved that may result in a person becoming lost while hiking or mountaineering. The age, physical condition, and the activity in which the subject was participating all contribute to the cognitive abilities of the subject and are considered when conducting a search (Doherty et al. 2014). Those individuals may also be prone to spatial disorientation initiated by dementia, which can cause a reduction in the memory of topographical features, and object recognition (Bantry-White & Montgomery 2015). Search and rescue teams are often dispatched on missions for missing persons with dementia (PsWD) due to the increased risk of death from drowning or exposure (Rowe et al. 2011). It is probable that most PsWD will have at least one incident of wandering at some point throughout the duration of the disease (Rowe et al. 2015). For these reasons, PsWD are categorized under the *lost* search scenario.

Often, there is a high probability of death for some of those who are lost due to pre-existing mental health issues. Many despondent persons suffer from depression or suicidal thoughts, so the amount of time that the subject is missing can prove fatal if their intentions are suicidal or self-harming (Koester 2008).

Lost person behavior cannot, however, be purely described by the mental health of the subject or by the diseases that impair them. Many healthy individuals find themselves lost from time to time and search teams must account for their ability to traverse difficult trails. Some characteristics that searchers may need to consider about a healthy lost person are consistent with the years of experience the individual has in hiking or wilderness exposure. Their navigational capabilities as well as their access to a compass or GPS equipment will be questioned. Some healthier individuals may find themselves searching for a cellular signal at higher elevations, which also poses a threat to safety (Koester 2008). To find the subject in as little time as necessary, rescue teams must assess all possible factors. These factors all carry spatial properties so GIS tools and analytical techniques prove useful in situations where the IPP is not exactly evident (Doke 2012).

2.3 GIS Tools and Analysis in SAR

Lanny Lin and Michael Goodrich conducted a study in 2010 that commissioned the use of Bayesian modeling in Wilderness Search and Rescue (WISAR). The researchers used publicly available terrain data along with known behaviors of lost persons to create a Bayesian probability map. The product of this study allowed search commanders to allocate resources to areas identified in the GIS (Lin and Goodrich 2010). The longer that a subject is lost, the less likely the search will be a success (Koester 2008), so the probability of a subject’s location can assist with the potential rescue. Some tools that SAR teams may use include MapSAR, SARTopo, and Integrated Geospatial Tools for Search and Rescue (IGT4SAR).

2.3.1. MapSAR and MapSAR Online

MapSAR is a template tool created specifically for ArcGIS Versions 10, 10.1, and 10.2. The tool’s basic uses are consistent with the creation of field maps specific for search and rescue missions as well as the collection of subject search data that is to be stored in a robust geodatabase linked to the tool. The geodatabase can store data on the subject, the reporting party, and the configuration of field teams (Esri 2012). This tool also provides the capability for incident commanders or assigned GIS specialists to create maps for briefing and debriefing that present the PLS of the subject and the progress that the teams have made throughout the search mission (Pedder 2012).

MapSAR Online is a newer version of MapSAR that requires an ArcGIS Online (AGOL) account. The advantage of using this tool is that it allows for the simultaneous collection of data as well as map production. Other applications like Survey123 and Collector are useful for collecting clues or other field data that can interact with the application. This map tool and many other related tools are undergoing constant revision. The creators of MapSAR Online created the tool using AGOL Web App builder.

2.3.2. Integrated Geospatial Tools for Search and Rescue (IGT4SAR)

Research conducted throughout this study led to the discovery of another tool that was useful for analysis to determine the POA for more intricate searches. Johnson conducted a study on mobility models in the realm of search and rescue in 2016 that addressed the use of IGT4SAR. He used two tools within this tool set, specifically to study the Oregon Emergency Management SAR database. Those tools were the least cost path analysis and the theoretical search model (Johnson 2016).

There are six video tutorials that the creator of IGT4SAR, Don Ferguson, recorded to assist with understanding the steps needed to complete the analyses. These videos reside on a YouTube channel (https://www.youtube.com/channel/UCrW NjhnpNOiEAATDzNw3lFg) dedicated to IGT4SAR. Due to the intricate python scripting built within the tools, many of the processes for completing tasks with this toolset are described in detail in these videos.

Considering the different search scenarios that can occur in the field of SAR, the analytical aspects of this GIS tool set must be used by one who is knowledgeable with ArcGIS and geodatabases as well as SAR (Ferguson 2013). This analytical tool set requires the data pulled into the script to be placed in the database according to the standards that the geodatabase requires. The most important role that this tool set plays relies on its capability to predict the probability of success (POS) of finding the search subject. The tool set first finds the probability of area (POA) of the search subject and then the probability of detection (POD) (Ferguson 2013). Relevant to this study, IGT4SAR allows the technician to analyze the distance and direction that the subject may have travelled with the use of least cost distance analysis. The cost path capability of this tool assigns different impedances to foot traffic given different terrain features. Those features include stream order, land cover, and slope (Doherty et al. 2014). The impedance parameters established for this tool set were used to guide the analysis in this study.

2.4 Trail Construction and Signage

Often, trails are constructed with the intention of providing an avenue into natural areas that serves as a guide for visitors while also providing a sense of civilization and security (Hammitt 2010). Surface erosion and vegetation growth throughout trails that are already established can create a financial burden on park staff and operational organizations. If trails are not properly maintained, park visitors may not retain a sense of security during their visit or they may become lost due to over grown vegetation or poorly maintained trails.

Park signs are also an important part of a visitor's experience. Often, signs can allow a visitor to relax by not being preoccupied with finding the correct direction while exploring park trails (Bell 2008). Designing trails as loops is beneficial so visitors are able to hike back to the trailhead without difficult navigation and planning. This is one method of preventing hikers and other park visitors from becoming lost. Figure 2 contains examples of sign placement in different parts of park trails. Listed in Table 2 is the Key for Figure 2.

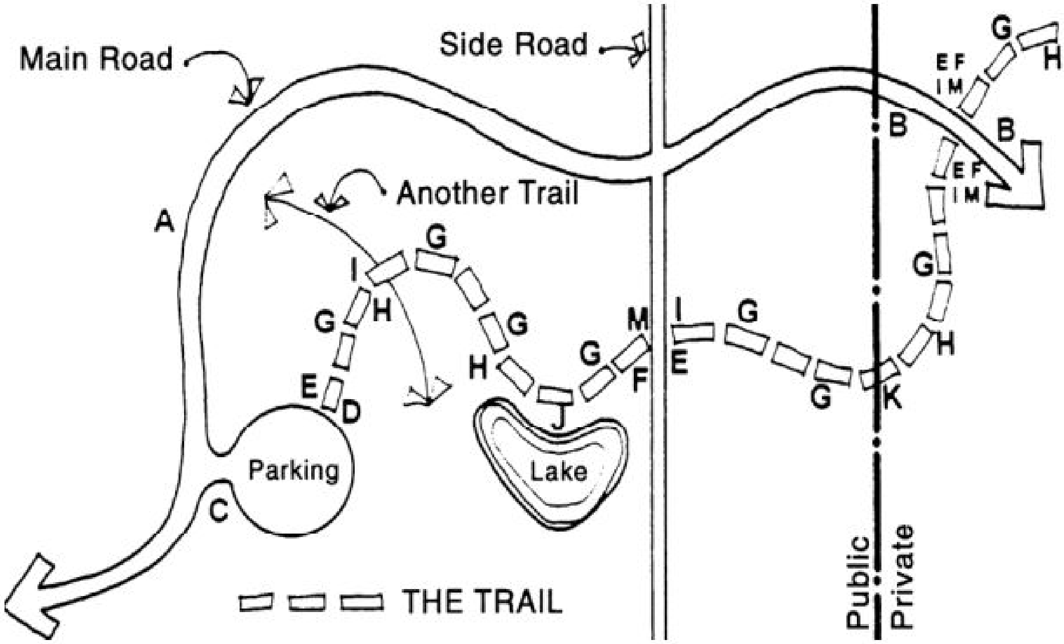

Figure 2 Park trail sign placement options. Source: US Department of the Interior 1996.

Table 2 Key for Figure 2 Source: US Department of the Interior 1996.

Sign Type	Relative Location	Sign Type	Relative Location
Information signs for highway users	A	Confirmation/Identification Signs (Trail logos)	G
Warning (Pedestrian Crossing) Signs for highway users	B	Interpretive signs	E
Entrance Sign	C	“Crossing Private Land” signs	F
Trailhead Information sign/ Kiosk	D	You-Are-Here signs	H
Regulatory (Usage control) signs	C	Destination signs	I
Direction Change indicators	F	Adopter sins	O
Boundary signs	N		

Nature tourism has become a popular recreational activity for many people (Bell 2008). Part of the responsibility of park maintenance is to keep visitors off the natural terrain, as heavy foot traffic can disrupt delicate ecosystems (Hammitt 2010). Some trails are often groomed for thrill seekers, who enjoy the adrenaline rush from climbing a rock wall or canyon. Because of the inherent danger, warnings and other signage are placed strategically to warn visitors of possible hazards in the park (Bell 2008).

Since most landscapes vary in terrain, vegetation, and elevation change, each trail constructed is different from the last. Many natural viewpoints are often difficult to reach, depending on a park visitor's physical capabilities. For these reasons, many park trails are not constructed using the least cost path or path of least resistance (Bell 2008).

2.5 Least Cost Path Analysis

Cost distance in GIS analysis has become a contributing technique to the field of search and rescue. For maritime rescues and rescues in rocky terrain, cost distance is used to determine the path by which a subject would have traveled (Siljander et al. 2015). Least cost path analysis is used to find paths used by herds of animals throughout the world (Hashmi et al. 2017) and can provide insight into the traveling behaviors of lost persons.

Because terrain can often differ depending upon where national parks are located, many of the park staff must be familiar with intelligent navigation routes throughout. The Travel Time Cost Surface Model (TTCSM) was created as a means by which park staff can find the fastest travel routes throughout their assigned parks. The model uses land cover data, elevation, and Tobler's hiking function to create least cost paths from one point or cell in the park to another (Frakes, Flowe, and Sherrill 2015). The logic presented in TTCSM was also present in other studies that included least cost path methodologies. Finding a probability of area, for example, of a lost individual also includes the creation of least cost path logic. The terrain and elevation must be reviewed to find the possible routes that lost individuals may have taken. Doherty, Guo, Doke, and Ferguson conducted a study using the same lost persons data that were used in this study to find the POA's of lost persons in YNP. Their research used ISRID statistics, mobility models, as well as a cost surface to calculate probability levels (Doherty et al. 2013). The parameters and methodologies used in their research were used to create the cost surface in this thesis. Ferguson's IGT4SAR also incorporates some principles from the research conducted in their study.

2.6 Summary of Related Research

This chapter covered the research related to search and rescue and related GIS analysis techniques. It outlined the scenarios that most searchers use when attempting to use their time most wisely during search missions. Research that informed the methodology of this study is the work on lost person behavior described in Robert Koester's book *Lost Person Behavior: A Search and Rescue Guide on Where to Look – for Land, Air and Water*. Other relevant research is related to park trail construction and least cost path analyses. The next chapter expands further on these key themes in the context of this study's implementation.

Chapter 3 Data and Methodology

The least cost path analysis in this study uses the impedance values from Ferguson’s Integrated Geospatial Tools for Search and Rescue to construct a travel cost surface. Terrain data including elevation, land cover, streams, lakes, trails, and roads were assigned those impedance values. Completing cost path analysis required missing persons incident planning point vector data and their corresponding found locations vector data. Those data were obtained from Paul Doherty’s ArcGIS Online Data Portal.

The streams, lakes, trails, roads, and elevation data used in this study were obtained from the National Park Service (NPS) Integrated Resource Management Applications (IRMA) portal. The IRMA portal provided all primary data for this study aside from SAR incident data obtained from Paul Doherty’s ArcGIS Online data portal and the land cover data set acquired from the Multi-Resolution Land Characteristics Consortium (MRLC). All map layouts and data storage were completed with the use of ArcMap 10.2 and ArcCatalog, respectively. Preliminary and primary analyses were conducted using both ArcMap 10.2 and ArcGIS Pro 1.2 with Spatial Analyst extensions at different stages in the study. Any script editing or script viewing were completed with the use of PyScripter software.

This chapter begins by discussing the workflow of data collection, steps in the preliminary analyses, and steps in the primary analyses. The second part of the chapter discusses each data set and the purpose behind its acquisition. Further into the chapter, the data exploration process is explained along with explanations of each data set. The preliminary analysis steps, including raster conversion, stream order, and reclassification are discussed and, finally, the chapter concludes with a description of the process to create the cost surface and the steps in the least cost path analysis.

3.1 Data and Workflow

The main objective of this study was to find if SAR case data and least cost path analysis could reveal the locations of possible trail divergence. The workflow of this study started with basic research into the subject matter. Then, once the required data sets were acquired, the preliminary and primary analyses were conducted. Represented in Figure 3 is the overall workflow of this study.

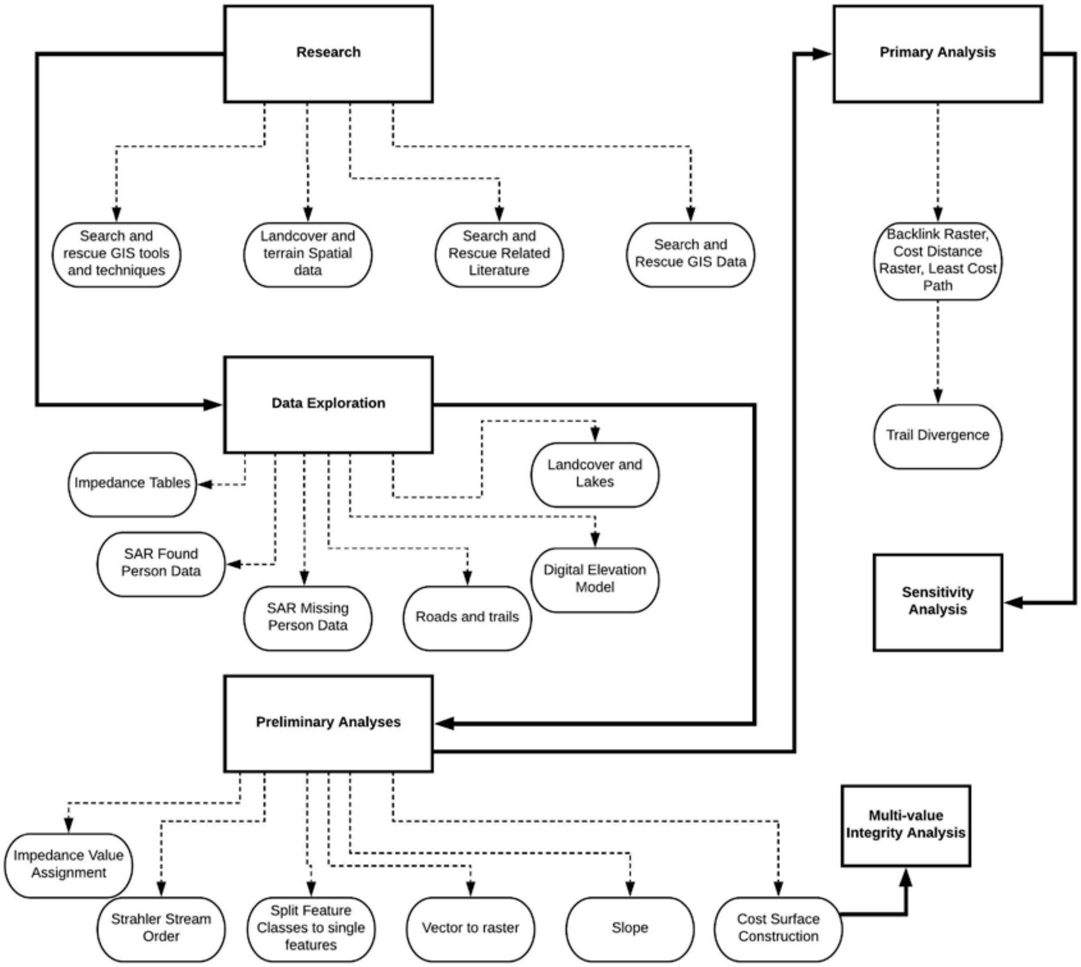

Figure 3 Study workflow

After researching and contacting several SAR teams and government emergency management offices, it was apparent that GIS tools are often used for route-planning or fast map creation in SAR missions. Since the National Park Service participates in the searches that are within the park boundaries, they are required to submit three forms for every search. The required forms are a case incident report (NPS Form 10-343), a supplemental case incident report (NPS Form 10-344), and a search and rescue funding report (NPS Form 10-347) (Heggie, Amundson 2009). The required data, however, do not typically include geospatial properties. Because of this, it was crucial to find a study area that contained a robust SAR spatial dataset.

Each data set was projected to the projected coordinate system (PCS), North American Datum (NAD) of 1983 Universal Transverse Mercator (UTM) Zone 11N. The data sets were all clipped to the same extent for analysis purposes. Table 3 lists the data used for this study. The following subsections describe the data in detail and the purpose of the data within the scope of this study.

Table 3 Data used

Data	Temporal Resolution	Source	Data Format
Yosemite Boundary	Updated yearly; 2017 version used	National Park Service/ Integrated Resource Management Application	Polygon Shapefile
Digital Elevation Model	Updated March 2018	NPS/IRMA	Raster File
Missing Persons IPP point Data	SAR Cases from 2000 - 2010	Paul Doherty and Jared Doke	Single Feature Class
Land Cover	NLCD 2011 used for this study. NLCD 2016 not available at the time of this study.	Multi Resolution Land Characteristics Consortium	Raster File
Roads Data	Updated yearly; 2017 version used.	NPS/IRMA	Line Shapefile
Found locations point data	SAR Cases from 2000 – 2010	Paul Doherty and Jared Doke	Single Feature Class
IGT4SAR Tools	Updated 2012	Don Ferguson/Github.com	ArcGIS Tools
Hiking Trails	Updated 2012	NPS/IRMA	Line Shapefile
Lakes	Updated 2006	NPS/IRMA	Polygon Shapefile

3.1.1. Missing Persons Incident Planning Points and Found Location Data

The missing persons IPP and found locations data sets contain details about the subject that became lost or missing. These two data sets each contain 213 matched records (i.e. for every IPP in one data set there is a found location in the other) for searches within YNP from 2000 to 2010. They were compiled by Paul Doherty and Jared Doke for a study on search incidents and lost person behavior in YNP in 2012 (Doke 2012). The 213 records selected required a distinct IPP as well as a distinct found location. Using criteria that related to hiker and search characteristics, Doherty and Doke selected pertinent records from a larger SAR data set containing 2,201 cases (Doke 2012). Records in this larger data set were georeferenced using *point-radius* and *shape* methods in a study conducted by Paul Doherty, Qinghua Guo, Yu Liu, John Wieczorek, and Jared Doke in 2011. Many of the SAR case reports contained vague location descriptions, so these georeferencing techniques helped to derive the most accurate points possible (Doherty et al. 2011).

The point-radius method relies upon the precision of a single named locality. Steps taken in the point-radius method include identifying any places with names that may be included in the description, determining any offset features such as distances from roads, water features, or landmarks, and calculating any uncertainties (Wieczorek et al. 2004). Uncertainties are caused by unknown extents, datums, directional precision, or distance precision and can be represented by a circle surrounding the reference point. The radius of the circle is the uncertainty measurement. Most of the data in the Doherty data were georeferenced using this method. The researchers calculated a mean uncertainty radius of 560 ± 51m and a mean uncertainty area of 3.60 ± 0.840 km^2 (Doherty et al. 2011).

The shape method georeferences localities using polygons, buffered points, or buffered line features (Wiecksorek et al. 2004). Like the point-radius method, this method also relies upon locality descriptions. Uncertainties result from unknown pieces of information but utilize the shapes of the features instead of using a radius and a circle. Both methods seek to create a spatial description from the textual information provided, but the shape method attempts to only include locations described in the text (Doherty et al. 2011). For example, if an individual was found somewhere along a creek, the point-radius method may overlap another creek or feature that is not part of the original description. The shape method does not allow that. Because of the uncertainty of these techniques, many of the points in this data set have the same coordinates. This led to some problems in the analysis in this study discussed later.

For the Doherty et al. study, the researchers added temporal and environmental data that was used to validate their findings (Doherty et al. 2012). For the study described here, the rich amount of data in each record was useful when reviewing hiker logic once the primary analyses were completed. Both point feature classes contain the same schema and same case descriptions. The only difference between the two data sets is the point location associated with each record. In one data set, the point associated with each record is the case's IPP and in the other, the point is the case's found location. As shown in Table 4, the attribute data for both the IPP and the found location are included in each record. The separate sets of Doherty data are shown in Figure 4 and Figure 5.

Table 4 Sample of Doherty data schema (for missing persons IPP and found locations)
Source: Paul Doherty's AGOL Data Portal, http://data-pjdohertymaps.opendata.arcgis.com

Field	Description
CaseNumber	Year + 4 digit case number (20100060)
SARNumber	Year + 3 digit SAR number (2010250)
Incident Year	Year incident occurred
DateTimeLastSeen	Date subject was last seen alive
DateTimeInitiated	Date the SAR was initiated
DateTimeSubLocated	Date the subject was located
DateTimeIncidClosed	Date the incident was closed
DayLastSeen	Day of the week subject was last seen alive
ContactMethod	Way in which subject was reported missing
EcoRegionDomain	Eco-region domain as listed by Bailey
EcoRegionDivision	Bailey EcoRegion Division number including the M designator if a mountainous Division from the list
IncidType	Type of Incident
NumberofSubjects	Number of subjects involved
GroupDynamics	Describes if there are more than one subject and if the group stayed together or not
SubjectCategory	Subject category as described by Koester
SubSex	Subject Sex
SubAge	Subject age
IPPType	Type of initial planning point
IPPClassification	Phyiscal feature that best represents IPP
IncidContribFactors	factors contributing to subject being reported missing
IncidOutcome	Outcome of incident
Scenario	Reason for incident outcome
SubjMedinType	Subject injury
RescueMethod	How subject was rescued
LostPersonStrat	Strategy, as described by Kenneth Hill PhD, undertaken by lost subject to reorient themselves
IPP_GR_Locality	Locality associated with the IPP georeference
IPP_GR_Type	Georeference type for IPP
IPP_GR_Path	Path used for georeference IPP
IPP_GR_Notes	Notes for IPP georeference
Intended_Destination	Subject's intended destination
FindFeature	Terrain feature that best describes where the subject was found
Found_GR_Locality	Locality associated with the found location
Found_GR_Type	Georeference Type for found location
Found_GR_Path	Path used to georeference found location
Found_GR_Notes	Notes for found location
Motorized_Transport	Subject used motorized transportation prior to being found (Hitchhiking, bus, etc.)

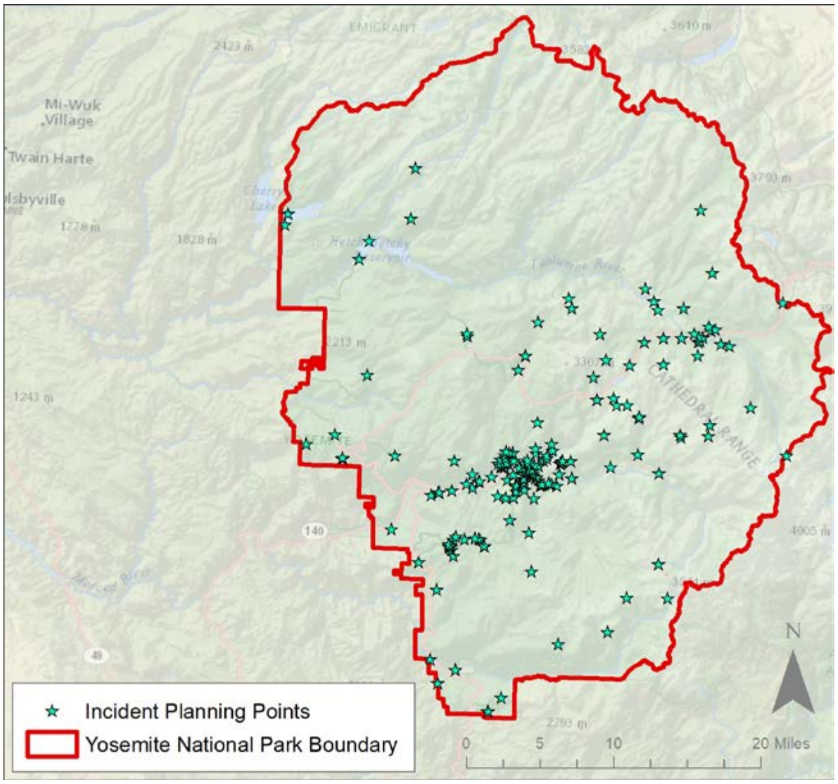

Figure 4 Doherty data incident planning points

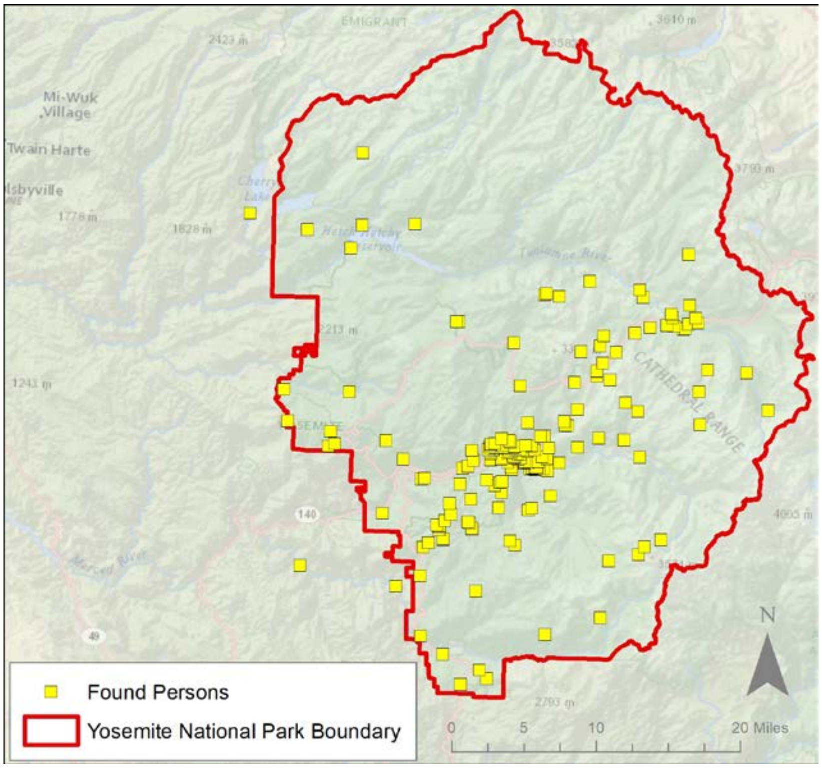

Figure 5 Doherty data found locations

The Doherty data sets contained many search subject categories including hikers, skier-nordics, climbers, those with mental illness, those with autism, despondent, children, workers, snowboarders, anglers, and snowshoers. Hikers are the only records that were used in the analysis in this study. Of the 213 missing persons IPP points and matched found locations in the Doherty data, only 133 were hikers. Sixteen of the matched records contained values of zero in distance traveled. Case notes stated that the individuals were either not lost or were found near the IPP. Thus, the remaining 117 records were used in the least cost path analysis in this study.. From this point on, the missing persons IPP data is called simply *IPP data*. When referring to both the IPP data and found locations data, together, *Doherty data* is used.

It is also important to note that the distance traveled in this data set is a straight-line measurement between the IPP and found location for each case. Since it is not explicitly the exact path taken, the recorded distance traveled is not relevant in this study, aside from those who did not travel any distance. It is also important to note the intended destinations of the subjects. Many of the subjects intended to arrive at popular points of interest while hiking. This assumes that hikers followed park trails or roads prior to becoming lost.

3.1.2. Extent

The Yosemite National Park boundary does not encompass all features of the data in this study, so a new boundary needed to be created. The Yosemite National Park contains many trails and roads but holds no physical boundaries that designate the park from other land features on many of the park's border regions. Upon initial investigation of the Doherty data, it was discovered that many of the IPP data and found locations lie outside the park's designated boundary.

To include all datasets within the same extent, a near table was created, using both tables in the Doherty data. The analysis conducted used the boundary of the park as the feature measured against. The distance from each point was measured to the park boundary. The furthest point outside of the boundary of the park was 5.1 miles and is identified in Figure 6. Ultimately, a 5.2 mile buffer was created around the boundary of the park and used as the extent for this study.

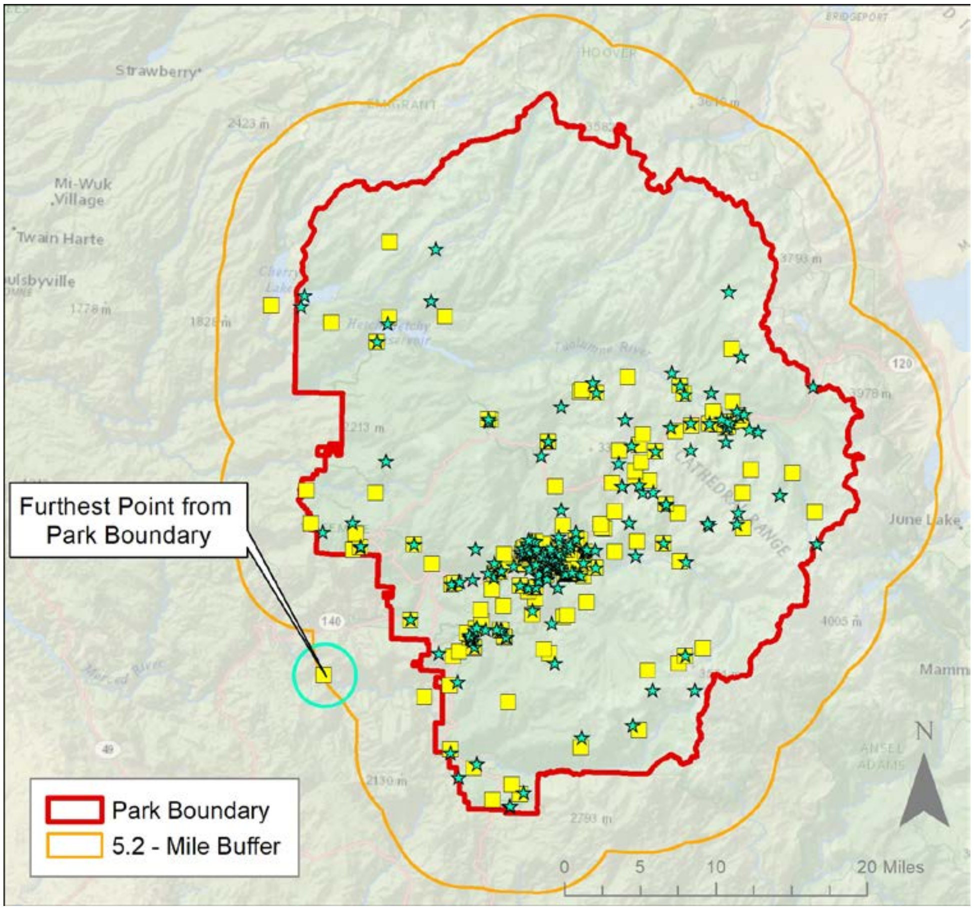

Figure 6 Buffer (5.2 miles) extent using near analysis

3.1.3. Trails and Roads Data

This study assumes that lost persons will follow the path of least resistance when lost. Trails and roads are an obvious path that if taken, will lead a lost individual to safety or will allow them to be discovered more easily. For this reason, and to determine if least cost path analysis can indicate locations where visitors are deviating from designated trails, trails and roads were prioritized. While most of the trails within the national park have some sort of name, some of the more popular trails have unnamed trails that stem from them. Both named and unnamed trails were included in the GIS data and were used in this study.

The roads data set contained all major roads within the park as well as access roads. Figure 7 illustrates the trails and roads used in this study. The park trails table in Appendix A lists the name and length of each trail in miles.

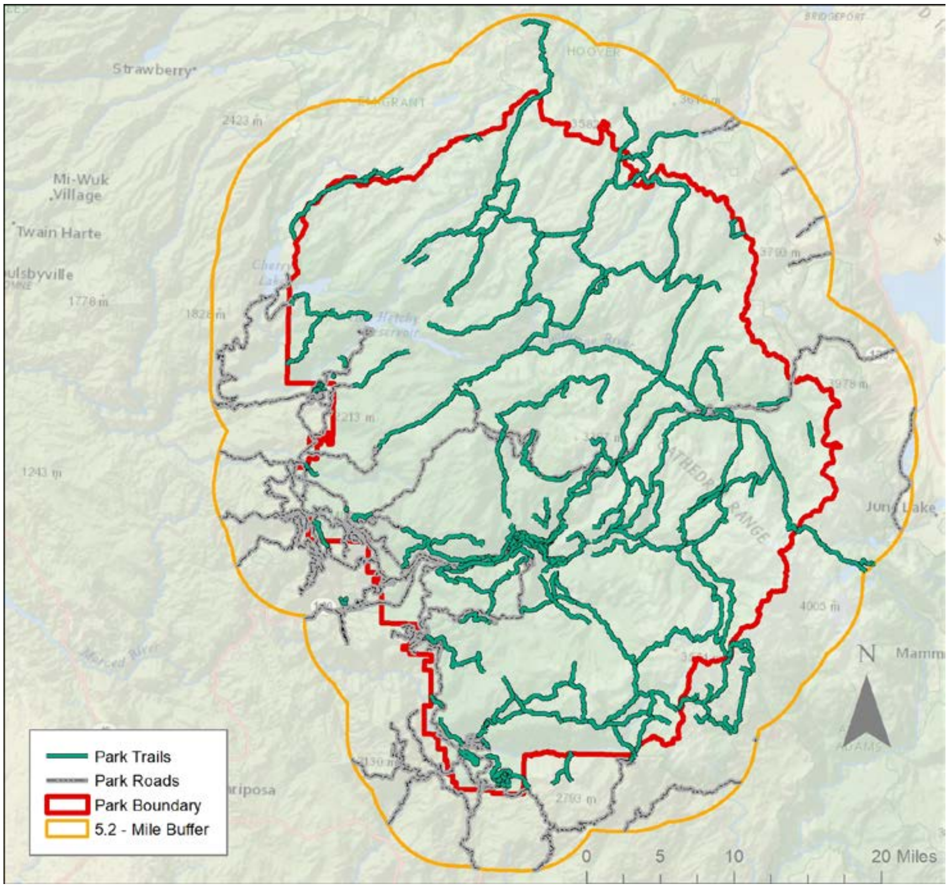

Figure 7 Study roads and trails

3.1.4. Digital Elevation Model

Slope analyses and stream order analyses require the use of a digital elevation model (DEM). The DEM used for this study was acquired from the NPS IRMA data portal. The same version of this DEM was also available from the United States Geological Survey (USGS). The resolution of this DEM is 10m by 10m. This data set was used as the analysis template throughout this study such that all rasters created were snapped to this raster using the same resolution.

This DEM, along with all the other data sets, was clipped to the 5.2-mile buffer boundary that was designated as the extent for this study. The DEM, visible in Figure 8, has a maximum elevation of 13,146 ft. and a minimum elevation of 1,470 ft.

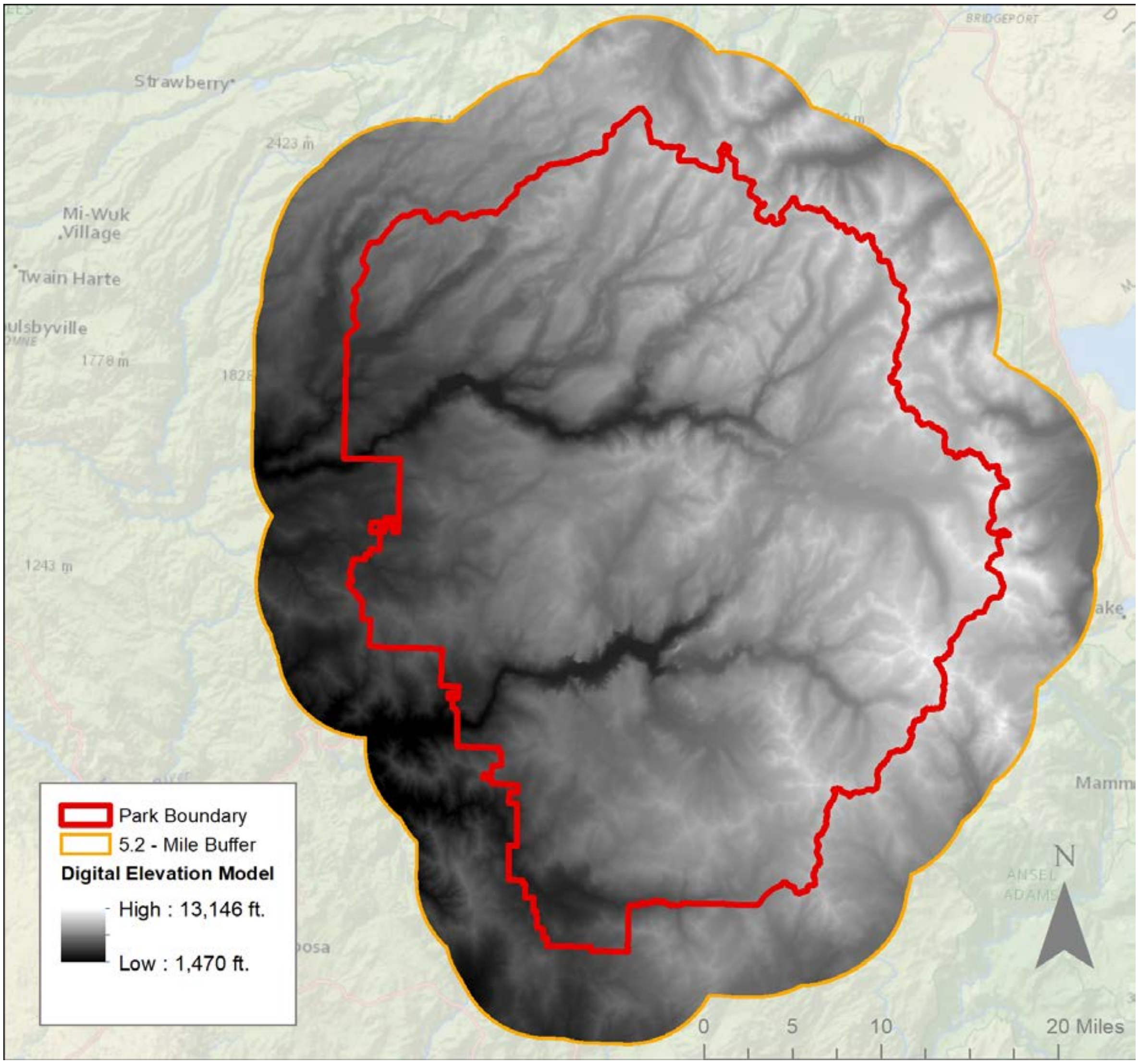

Figure 8 DEM of Yosemite National Park

3.1.5. National Land Cover

As described in the IGT4SAR literature review, the impedance levels for land cover, slope, and stream order were all needed for the success of this study. The national land cover dataset (NLCD) was obtained from the multi-resolution land characteristics consortium (MRLC). From the impedance tables provided as part of the IGT4SAR tool set, impedance levels were assigned to each of the different land cover types, according to Don Ferguson's model. The land cover categories that were assigned impedances in the cost surface are represented in Figure 9.

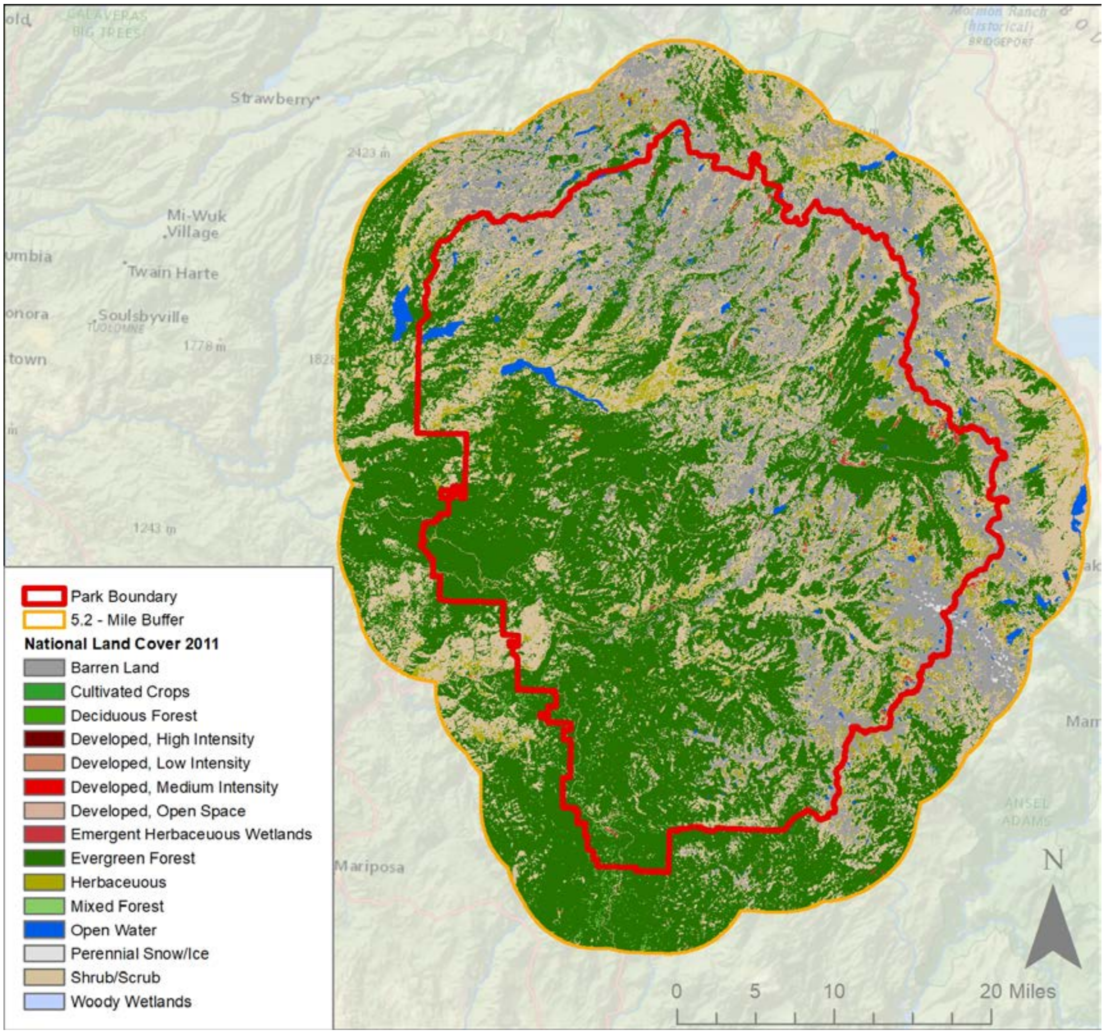

Figure 9 Land cover from the NLCD within Yosemite National Park

There was one other option for land cover that is available on the YNP IRMA data portal. It has many more features, which provides much more detail in the end. However, since IGT4SAR uses the NLCD Land Cover Classification to assign hiker impedances, this land cover from the MRLC was selected for this study. The NLCD data set was downloaded in raster format. The cell size for this data set was 30m by 30m and needed to be clipped, projected, and resampled to the extent, projection, and cell size used throughout this study. Raster resampling changed the size of the cell to match that of the elevation model. Changing the image quality through resampling was not the intention with this process.

3.1.6. Lakes

Trail and route design in state and national parks can often lead visitors to areas where views of waterways or water bodies are at their best while also leading them in safe directions during their stay (Bell 2008). Lakes were included in this study as an element in the cost surface. The NLCD 2011 data set also contains waterbodies. Since lakes and waterbodies were complete barriers in the cost surface, the addition of a separate lakes layer in the cost surface was appropriate. This provided reassurance that lake and waterbody barriers were firm. This data set was obtained from the NPS IRMA data portal in vector format. The lakes data are represented in Figure 10.

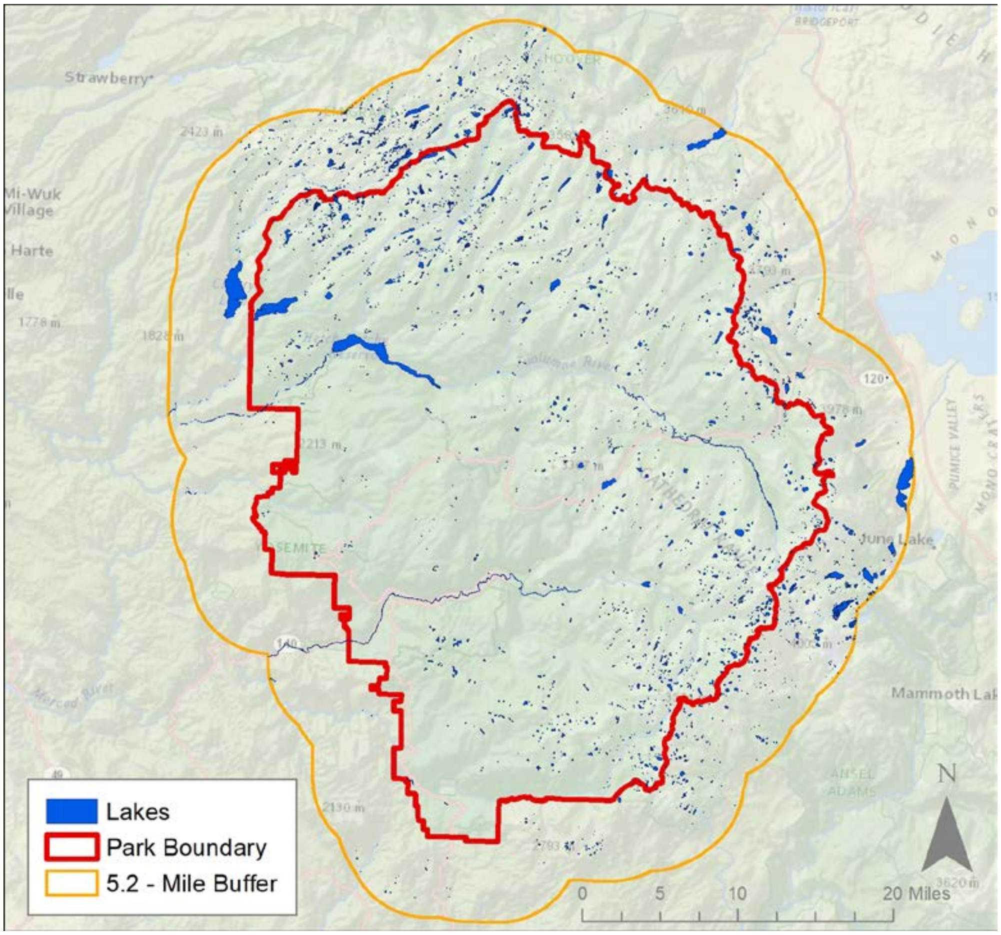

Figure 10 Lakes within Yosemite National Park

3.1.7. IGT4SAR Impedance Tables

The tools written within the IGT4SAR are typically used for active SAR missions. The tools were all written using Python script and can run in ArcMap 10.1 & 10.2 (Ferguson, 2013). Because of the nature of the tools, they were investigated for their suitability for incorporation into this study. Many of the tools within IGT4SAR use the same data types used in this study and because of this, the scripts written for these tools were examined. IGT4SAR uses the cost distance tool that is provided in the ArcGIS Toolbox as part of its cost distance model. The cost distance model is used so the user has the capability to create cost distances, theoretical search areas, segment search speeds, and estimates of the probability of success rates (Ferguson 2013).

Each of these tools require the use of hiker impedances and hiker speeds as travel costs. The tools also put a restriction on any slopes higher than 60 degrees because it is assumed that hikers will not traverse any terrain steeper than 60 degrees when lost (Ferguson 2013). For this study, hiker impedance values were used as costs on the final travel surface, but speeds were not.

The impedances that are used in IGT4SAR are the same impedance levels that were used in a study conducted by Doherty, Doke, Guo, and Ferguson in 2013. In their study, the cost to traverse each cell of the travel surface was defined by the impedance to foot traffic over various geographic features (Doherty et al. 2013). The impedance values ranged from 0% to 100%. Zero percent identifies a surface with no impedance such as a level park trail or developed roadway. One hundred percent identifies a complete barrier such as a cliff or lake. Because there were several different geographic features like waterways, water bodies, slope, and land cover, each data type required a different impedance table to be matched with the various geographic feature types. For example, deciduous, evergreen, and mixed forest land cover types were assigned impedance levels of 45, 50, and 55, respectively. The land cover impedance levels are listed in Table 5. The light gray rows indicate land cover types included in this study area.

Table 5 National Land Cover impedance levels used in IGT4SAR. Gray rows indicate the cover types and impedance values included in this study. Source: Doherty et al. 2013

LAND COVER CODE	DESCRIPTION	IMPEDANCE
11	Open Water	99
12	Perennial Ice/Snow	85
21	Developed, Open Space	5
22	Developed, Low Intensity	10
23	Developed, Medium Intensity	15
24	Developed, High Intensity	20
31	Barren Land (Rock/Sand/Clay)	30
32	Unconsolidated Shore	40
41	Deciduous Forest	45
42	Evergreen Forest	50
43	Mixed Forest	35
51	Dwarf Scrub	45
52	Shrub/Scrub	45
71	Grassland/Herbaceous	20
72	Sedge/Herbaceous	45
73	Lichens	20
74	Moss	25
81	Pasture/Hay	25
82	Cultivated Crops	30
90	Woody Wetlands	80
91	Palustrine Forested Wetland	80
92	Palustrine Scrub/Shrub Wetland	80
93	Estuarine Forested Wetland	80
94	Estuarine Scrub/Shrub Wetland	80
95	Emergent Herbaceous Wetlands	80
96	Palustrine Emergent Wetland (Persistent)	80
97	Estuarine Emergent Wetland	80
98	Palustrine Aquatic Bed	99
99	Estuarine Aquatic Bed	99

Stream order classifications were used to assign impedance levels because small streams can easily be traversed by most hikers and large rivers may represent a complete barrier. The higher the order, the higher the likelihood of foot traffic impedance (Doherty et al. 2014). The impedance values assigned to the stream orders in IGT4SAR are listed in Table 6. The process by which the streams in this study were assigned orders and, ultimately, impedances is discussed in more detail in Section 3.2.3.

Table 6 Stream order foot traffic impedance used in IGT4SAR. Source: Doherty et al. 2014.

Stream Order	Impedance
1	30
2	40
3	50
4	70
5	80
6	90
7	99

3.2 Preliminary Analyses

The data sets discussed in the previous section required manipulation before they were used in the primary analyses. The steps taken to process the data sets included slope analysis, raster resampling, identification of Strahler stream order, raster to vector analysis, and impedance value assignment. This section of the study is organized by the final inputs required for the cost surface. The processes that were part of the preliminary analysis stage of this study are shown in the workflow diagram in Figure 11.

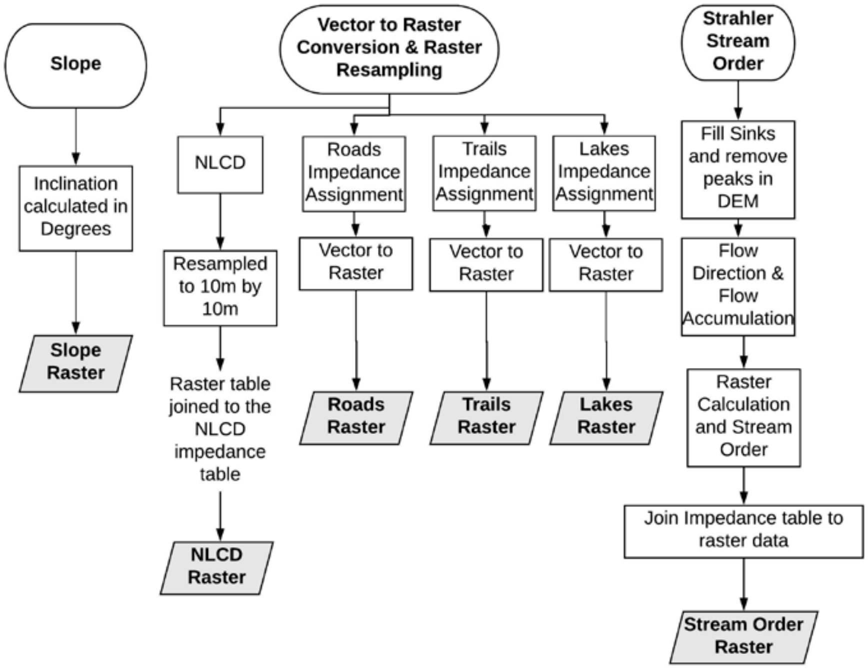

Figure 11 Preliminary analysis workflow

3.2.1. Trails, Roads and Lakes

Trails, roads, and lakes data sets were all assigned single impedance values. Lakes were assigned values of 99 because they are complete barriers. Trails and roads were assigned impedance values of 1 because they are ideal travel routes in this study. Because there was no variance in the impedance values and thus no need for a look up table, an attribute field was simply added to the vector features for impedance value and either 1 or 99 was entered for every record, depending on the data set. Values of 0 and 100 were not used because the impedance tables in IGT4SAR and the Doherty et al. (2013) study did not use those values.

Trails, roads, and lakes were originally acquired as vector data sets. The impedance values for trails, roads, and lakes were assigned prior to raster conversion because the impedance fields in these data were used as cell values during raster conversion. The output cell size was set to match that of the DEM. Trails and roads vector data were converted to raster data using the polyline to raster tool in ArcGIS 10.2 toolbox. Cell assignments were based on the "maximum length of polyline per cell" option which in this case simply assigned the impedance value to any cell in which a line segment entered. The polygon to raster tool was used to convert the lakes using the cell center assignment option.

3.2.2. National Land Cover Raster

The original resolution of the NLCD data set did not match that of the resolution used in this study so it required raster resampling before assigning impedance values. The 30m by 30m cell size was resampled to match the DEM's 10m by 10m resolution. A tabular join from the impedance table to the NLCD table was completed based on the land cover type.

3.2.3. Slope Analysis and Assignment of Slope Impedance

A slope layer was created using the DEM. The inclination of the slope layer was measured in degrees for this study. For the slope impedance values, it is assumed that anything above 60 degrees is impassable by hikers (Doherty et al. 2014) so any values from 60 to 88 were reclassified to a value of 99. Otherwise, since there was no IGT4SAR reference table for slope impedance, slope values between 0 and 60 were reclassified to a value of 1. Figure 12 shows the slope raster created for these analyses.

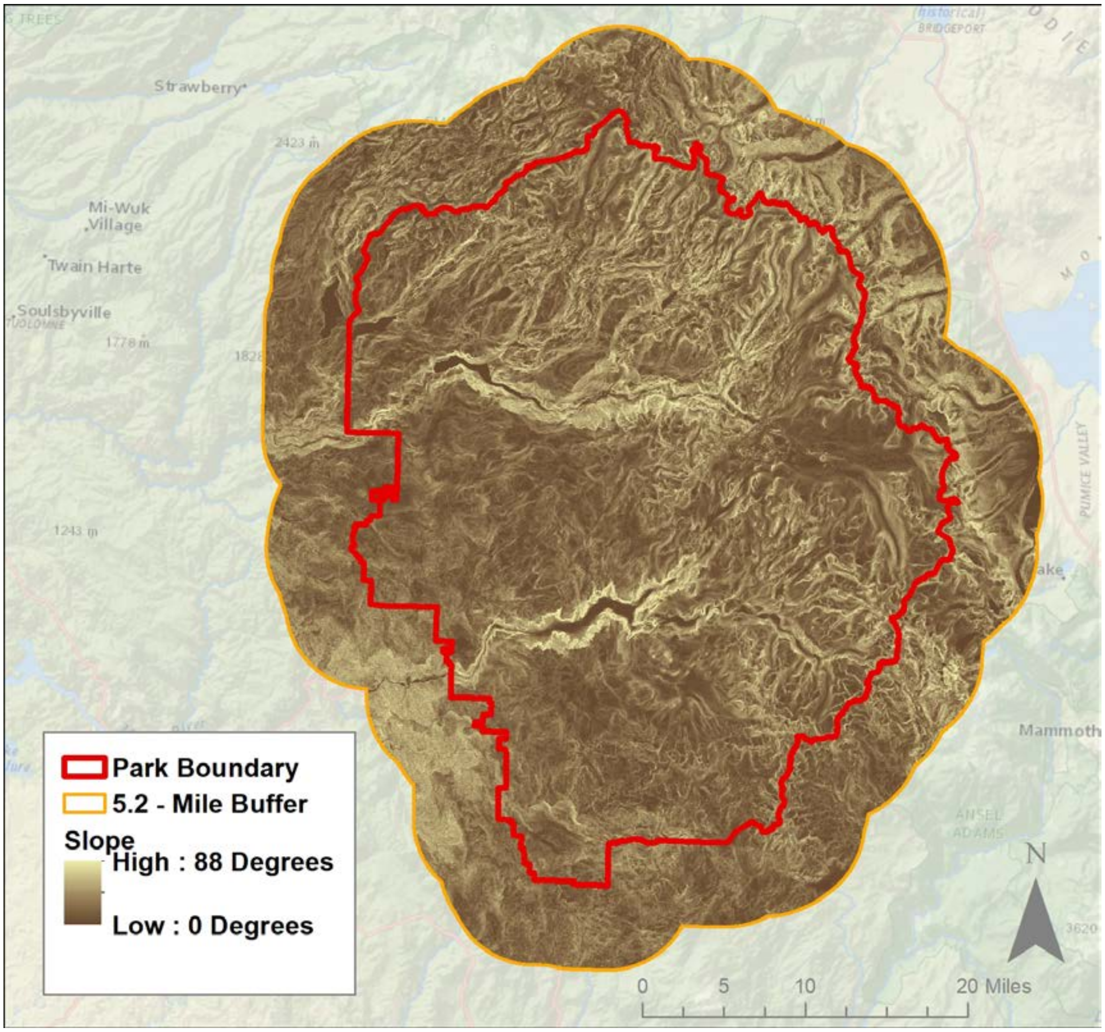

Figure 12 Slope raster created for cost surface

3.2.4. Stream Order Impedance Assignment

Strahler stream order is typically used for the classification and prediction within channel branching waterway networks and to explain diversity of riparian organisms (Hughes et al. 2010). This study used Strahler stream order to classify streams and relate streams of a certain order to the IGT4SAR impedance values. There are several steps required to identify the stream network from a DEM and to classify them according to stream order.

3.2.4.1. Fill Sinks and Remove Peaks

Many DEM’s contain flaws such as sinks and peaks. This can be caused by errors in the resolution or by the rounding of values to the nearest integer (Esri 2016a). These imperfections will generate errors in the stream order analysis if not smoothed beforehand (Tarboton, Bras, and Rodriguez-Iturbe 1991). Because of this, all peaks and sinks in the DEM that was included in this study were smoothed using the Fill ArcGIS tool. The graphic in Figure 13 describes the process.

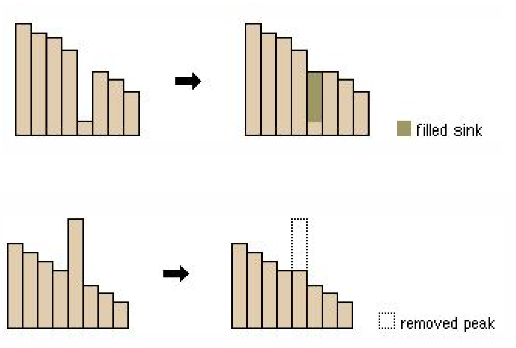

Figure 13 Illustration of concept of sink and peak fill process. Source: Esri 2016a

3.2.4.2. Flow Direction

The flow direction process was executed once the new, smooth, elevation surface was created. The flow direction uses the elevation model to predict the direction that water in each cell will flow. The direction of the flow of water is calculated by the direction of the sharpest descent. The distance is calculated between cell centers (Esri 2016b). Using the Flow Direction ArcGIS tool, each cell is assigned a coded value indicating the direction that the water will travel. Figure 14 illustrates the resulting flow direction raster and shows how each assigned value represents a cardinal direction.

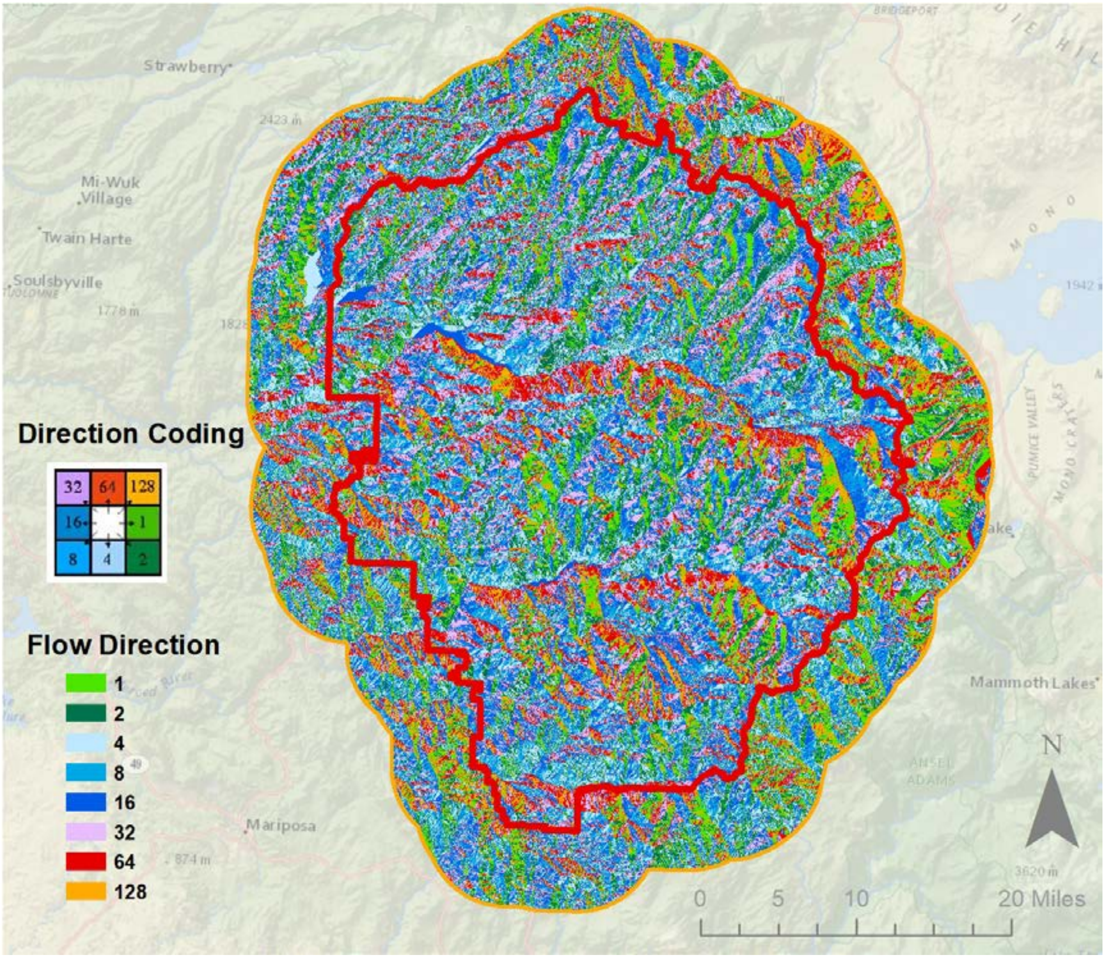

Figure 14 Flow direction calculated from elevation model

3.2.4.3. Flow Accumulation

In this study, the flow accumulation was calculated using the Flow Accumulation ArcGIS tool with the flow direction raster. The resulting value for each cell in the raster indicates the number of cells that are upstream of it (Esri 2017b). Assigned values to cells ranged from zero to over 2 million.

3.2.4.4. Stream Network Delineation

Using the Raster Calculator ArcGIS tool, each cell of the flow accumulation raster was assigned a value of 1 if there were more than 100 cells flowing into it. Any cells that were not assigned a value of 1 contained no data (Esri 2017c). This threshold was used to select cells with sufficient accumulated volume for channelized flow to begin. The value of this breakpoint is arbitrary, but 100 is commonly used. The resulting raster contained delineated streams indicated as cells with values of one surrounded by cells with no data.

3.2.4.5. Stream Order

Once the flow direction raster was created and the stream network was delineated, the Strahler stream order analysis could proceed using the Stream Order tool in ArcGIS. The logic of the Strahler stream ordering is that streams begin as first order. When two first order streams converge they become second order streams. Second order streams converge to become third order streams and so on. The result of the Stream Order tool is the same stream network raster with cell values indicating stream order for the segment of the stream crossing a raster cell.

Once the stream order analysis was completed, the stream order impedance table (shown in Table 4 above) was joined with the final Strahler stream order raster table. For visualization purposes, the stream order raster was then converted using Raster to Polyline ArcGIS tool. Polylines were not simplified. Figure 15 shows the stream order data in raster and vector format.

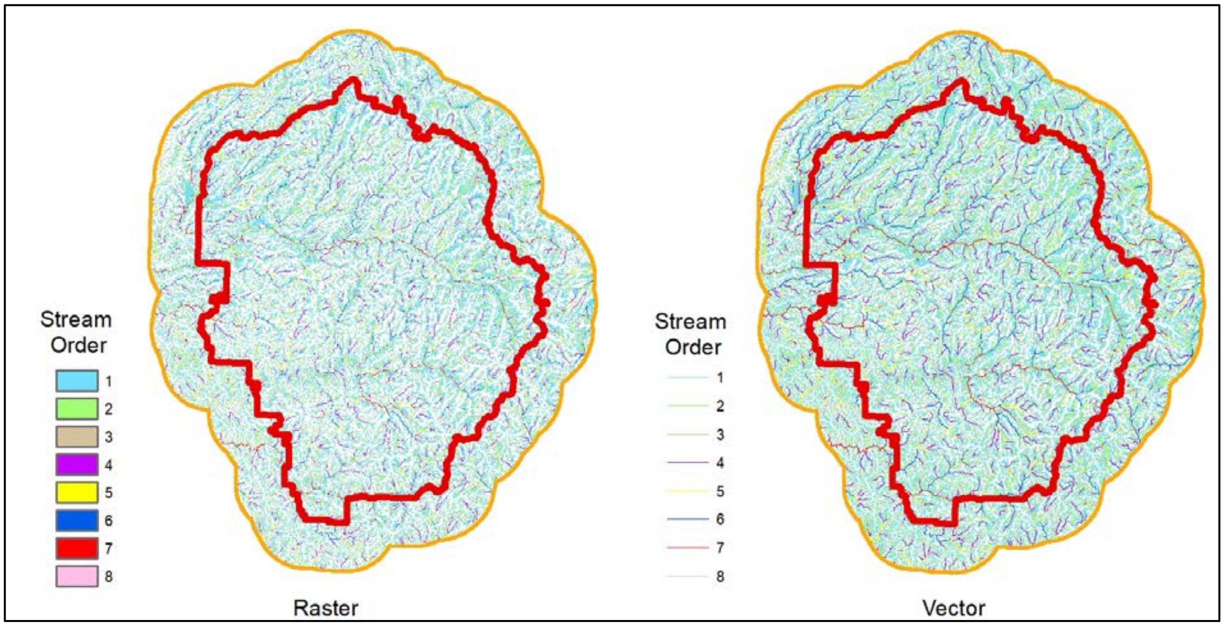

Figure 15 Raster and vector Strahler stream order data

3.2.5. Feature Class Division

Both the IPP and found locations data sets were acquired as separate feature classes containing 213 records a piece. As explained above, queries to extract the 117 hikers who traveled more than 0 mi. resulted in two new feature classes containing 117 features each. Since the cost path analysis requires each path's start and end point to be a shapefile or feature class containing one point, it was necessary to break up the Doherty data sets into 234 individual shapefiles. For this, a model was written using ArcGIS 10.2 Model Builder that iterated through the feature classes, creating a single shapefile for each object within. Each shapefile was named by its case number using the naming conventions IPP_(Casenumber) and Found_(Casenumber). The shapefiles were then converted to feature classes and imported to two separate geodatabases; one for IPP data and the other for found locations. Figure 16 is the model written for this part of the study.

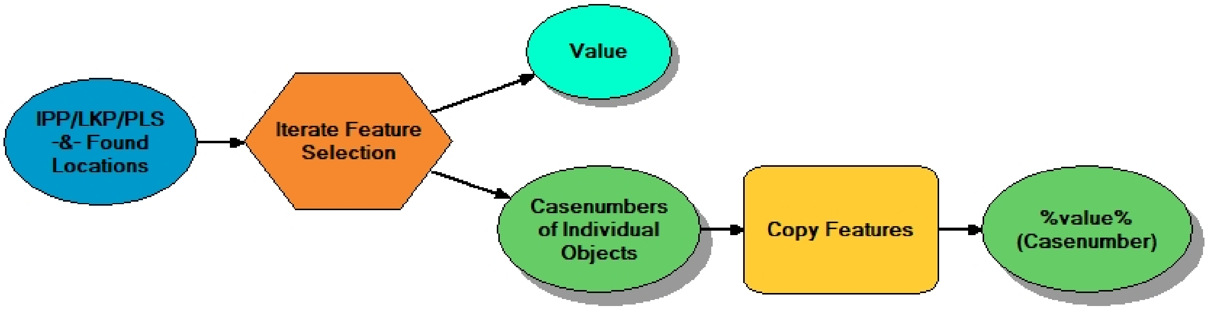

Figure 16 Model used for breaking feature classes into separate object shapefiles

3.2.6. Raster Reclassification to Final Impedance Values

Reclassification was required for lakes, stream order, trails, roads, NLCD, and slope raster files. Assigned impedance values were all left unchanged in this process. Trails, roads, lakes, NLCD, and stream order raster files were assigned reclassification values of 0 where cells with no data existed. As described in Section 3.2.3, the slope was reclassified to a value of one for any cells representing zero up to 60 degrees and to 99 for any values between 60 and 88 degrees. This provided a complete surface for raster calculation.

3.3 Calculation of the Cost Surface

At this point in the study, all data sets to be used to create the cost surface had been assigned impedance values, converted to raster formats, and reclassified. The first step in creating the cost surface involved summing the values in the land cover, lakes, stream order and slope raster files. To replicate the approach taken in IGT4SAR, no weights were added to the raster layers prior to calculation. Since an assumption was made that hikers will tend to stay on developed paths (which thus should have a very low cost value), the trails and roads were not included in the initial raster sum. The maximum impedance level after adding the four raster files was 298. It is important to note that the lakes raster was added to the land cover raster which also contained cells coded as lake. This doubling of the impedance value for lakes is not a problem, for lakes and other smaller bodies of water are assumed to be complete barriers in this study.

The second part of the cost surface calculation required the trails and roads to be superimposed on it (i.e. burned in), for the values contained in the cells in the trails and roads raster must be equal to the least cost possible. Using a conditional function, the trails raster was combined with the initial summed raster with the condition that the raster outcome would be “true” if the cell value in the roads raster were equal to 1. Any cell value that was not equal to one on the roads raster was “false” and the raster outcome was assigned the value from the initial cost surface. This process prioritized the roads raster, while retaining all other values on the cost surface from the previous calculation. Once this was completed, the trails raster was put through the same process on the surface that contained the prioritized roads raster. The final product was a surface that has a minimum value of one and a maximum value of 298. Figure 17 depicts the final cost surface that was created for use in the least cost path analyses. The pink portions of the graphic display the highest cost portions of the surface, such as the lakes and waterbodies. The light blue portions display the roads and trails, or lowest cost values.

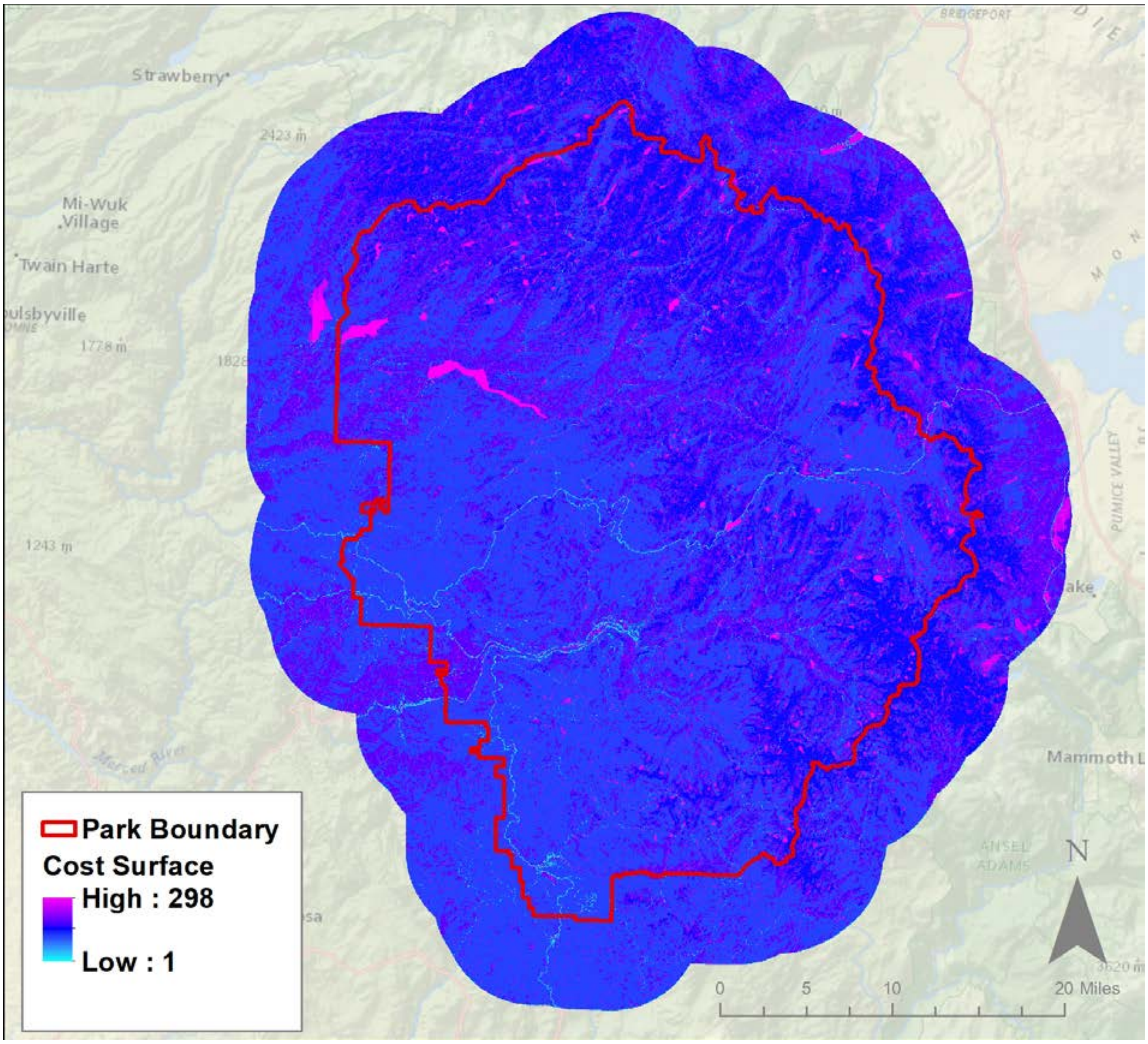

Figure 17 Final cost surface

3.3.1. Integrity Test

Once the cost surface was created, values were extracted from several randomly placed points to be sure that the cell values in those locations made sense. Missing persons IPP points were used as the random points in this test. The last case of each year was chosen, so there were ten points used for multi-value extraction. The IPP data points were used because the value extraction process measured where searchers would have been putatively located.

For example, if a value extracted from a point has a value of 99 on the lakes raster, that would place the IPP in the lake or body of water. Values were extracted to test the accuracy of the methodology in creating the cost surface. Trails and roads needed to represent the preferable cells with the lowest possible impedance. Features like lakes, dense land cover, or rivers needed to show higher impedance levels at the extraction points. Figure 18 illustrates the points chosen for the value extraction. The values in Table 7 are the cell values at each point.

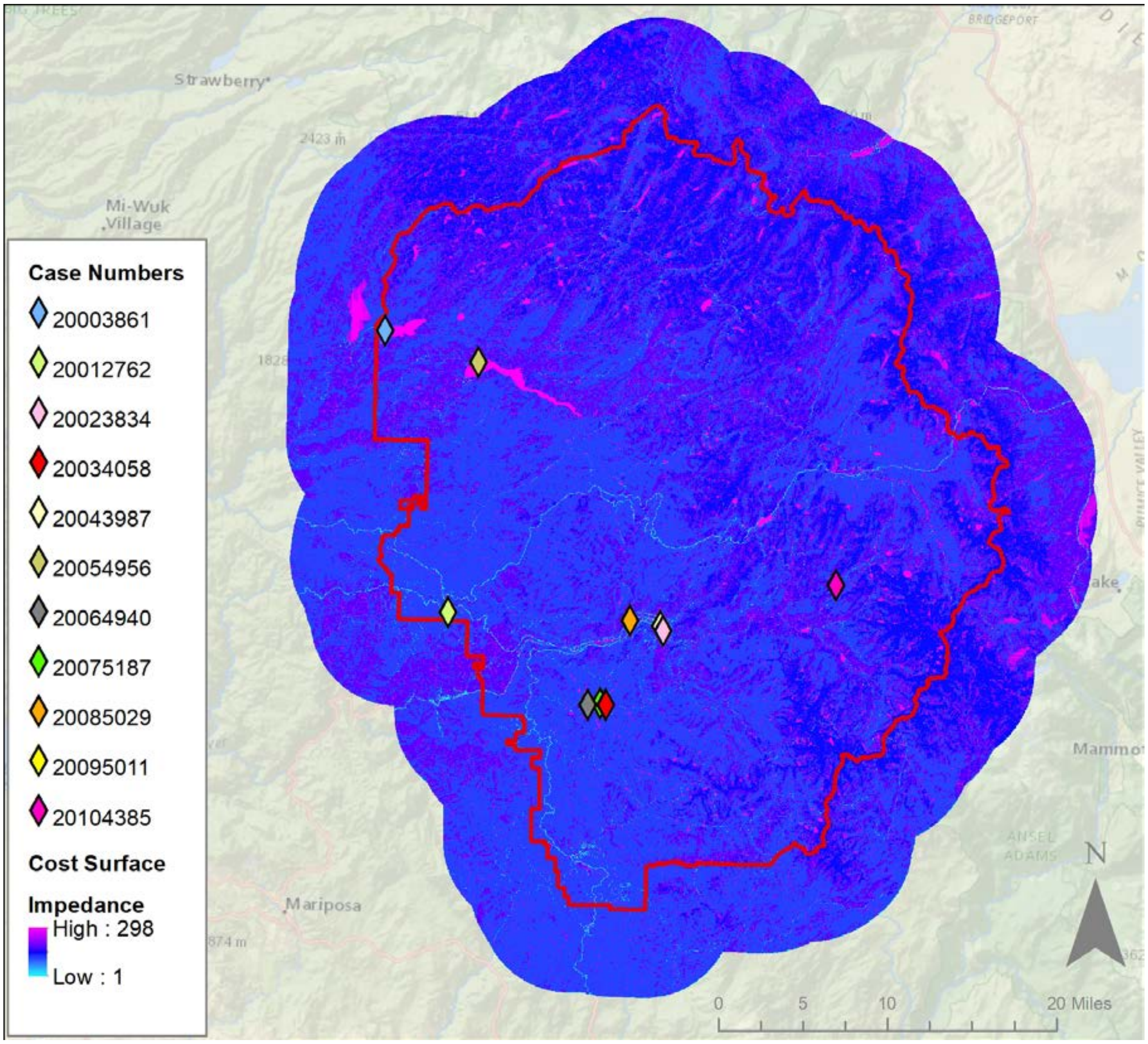

Figure 18 Impedance value extraction points

Table 7 Impedance values for each raster layer at test points

Case Number	Roads	Trails	Slope	Stream Order	Land Cover	Lakes	Cost Surface
20003861	0	0	1	0	50	0	51
20012762	0	0	1	0	50	0	51
20023834	0	0	1	0	50	0	51
20034058	0	0	1	0	50	0	51
20043987	0	0	1	0	75	0	76
20054956	0	0	1	0	75	0	76
20064940	0	1	1	0	50	0	1
20075187	0	0	1	0	50	0	51
20085029	0	1	1	0	50	0	1
20095011	0	0	1	0	50	0	51
20104385	0	0	1	0	75	0	76

The values extracted from each raster layer show logical values of where the IPPs were located. If there were any values of 99 in the stream order or lakes columns, it would suggest that the IPP started in a river or lake. The only slightly puzzling outcome is that there are many values of zero in the roads and trails raster layers. This suggests that the IPPs were in cells outside the 10m by 10m roads or trails cells. However, the values in the final cost surface column explain that the IPPs were in cells dominated by land cover impedance.

3.4 Least Cost Path Analysis

Least cost path analysis reveals the paths of least resistance from starting points to ending points. For this portion of the study, ArcGIS Pro was used because of far faster geoprocessing speeds than that of ArcGIS 10.2. The process began with the cost surface and the IPP starting point. Backlink raster files and cost distance raster files were created, first, to suggest the direction that might be traveled through each cell from the IPP source as well as the least accumulative cost distances for each cell to the nearest source over a cost surface. After the first part of the process, the backlink and cost distance raster files were used with the found location ending point to complete the least cost path raster.

The process was run once for every one of the 117 pairs in the Doherty data cases. Batch processing was not yet available for this version of ArcGIS Pro (1.2). This would have automated the process. The model had to be run one pair at a time. Each analysis ran for about two minutes. The model built for this part of the primary analysis is shown in Figure 19.

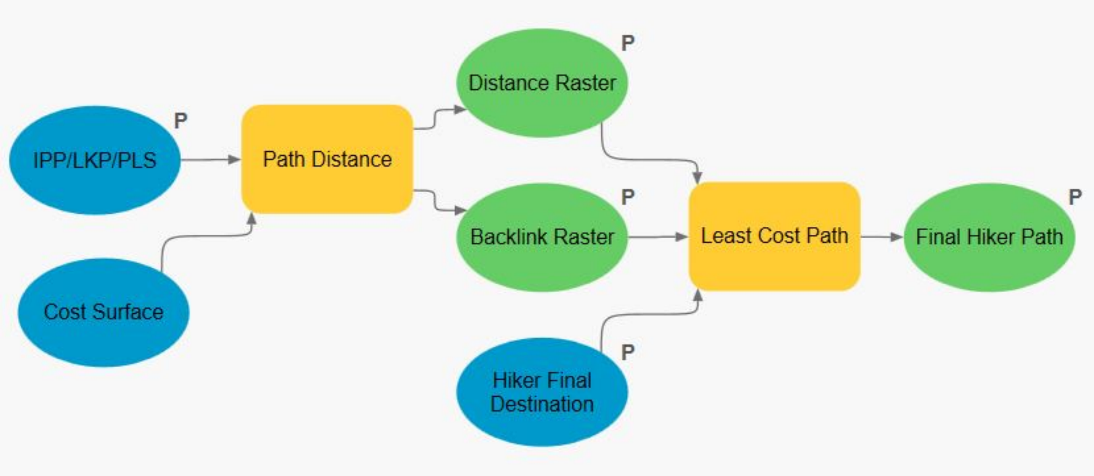

Figure 19 Least cost path model

Case number 20001009 was randomly chosen as an example of representation in Figure 20 and Figure 21. The case starting point is depicted as well as the backlink and cost distance raster related to it. Results of the analysis are shown in the next chapter.

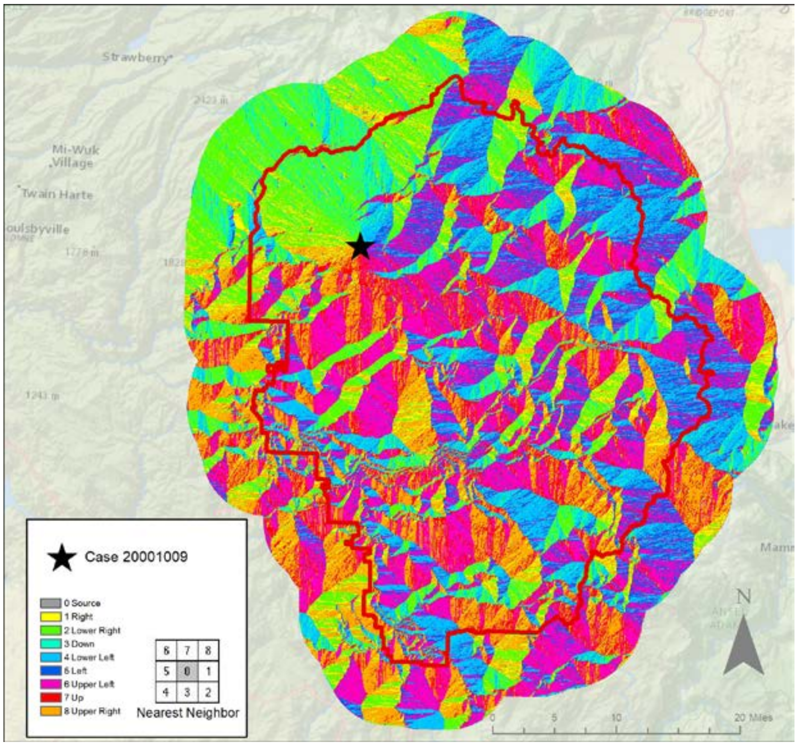

Figure 20 Cost backlink raster

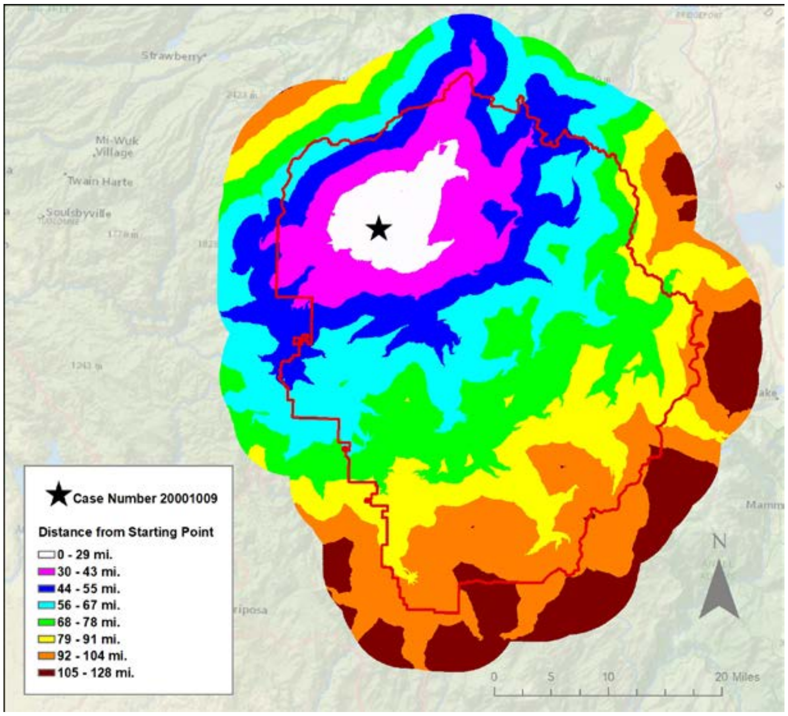

Figure 21 Cost distance raster

3.5 Trail Divergence

The last part of this study is the identification of locations of trail divergence, a process that was done manually. Each of the paths successfully generated was visually reviewed from start to finish. A new point data set was created manually to contain the points on the cost paths where they diverged from a trail or road.

Since the paths did not follow the trails and roads polylines to an exact degree, slight deviations from the park trails and roads were not noted. The only points considered locations of divergence were those where the cost paths explicitly deviated from designated trails or roads. Many paths did not follow trails or roads because the IPPs were not located near those features. For ease of access purposes, each divergence point record contained the case number, trail or road name from which its cost path diverged, and the subject's intended destination. The results of this study were uploaded to ArcGIS Online, so those attributes were added to facilitate future research.

Divergence points were counted per trail to locate any possible clusters. All park trails and roads vary in length so measuring the divergence point clusters on a trail by trail basis was accompanied with a degree of uncertainty. Clusters of divergence points were also highlighted visibly because trails with different names often converge with one another.

3.6 Sensitivity Tests

To make certain that the cost path analyses were done as accurately as possible, a sensitivity test was completed. A second cost surface was created that contained many of the same values that were part of the original cost surface, though the slope values between zero and 60 were assigned distinct impedance values and the stream order raster values were also altered. Land cover, lakes, trails, and roads were not altered. Logically, lakes were always complete barriers. Trails and roads also needed to remain priority. Land cover required in-depth research to alter impedance values in a logical way. This was outside the scope of this portion of the study.

Waterway impedances for stream orders 1 and 2 were decreased to no impedance. The logic here is that, particularly in sandy, desert terrains, first and second order streams are typically intermittent (Hughes, Kaufmann, and Weber 2010) and they would easily be crossed by hikers. While it is possible that first and second order streams in Yosemite will not be easily crossed given the likelihood of year-round flow due to snowmelt and plentiful groundwater, for this test, the low order impedance values were removed. Impedance levels for orders 3 through 7 were also decreased to test the sensitivity of results to changes in the cost surface.

Table 8 contains the values used in the test cost surface. The test cost surface contains costs that range from one to 301 and is illustrated in Figure 22.

Table 8 Impedance values adjusted for sensitivity test surface

DEM Degrees	Reclassification
0 – 9	10
10-19	20
20-29	30
30-39	40
40-49	50
50-59	60
60-88	99

Stream Order	Impedance
1	0
2	0
3	30
4	40
5	80
6	90
7	99

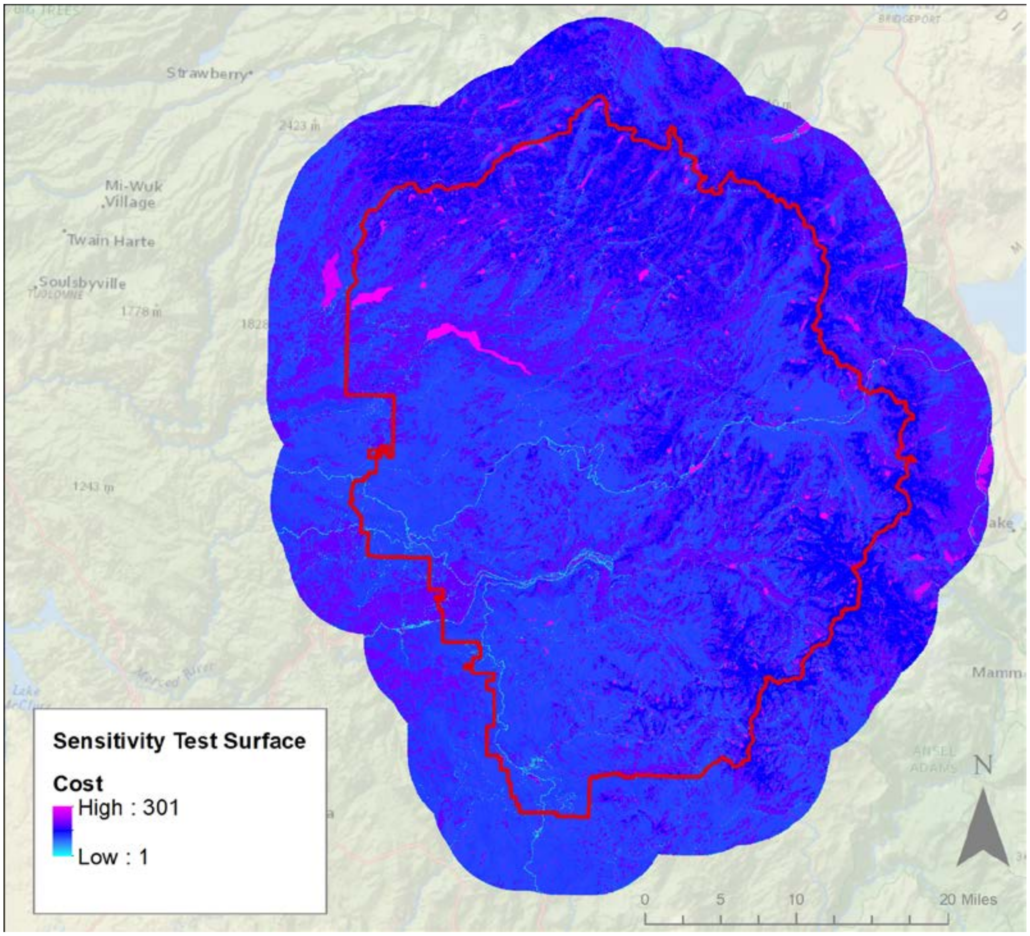

Figure 22 Test cost surface for sensitivity analysis

After the initial path analysis was completed and the trail divergence analysis was done, the trails that showed the most numerous incidents of path divergence were analyzed using the second cost surface with different reclassified raster values.

3.7 Summary of Data and Methodologies

This chapter outlined the most important parts of this study. All the data sets acquired for this study were described. Impedance values were assigned to acquired data sets in accordance with IGT4SAR and the Doherty et al. (2013) study. All data sets were prepared for raster calculation using analytical methods such as Strahler stream order analysis, slope analysis, and vector to raster conversion. After the cost surface was produced, least cost path analyses were conducted. Resulting cost paths were then traced along trails and roads to reveal points where cost paths diverged from them. The results of these analyses and procedures are discussed in the next chapter.

Chapter 4 Results

This chapter examines the results of the methodologies presented in Chapter 3 of this study. The results of the least cost path analyses conducted on the matching pairs of points are reviewed as well as the points identified where paths diverged from designated park trails and roads. Locations where there were the most occurrences of cost paths diverging from park trails and roads are discussed as well as any clusters that were evident on trails and roads in the park. Finally, the results of the sensitivity analyses conducted in the areas with divergence clusters are discussed.

4.1 Least Cost Paths and Trail and Road Divergence

As expected, the paths created from the least cost path analyses presented clear points where cost paths appeared to diverge from park trails and roads. Of the 117 cost paths created, 81 paths ended on park trails or roads. There was a total of 36 cost paths that showed points of divergence from park trails and roads. Five of the path divergence points were from park roads and 31 were from park trails. Since trails were the focus of this study, the 31 paths that diverged from trails are discussed in the remaining sections. The resulting paths are displayed on the map in Figure 23. It is important to note that any solid purple lines represent overlapping cost paths.

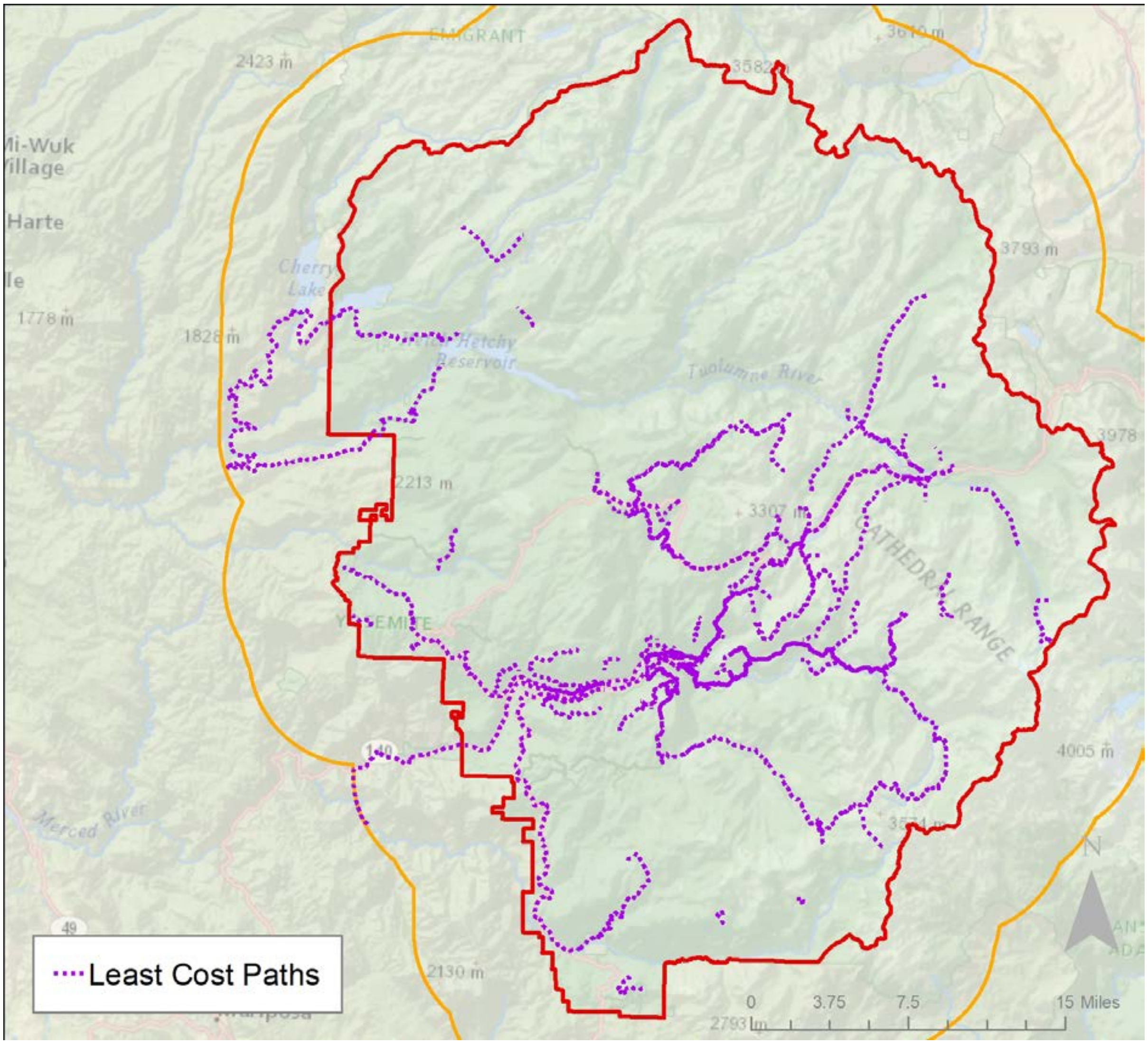

Figure 23 Resulting cost paths from least cost path analyses

The table in Appendix B details each path created as well as whether the path contained a trail divergence point. The zoomed in map in Figure 24 still contains all 117 paths created during this study, along with the 36 points where cost paths diverged from park trails or roads. Visually, the divergence points do not appear to follow any patterns.

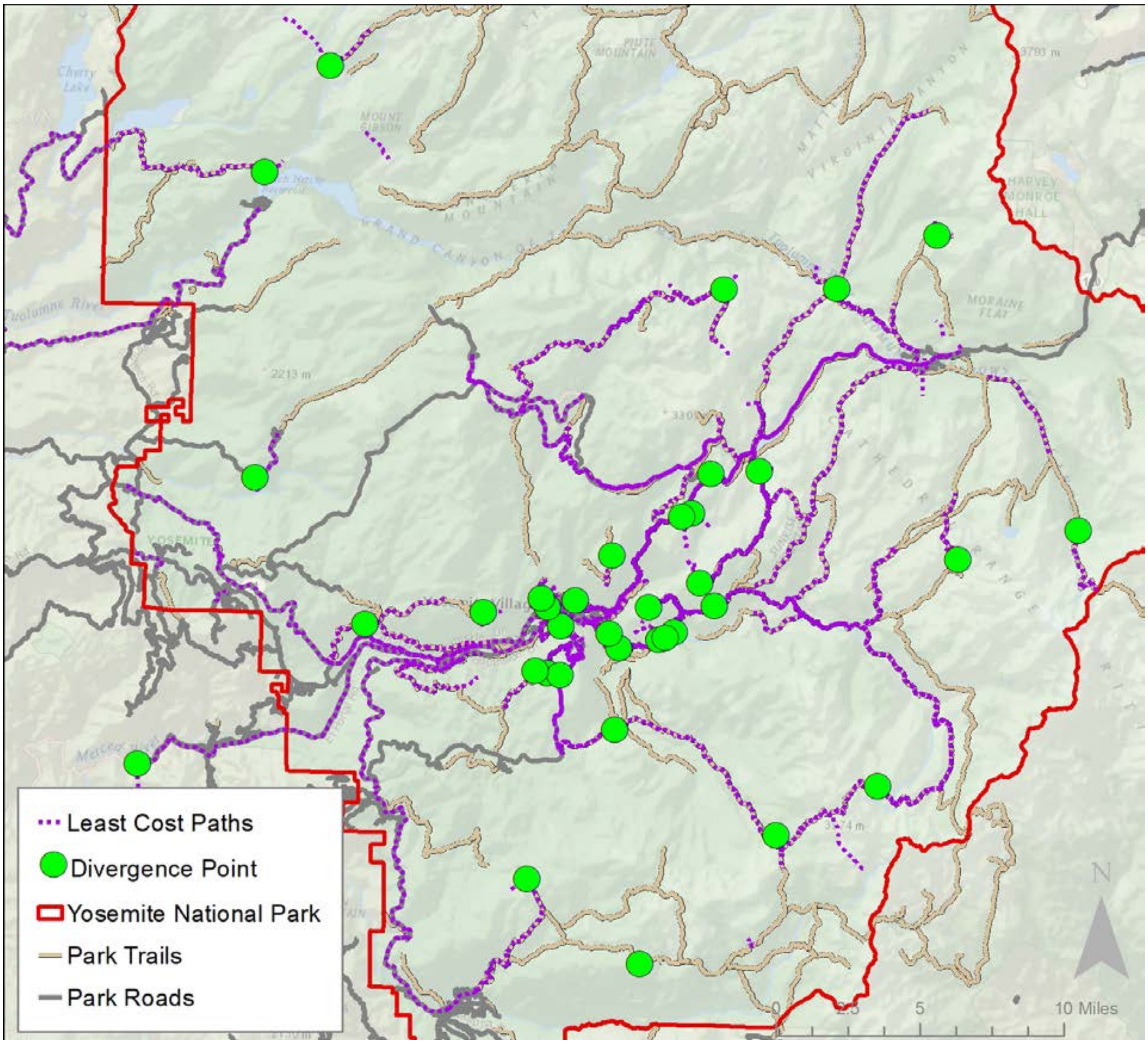

Figure 24 Trail and road divergence results

It is also important to note that all solid lines in Figure 24 represent overlapping paths. Not all park trails or roads contained cost paths. Eleven of the path divergence points rested on trails with no names. Since there are 316.1 miles of un-named trails, this may hold no significance. However, the maintenance and future naming of the trails with no names may be a future necessity. Park trails containing cost path divergence points are listed in Table 9.

Table 9 Park trails containing cost path divergence points

Park Trail	**# of Points**	**Trail Length**
Bike Path	1	10.3 mi.
Crescent Lake Trail	1	0.1 mi.
El Capitan Trail	1	5.1 mi.
Four Mile Trail	1	4 mi.
Half Dome Trail	1	2.2 mi.
John Muir Trail	4	24.8 mi.
Miguel Meadow Fire Road	1	8.7 mi.
No Name (multiple trails)	11	316.1 mi.
North Dome	1	4 mi.
Old Big Oak Flat Road Trail	1	6 mi.
Pacific Crest Trail	2	64 mi.
Pohono Trail	2	11.5
Snow Creek Trail	1	16.3 mi.
Stock Trail	1	1.1
Valley Loop Trail	3	16.5 mi.

4.1.1. Divergence Clusters

Of the 31 park trail divergence points that were discovered, several fell on the same park trails. Table 9 shows the John Muir Trail, Pacific Crest Trail, Pohono Trail, and Valley Loop Trail all contain more than one point of divergence. However, the frequency of these points per trail is difficult to compare due to varying lengths of the park trails. Also, a large proportion of the divergence points lie on trails with no names. Because of this, rather than using a mathematical measure to identify clusters on certain trails, clusters of points were visibly detected.

Each of the cluster locations were numbered to later match with sensitivity analysis outcomes. There were only 2 clusters worth noting in this study. A cluster of four divergence points is illustrated in Figure 25.

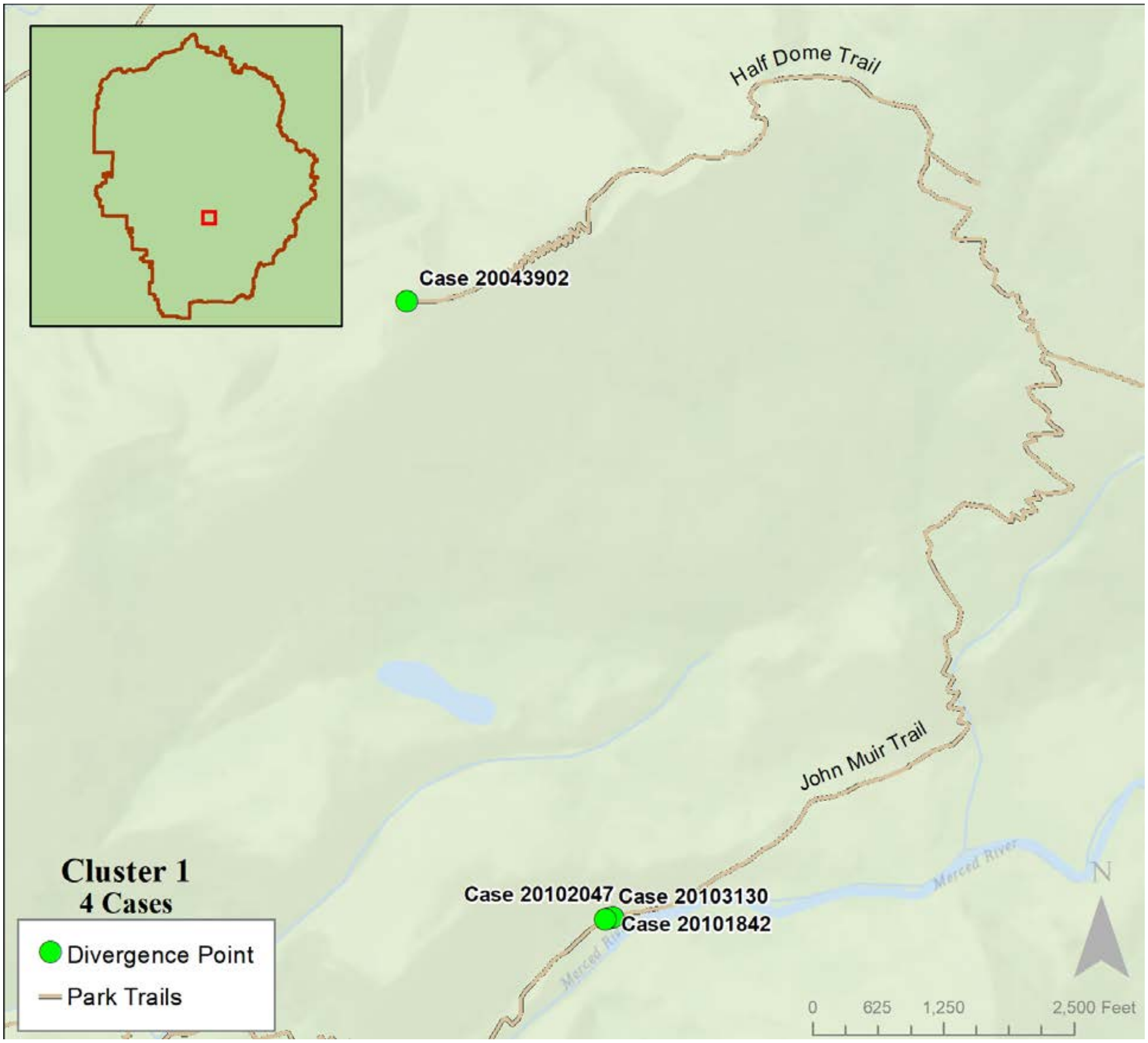

Figure 25 First divergence point cluster example

Since many of the IPP locations and found locations were georeferenced using the same point locations, many of the cost paths overlap one another. In the example illustrated in Figure 25, the three cases on the Southern part of the map all contain the same found location georeferenced point. Because of this, the paths in this example were represented individually in Figure 26 for legibility purposes. Arrows on the maps demonstrate the directions that the paths took from start to finish.

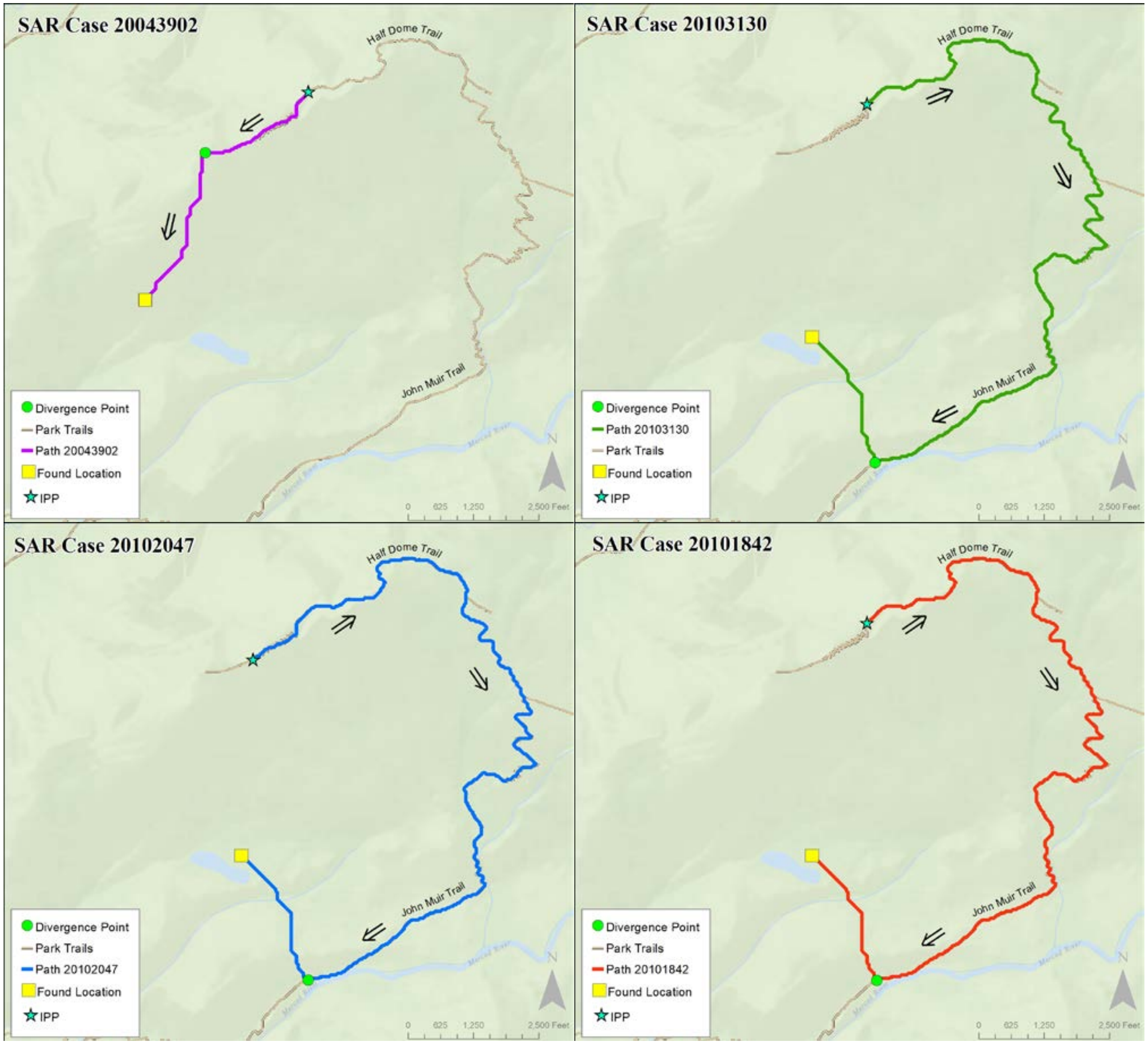

Figure 26 First divergence point cluster cost paths

There was only one other location with a small cluster of cost path divergence points. Though there are many other locations within the study area that contained what appeared to be clusters, closer examination showed more of a random distribution among several different park trails and roads. The second cluster example shows two divergence points that lie on the same park trail. Figure 27 shows the second divergence point cluster.

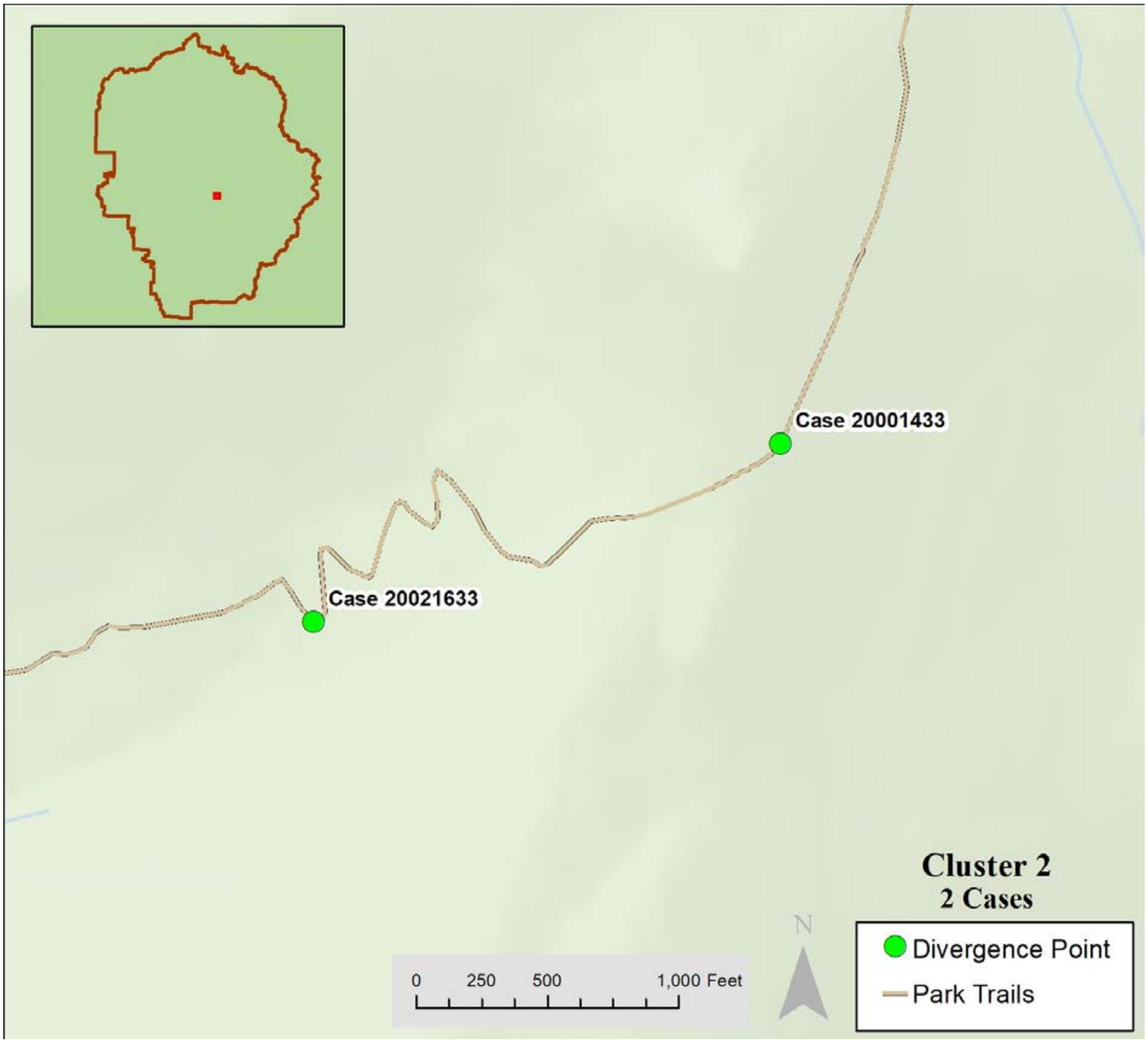

Figure 27 Second divergence point cluster example

The cost paths in the second cluster example did not have matching georeferenced IPP data or found locations like those in Figure 25. The second cluster example paths are shown in Figure 28.

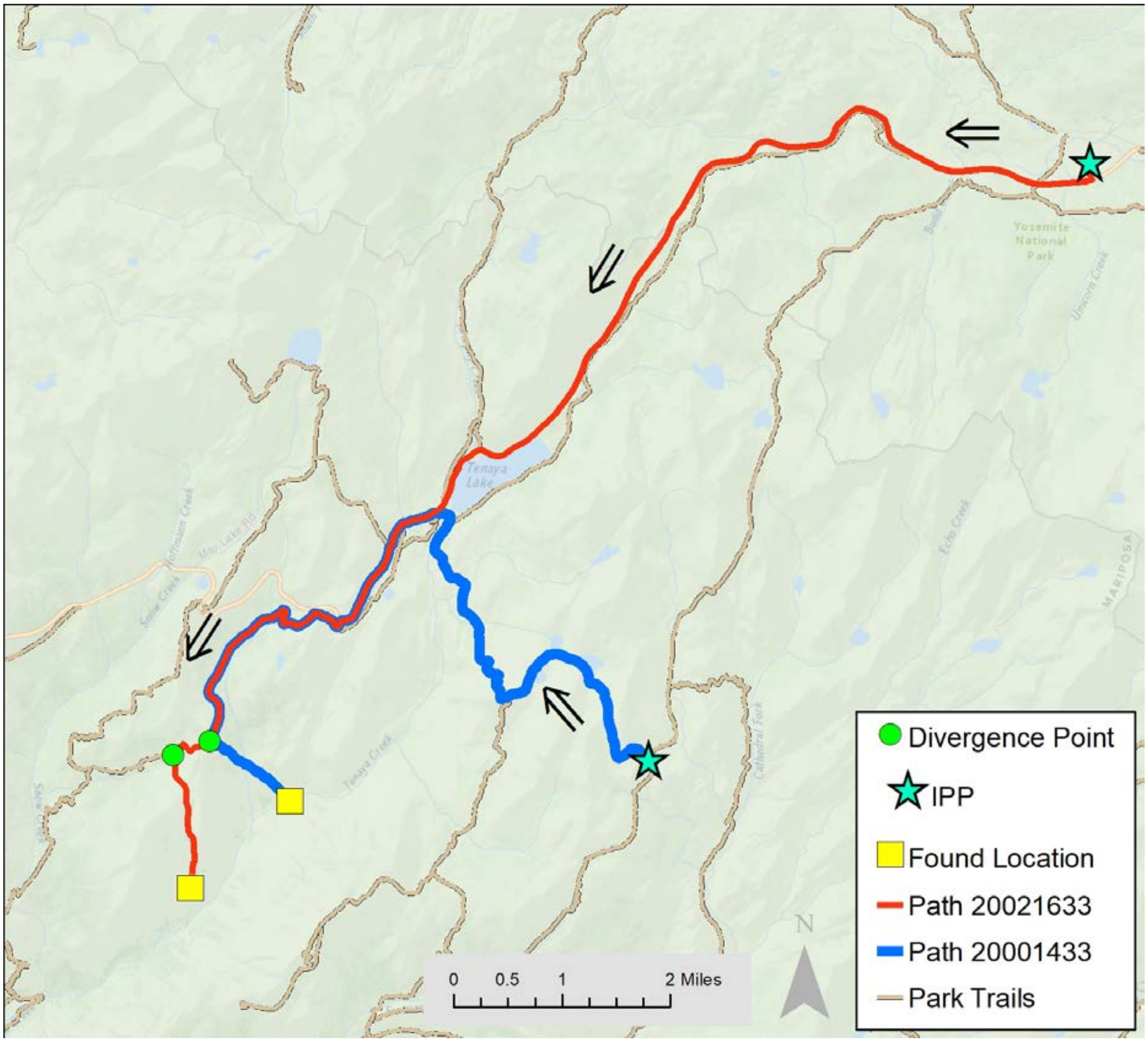

Figure 28 Second divergence point cluster cost paths

The paths that contributed to the first and second cluster examples were the paths tested using the second cost surface described in Section 3.6. The results of the sensitivity testing are discussed in the next section.

4.2 Sensitivity Tests

The purpose of the sensitivity testing was to find if any logical changes in impedance values could alter the outcomes of the cost path analyses and possibly invalidate the cost paths created using the primary cost surface. The first divergence cluster sensitivity test results appeared to follow similar paths that the original cost paths followed. The paths followed the designated park trails and diverged in a bit of a different fashion toward the found locations than the original cost paths. However, the difference between the two analyses is not drastic enough to invalidate the primary cost surface of this study.

The second set of sensitivity tests conducted on the second divergence cluster also showed very similar results to those of the primary analyses. The cost paths produced appear to be almost identical to those of the primary cost path results. This further suggests that the original cost paths created upon the original cost surface are sufficiently stable.

Figure 29 and Figure 30 show the results of the first two paths of the first sensitivity analysis. The light blue line in the first two tests, as well as the remaining tests, represents the path created on the test cost surface. All other symbology was retained from the original paths from the cluster examples. Figure 31 and Figure 32 show the second two paths resulting from the first sensitivity analysis. Figure 33 and Figure 34 show the results from the second sensitivity test conducted on the second divergence cluster.

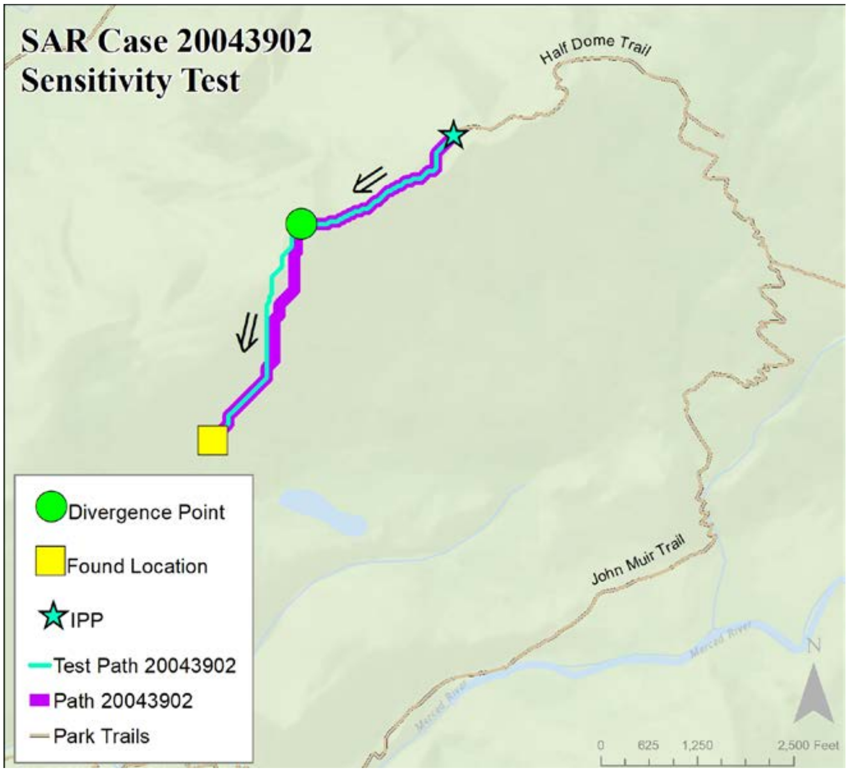

Figure 29 Sensitivity test 1 part 1

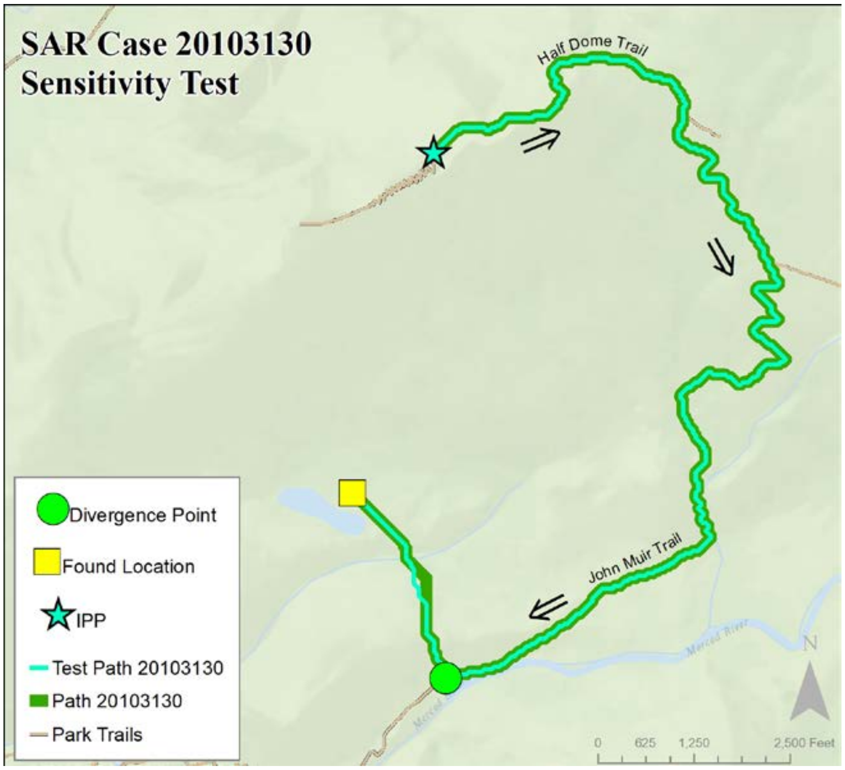

Figure 30 Sensitivity test 1 part 2

Figure 31 Sensitivity test 1 part 3

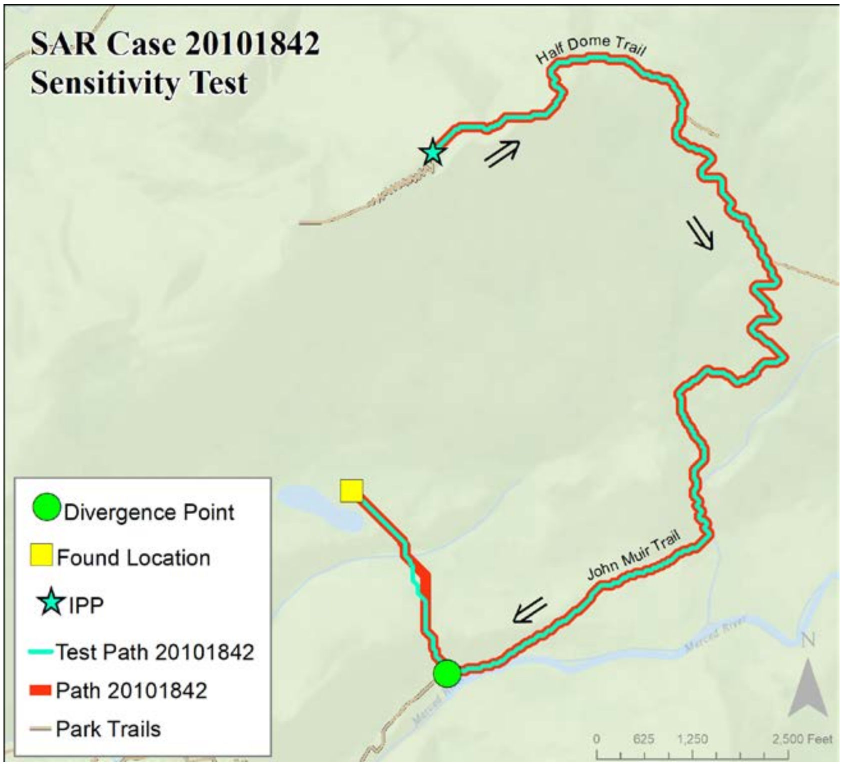

Figure 32 Sensitivity test 1 part 4

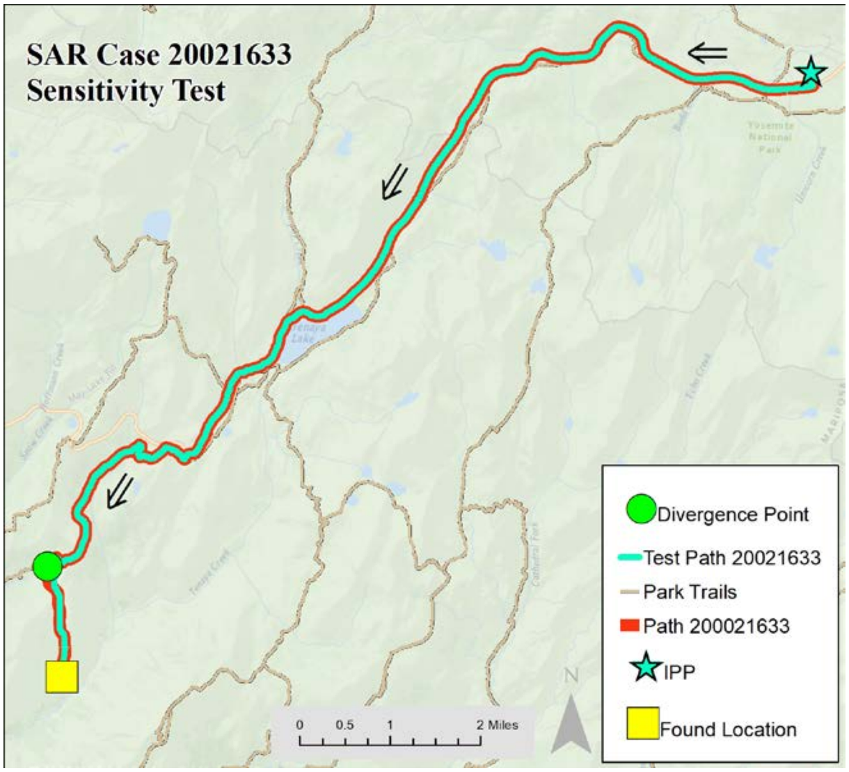

Figure 33 Sensitivity test 2 part 1

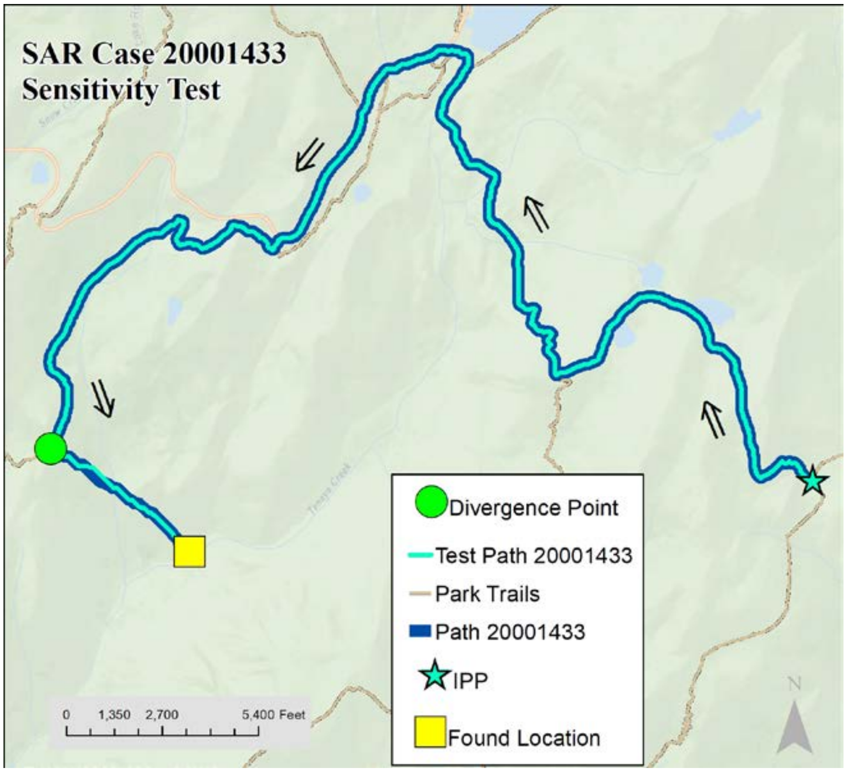

Figure 34 Sensitivity test 2 part 2

4.3 Results Summary

In this chapter, the immediate results of the cost path analysis, trail divergence analysis, and sensitivity testing were discussed. Trails and roads were inundated by the least cost paths of this study. Most paths followed trails or roads, entirely. This was due to the nature of the search cases as well as the impedance values that were assigned to park trails and roads in the final surfaces. Some paths, however, deviated from park trails and roads, pointing out possible portions of park trails or roads that may require examination. Some park locations showed signs of clustering of points where cost paths diverged from designated trails and roads. The clusters discovered revealed that the use of this study's methodology can identify portions of park trails where cost paths deviated, suggesting hiker divergence from trails that may need maintenance or evaluation. These and other conclusions are discussed in Chapter 5.

Chapter 5 Discussion and Conclusions

The objective of this study was to assess the ability of the least cost path analysis technique to reveal locations where least cost paths diverged from designated park trails, using past SAR missing persons data as well as data pertaining to land features and elevation. The techniques used in this study mirrored many of those used in the past by GIS professionals in the realm of SAR. The Integrated Geospatial Tools for Search and Rescue provided concrete methodologies to complete the analyses required to logically reach the initial objectives.

Determining the validity of a least cost path travelled over a travel cost surface relies heavily on the starting and ending points in the data. Since the IPP and found locations of many SAR missions do not typically provide the actual points where individuals began and ended their journeys, assumptions must be made while acknowledging any uncertainties. In this chapter, conclusions are addressed as well as any observations from the results of the methods outlined in Chapter 3. It is also important to note any limitations or shortcomings that may have been apparent in the data and analyses and to acknowledge their impact on the analytical techniques used in this study. Finally, this chapter discusses any recommendations for future projects and work.

5.1 Study Observations

The results of the cost path analysis were as expected. The trails and roads were given priority and many of the IPP's were located on trailheads, parking lots, or trail forks. Because of this, most of the cost paths explicitly followed trails or roads until the end of the line segment or until the path neared the point where the lost individuals were found. Not all the cost paths followed park trails or roads. Some of the paths began and ended in areas where trails or roads were not designated. Some areas, like the one depicted in Figure 25, show that the IPP and found locations of several SAR cases contain the exact same coordinates of IPPs or found locations of other cases. The resulting data sets would have been far more robust had there been different coordinates for each IPP or found points. Unfortunately, the methods used for georeferencing the IPP and found locations data sets would not allow for it.

An interesting byproduct of this study could have highlighted the trails and roads that were the most or least traversed. However, since there is no way to prove that the lost hikers represented in this study traversed the resulting paths, that assumption cannot be made. An interesting observation of this study was that there were not as many clusters of divergence points as expected. Figure 35 shows an area of YNP that is densely populated with roads, trails, and what appear to be human infrastructure. The divergence points in this area show no strong patterns. Arrows were included in this graphic to display the directions in which the paths diverged.

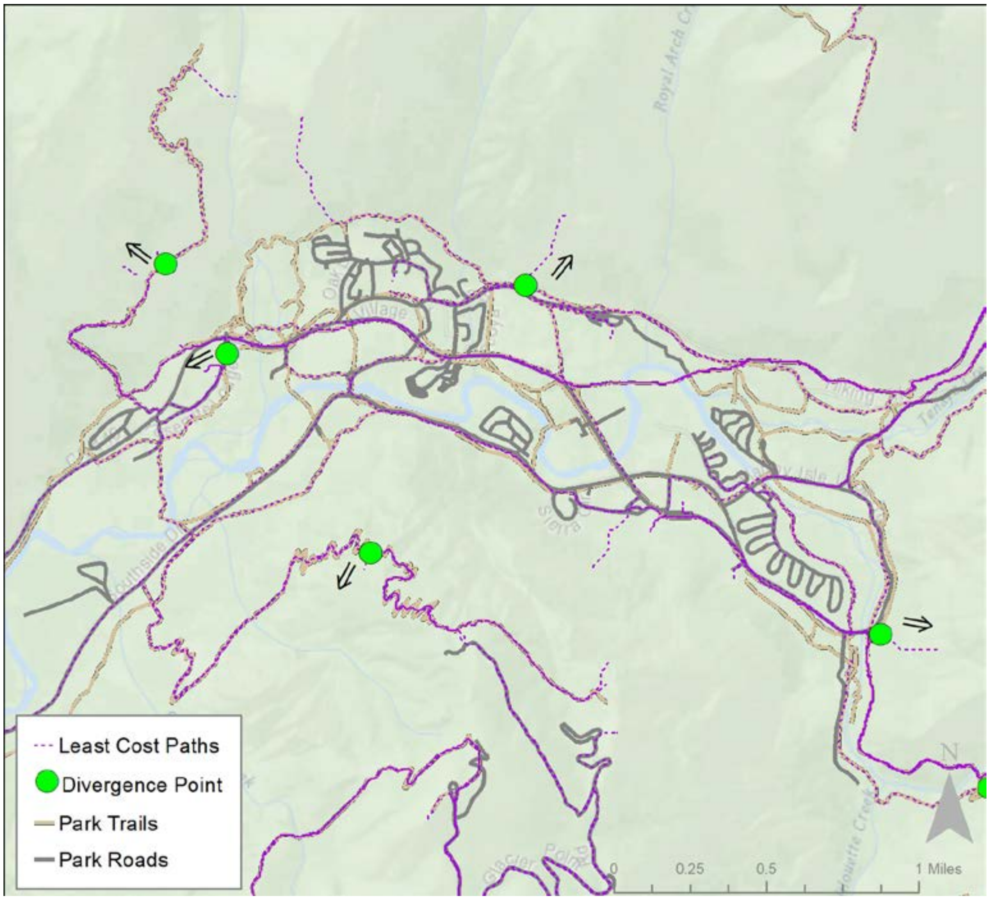

Figure 35 Heavily frequented area with divergence points

Typically, one would assume that heavily frequented areas would be more prone to park trail deviation, due to higher activity of more inexperienced visitors. However, another assumption is that one can more easily find their way back by following others. The presence of more human infrastructure may also explain why these areas do not show any path trail divergence patterns. The divergence points in Figure 35 do show that the paths became divergent when moving away from the populated area of the park. This is not significant, as there are only five divergence points that appear to show this behavior in an apparently random distribution. However, finding more examples of such behavior may be of future use to park planners or park maintenance staff.

5.2 Use of Results

The least cost paths created in this study can suggest ways that these methodologies might be applied. The clusters of divergence points can be used to evaluate possible maintenance issues with park trails. Roads may be misleading or may appear to be hiking trails if not paved. If all points of divergence are illustrated in a similar fashion to those in Figure 34, park maintenance and planning staff can visualize where trails contain possibilities of deviation as well as the directions in which the paths are deviating. The points where paths diverged from designated trails can provide possible insights into where trails can be extended or where trail loops may be useful.

Many visitors are attracted to the natural beauty of national parks, but do not possess the skills to properly navigate wilderness terrain. Least cost paths and divergence point clusters may provide park staff with the information they need to make changes that can directly influence park visitors’ safety. Some examples of uses may be to implement call boxes with lights that can be seen clearly in problematic areas at night. First aid boxes or water coolers may also be strategically placed in areas that are further from areas with higher foot traffic. Park staff could invite visitors to leave what they did not use so others may use it in case of emergency.

5.3 Recommendations

Some questions come to mind when reviewing the results of this study. Why would hikers strictly follow trails and then abruptly become lost? Were there any other landscape conditions that caused the hikers to become lost aside from terrain features and elevation? The answer to the first concern is that most of the hikers may have begun their journeys with the best of intentions. Intended destinations, available in Appendix B, can verify that many of the lost hikers meant to make their way to popular points of interest in the park. These points of interest all have designated trails meant to guide visitors to them. Because of this, this study assumed that hikers used trails and diverged from the trail at some point and became lost. It was this assumption that caused the results to appear to prioritize the trails and roads.

Many other factors that may have contributed to hikers becoming lost on their journeys include time of day and seasonal weather changes. Snow fall, vegetation growth during different seasons, and unanticipated daylight loss could be to blame for many losing their way. It is recommended that impedance levels in IGT4SAR be augmented in a way that reflects the time of day or season during which the subject became lost.

There are also 316.1 miles of un-named trails in YNP. In this study, there were 11 points of path divergence from un-named trails. It is possible that lost individuals would have the ability to describe their location when lost more specifically if the name of the trail they were hiking is distinct. Also, if trails are named, there may be more effort taken to maintain and provide signage on them so they are more distinctive to lost individuals. For these reasons, naming un-named park trails is recommended as a step in maintaining them.

5.4 Study Limitations

Much of what made this study possible was the SAR missing persons data. Since data pertaining to lost persons typically only refers to the IPP or the locations where subjects were found, this complete data with paired starting and ending points was invaluable. The processes used to georeference the IPP and found locations in this study were useful in providing parameters for the analyses, however, they were not originally created for this specific type of analysis. Those original researchers were testing methodologies that could be used in the future (Doherty et al. 2012) so the accuracy of these points was not as critical as it was in this study.

Additionally, the study made the fundamental assumption that trails and roads would be priority modes of transit for those who had become lost. The limitations of the data as well as the least cost path limitations are discussed in the following subsections.

5.4.1. SAR Missing Persons Data Limitations

The SAR missing persons data provided a picture of the magnitude of missing persons from 2000 to 2010 in Yosemite National Park. However, how the data were originally georeferenced is what caused many of the paths to overlap and appear redundant. It is understood that there is no way to know exactly where a subject began their journey because subjects do not leave with the intention of becoming lost. Unless the subject was recording a GPS track of their journey, this is not possible.

The georeferencing techniques that were used by those who gathered the initial IPP and found locations data sets used common sites to plot points from descriptions. The uncertainties within the descriptions were calculated and included with each feature. This provides different tabular records, but spatially, many share the same data. Because of this data collection method, the cost path analysis produced many identical paths for different SAR cases.

5.4.2. Least Cost Path Analysis Limitations

The success of this study relied heavily on the cost surface and least cost path analysis being completed in an appropriate fashion. Trails and roads were set to the lowest cost in this analysis because one of the primary objectives addresses park maintenance and trail construction. However, it is unlikely that all hikers follow a logical least cost path sticking to trails and roads as long as possible. Many lost hikers may become lost while attempting to carve their own paths in wilderness areas. Many may also become lost while following routes that are not park designated trails. Therefore, one cannot assume that the results of this study provide concrete evidence that portions of park trails require maintenance.

Least cost path analyses typically include the variables of speed and time. This study did not account for the speeds at which the hikers were traveling, nor the time it took for search subjects to be found or recovered. If those variables were included, the outcomes may have changed, given the amount of time that it took for subjects to be recovered or found.

In addition, although the cost impedances from Ferguson's IGT4SAR tool were used here, that tool was not created to predict exactly where lost persons are during a search. It was created as a tool to assist searchers with POAs and provide theoretical search areas before the subject is found. The impedance levels that were implemented in the cost surface for this study were not tailored to each individual's characteristics and abilities as they can be when IGT4SAR is used for a single SAR mission.

5.4.3. Divergence Point Data

Clusters from the divergence point study were revealed by visually canvassing the resulting trails and divergence points. A density analysis would have been an ideal means by which to analyze these results but such an analysis could not be conducted with so few records. If more cases existed and many more paths revealed points of divergence, density analyses could produce more interesting and compelling results that could possibly expose problematic park trails.

5.5 Future Work

Search and rescue techniques have been studied a great deal, but the study of hiker loss prevention has not been widely researched. This area plays hand in hand with studies of lost person behavior and the psychology of lost persons. However, those two fields of study assume that individuals are already lost. Studying how to keep park visitors on trails or how to prevent further individuals from becoming lost or disoriented has future potential. If the data exist, further studies with larger sets of search and rescue data could be undertaken. The analyses conducted in this study can be replicated in different locations with different SAR data. Since it was addressed that many of the IPP's and found locations shared spatial locations in this study, the use of a data set that does not contain as many uncertainties may reveal some interesting results.

If one were to create a topologically correct trail and roads network, the divergence points could have been measured using segments of equal length. This could allow one to calculate statistics pertaining to specific trail segments or probabilities that specific park trails will incur trail divergence. Also, one could include the time of year and time of day as variables in the analysis of the lost individuals in the park, using the Doherty data set. An analysis including these variables may produce interesting results that can also assist park staff and maintenance with future processes.

5.6 Conclusion

This study began with the hope that finding clusters of paths that diverged from park trails would highlight opportunities for trail improvements and signage placement. This objective was achieved. However, the clusters located are not significant enough to stimulate action in those areas. The limited data pertaining to the actual paths traversed by lost individuals is the cause of this uncertainty. But, prevention of park trail diversion and, ultimately, prevention of costly SAR missions may be accomplished using the methodologies outlined in this study on new, more diverse, SAR data. Much of the prevention today comes from educating visitors about the dangers of wilderness and about difficult terrain. This study can provide another avenue for increasing park safety, given more specific data.

References

Abi-Zeid, Irène, and John R. Frost. 2005. "SARPlan: A Decision Support System for Canadian Search and Rescue Operations." *European Journal of Operational Research* 162 (3): 630-53.

Adams, Annette L, Terri A Schmidt, Craig D Newgard, Carol S Federiuk, Michael Christie, Sean Scorvo, and Melissa DeFreest. 2007. "Search Is a Time-Critical Event: When Search and Rescue Missions May Become Futile." *Wilderness & Environmental Medicine* 18 (2): 95– 101.

Bantry White, Eleanor, and Paul Montgomery. 2015. "Dementia, Walking Outdoors and Getting Lost: Incidence, Risk Factors and Consequences from Dementia-Related Police Missing-Person Reports." *Aging & Mental Health* 19 (3): 224-30.

Boore, Stacy M., and Dov Bock. 2013. "Ten years of search and rescue in Yosemite National Park: Examining the past for future prevention." *Wilderness & Environmental Medicine* 24 (1): 2-7.

Doherty, Paul J., 2013. "The applications of GISystems to wilderness search and rescue, an overview within a GIScience context and examples from Yosemite National Park." Doctoral Dissertation. University of California, Merced.

Doherty, Paul, Qinghua Guo, Yu Liu, John Wieczorek, and Jared Doke. 2011. "Georeferencing Incidents from Locality Descriptions and its Applications: A Case Study from Yosemite National Park Search and Rescue." *Transactions in GIS* 15 (6): 775-93.

Doherty, Paul J., Quinhua Guo, Jared Doke, and Don Ferguson. 2014. "An analysis of probability of area techniques for missing persons in Yosemite National Park." *Applied Geography* 47: 99-110.

Doherty, Paul J., Qinghua Guo, Wenkai Li, and Jared Doke. 2014. "Space-time analyses for forecasting future incident occurrence: A case study from Yosemite National Park using the presence and background learning algorithm." *International Journal of Geographical Information Science* 28 (5): 910-27.

Doke, Jared. 2012. "Analysis of Search Incidents and Lost Person Behavior in Yosemite National Park." Master's Thesis, University of Kansas.

Esri. 2012. "MapSAR User's Manual." Version 1.3. Accessed October 28, 2017. Retrieved from: www.mapsar.net/files/mapsar-users-manual.pdf.

Esri. 2016a. "How Fill Works – Help, ArcGIS for Desktop." Accessed March 25, 2018. http://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/how-fill-works.htm.

Esri. 2016b. “Flow Direction.” Accessed April 19, 2018. http://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/flow-direction.htm

Esri. 2017a. “Creating the Least-Cost Path.” Accessed September 22, 2017. http://desktop.arcgis.com/en/arcmap/latest/tools/spatial-analyst-toolbox/creating-the-least-cost-path.htm.

Esri. 2017b. “Flow Accumulation.” Accessed April 24, 2018. http://pro.arcgis.com/en/pro-app/tool-reference/spatial-analyst/flow-accumulation.htm

Esri. 2017c. “Identifying Stream Networks.” Accessed April 20, 2017. http://pro.arcgis.com/en/pro-app/tool-reference/spatial-analyst/identifying-stream-networks.htm

Ferguson, Don. 2013. “Integrated Geospatial Tools for Wilderness Search and Rescue – IGT4SAR: Electronic Mapping for Search and Rescue Operations.” Presented at Appalachian Search and Rescue Conference, Pennsylvania, 2013.

Frakes, Brent, Thomas Flowe, Kirk R. Sherrill. 2015. “National Park Service Travel Time Cost Surface Model (TTCSM).” *Natural Resource Report NPS/NRSS/NRR—2015/933*. National Park Service.

Green, H., J. Gilbert, R. James, and R. W. Byard. 2001. “An Analysis of Factors Contributing to a Series of Deaths Caused by Exposure to High Environmental Temperatures.” The American Journal of Forensic Medicine and Pathology 22 (2): 196-9.

Hashmi, Maaz Maqsood, Ludovico Frate, Syed Moazzam Nizami, and Maria Laura Carranza. 2017. “Assessing Transhumance Corridors on High Mountain Environments by Least Cost Path Analysis: The Case of Yak Herds in Gilgit-Baltistan, Pakistan.” *Environmental Monitoring and* Assessment 189 (10): 1-9.

Hill, K. A. 1998. "The psychology of lost." Lost Person Behavior. *Ottawa: National SAR Secretariat*: 1-16.

Hughes, Robert M., Philip R. Kaufmann, & Marc H. Weber. 2010. “National and Regional Comparisons between Strahler Order and Stream Size.” *Journal of the North American Benthological Society* 30, 103-21.

Hung, Eric K., and David A. Townes. 2007. “Search and Rescue in Yosemite National Park: A 10-year review.” *Wilderness & Environmental Medicine* 18 (2): 111-6.

Jobe, R., T., White, P., S. 2009. “A new cost-distance model for human accessibility and an evaluation of accessibility bias in permanent vegetation plots in Great Smoky Mountains National Park, USA.” *Journal of Vegetation Science*, 20 (6) 1099 -1109.

Johnson, Mark P. 2016. “Evaluating the Utility of a Geographic Information Systems-Based Mobility Model in Search and Rescue Operations.” Master’s thesis. University of Southern California.

Koester, Robert J. 2008. *Lost Person Behavior: A Search and Rescue Guide on Where to Look—for Land, Air and Water.* Charlottesville, VA: dbS Productions LLC.

Koester, R. & Stooksbury, D. 1992. "Lost Alzheimer's Subjects-Profiles and Statistics." *Response*. 11:4:20-26.

Lin, Lanny, and Michael Goodrich. 2010. “A Bayesian Approach to Modeling Lost Person Behaviors Based on Terrain Features in Wilderness Search and Rescue.” *Computational and Mathematical Organization Theory* 16, no. 3: 300-23.

National Park Service. 2006. “United States National Park Service Management Policy.” Accessed September 15, 2017. http:// www.nps.gov/policy/MP2006.pdf.

National Park Service. 2012. “Search and Rescue.” Last modified March 31. Accessed September 24, 2017. https://www.nps.gov/romo/search_and_rescue.htm.

National Park Service. 2017. “NPS Stats.” Accessed October 21, 2017. https://irma.nps.gov/Stats/Reports/Park/YOSE.

Pedder, John. 2012. “MapSAR—Life-Saving Maps.” Presented at Esri 2012 GeoDesign Summit. Redlands, California. January 5-6.

Rivera, James Anthony. 2014. “A Threat-Based Least-Cost Path Decision Support Model for National Security Resource Allocation Along the US-Mexico border.” Master's thesis. University of Southern California.

Rowe, Meredeth, Amy Houston, Victor Molinari, Tatjana Bulat, Mary Elizabeth Bowen, Heather Spring, Sandra Mutolo, and Barbara McKenzie. 2015. “The Concept of Missing Incidents in Persons with Dementia.” *Healthcare (Basel, Switzerland)* 3 (4): 1121-32.

Rowe, Meredeth A., Sydney S. Vandeveer, Catherine A. Greenblum, Cassandra N. List, Rachael M. Fernandez, Natalie E. Mixson, and Hyo C. Ahn. 2011. “Persons with Dementia Missing in the Community: Is it Wandering or Something Unique?” *BMC Geriatrics* 11 (1): 28.

Sava, Elena, Charles Twardy, Robert Koester, and Mukul Sonwalkar. 2016. “Evaluating Lost Person Behavior Models.” *Transactions in GIS* 20, no. 1: 38-53.

Siljander, Mika, Emilia Venäläinen, Floris Goerlandt, and Petri Pellikka. 2015. “GIS-Based Cost Distance Modelling to Support Strategic Maritime Search and Rescue Planning: A Feasibility Study.” *Applied Geography* 57 : 54-70.

Syrotuck, William G., and J. A. Syrotuck. 2000. *Analysis of Lost Person Behavior: An Aid to Search Planning.* Mechanicsburg, PA: Barkleigh Productions Inc.

Tarboton, D. G., R. L. Bras, and I. Rodriguez-Iturbe. 1991. “On the Extractions of Channel Networks from Digital Elevation Data.” *Hydrological Processes* 5: 81-100.

Theodore, J. 2009. “When Every Second Counts: Yosemite uses GIS for coordinating search and rescue operations.” *ArcUser* Summer 2009: 66-69.

Tomaszewski, Brian. 2015. *Geographic Information Systems (GIS) for Disaster Management.* Boca Raton, FL: CRC Press..

Trapp. Suzanne, Michael Gross, and Ron Zimmerman. 1994. *Signs, Trails, and Wayside Exhibits: Connecting People and Places.* Stevens Point, WI: UW-SP Foundation Press, inc.

US Department of the Interior. 1996. “North Country National Scenic Trail: A Handbook for Trail Design, Construction, and Maintenance.” Accessed May 1, 2018. https://www.nps.gov/noco/learn/management/upload/Handbook-complete-2.pdf

US Department of the Interior. 2018. “National Land Cover Database (NLCD 20110.” Accessed April 18, 2018. https://www.mrlc.gov/nlcd11_data.php.

Wieczorek, J., Q. Guo, and R. J. Hijmans. 2004. “The point-radius method for georeferencing locality descriptions and calculating associated uncertainty.” *International Journal of Geographical Information Science* 18, no. 8 (2004): 745-67.

Appendix A Park Trail Names and Lengths

NAME	Length (mi.)	NAME	Length (mi.)	NAME	Length (mi.)
	47.0	Housekeeping Bridge Trail	0.4	Overlook trail	0.3
Alder Creek Trail	2.8	Ireland Lake Trail	1.5	Pacific Crest National Scenic Trail	64.0
Babcock Lake Trail	0.5	Iron Creek Trail	2.5	Panorama trail	2.0
Bernice Lake Trail	0.5	Isberg Pass	0.6	PCT and JMT	17.6
Bike Path	10.3	John Muir Trail	24.8	Peeler Lake Trail	0.7
Bishop Creek Trail	1.3	Johnson Lake	0.1	Pohono Trail	11.5
Booth Lake Trail	0.3	Kendrick Creek Trail	1.6	Poopenaut Valley Trail	1.1
Bridalveil	0.4	Lower Yosemite Falls trail	26.1	Post Peak Pass	0.4
Buckeye Pass trail	0.7	Lukens Lake	5.0	Saddle Hill	0.0
Calif Tunnel Tree to Outer Loop trail	0.6	McCabe Lakes Trail	1.9	Sentinel Boardwalk	0.1
Californed Tunnel Tree North trail	0.1	McGurk Meadow Trail	1.9	Sentinel Dome Trail	0.4
Camp Mather Trails	1.8	Merced Grove Trail (Old Coulterville Rd)	1.8	Smith Peak Trail	1.3
Chilnualna Falls Trail	3.6	Miguel Meadow Fire Road	8.7	Snow Creek Trail	16.3
Cook's Meadow Boardwalk I	0.1	Mirror Lake Interpretive Loop	0.5	South Fork Tuolumne River Trail	1.6
Cook's Meadow Boardwalk II	0.2	Mirror Lake Loop	5.5	Spillway Lake	1.8
Cottonwood Meadow Trail	3.8	Mirror Lake Old Carriage Trail	0.4	Spur at Devil's Elbow	0.1
Crescent Lake	0.1	Mist Trail	0.6	Spur from Olmsted Pt	0.1
Dana Fork trail	0.0	Mt Hoffman	1.4	Stock Trail	1.1
Deer Camp Road	8.3	Museum to Outer Loop trail	0.2	Stoneman Meadow Boardwalk	0.2
Dog Lake trail	0.2	Nature trail	0.6	Summit Pass	1.0
El Cap Climbing Access	0.1	Nevada Fall Trail	0.9	Telescope Tree to Loop Road trail	0.0
El Capitan Trail	5.1	none	316.1	trail from Clothespin Tree to bathroom	0.5
Eleanor Creek Gaging Station Trail	0.4	North Dome	4.0	Trail from Museum to bathroom	0.1
Emeric Lake Trail	0.3	North Mountain	5.6	Trail from Museum to Fallen Tunnel Tree	0.2
Faithful Couple to Clothespin Tree	0.1	NPS Corral Stock Trail	0.2	Trail from Museum to Telescope Tree	0.2
Fallen Tunnel Tree to Outer Loop trail	0.0	Old Big Oak Flat Road	4.9	Trail from shuttle stop to trailhead	0.2
Fernandez Pass	0.7	Old Big Oak Flat Road (Gentry Rd)	2.0	Trail to Biledo Meadow	1.0

NAME	Length (mi.)	NAME	Length (mi.)	NAME	Length (mi.)
Forest Service trail	12.9	Old Big Oak Flat Road trail	2.2	Trail to Grizzly Giant	0.0
Four Mile Trail	4.0	Old Big Oak Flat Road Trail	3.8	Tuolumne Grove loop trail	0.0
FS trail	3.0	Old Bridle Path	0.6	Upper Falls Trail Access	0.1
Gravel Pit Lake Trail	0.5	Old Coulterville Rd	0.5	Upper Yosemite Falls Trail	2.5
Grizzly Giant to Faithful Couple trail	0.5	Old Glacier Point Road	3.1	Valley Loop trail	0.1
Grizzly Giant trail	0.5	Old Mine	0.0	Valley Loop Trail	16.4
group camp	0.3	Old road to Fish Camp	0.3	Valley Loop Trail / Mirror Lake Loop	0.4
Grouse Lake	0.1	Old Tioga Road	19.3	Vernon Lake Cabin Trail	1.3
Half Dome	2.2	Old Wawona Road	1.6	Virginia Pass Trail	1.6
Happy Isles Fen Boardwalk	0.1	Outer Loop trail to Faithful Couple	0.4	Wawona Meadow loop trail	3.3
Happy Isles HC trail	0.2	Outer loop trail to Fish Camp	0.3	Wawona Swinging Bridge Trail	0.8
Happy Isles Nature Center	0.3	Outer Loop trail	4.8	Wawona trail	3.2

Appendix B Least Cost Paths Explained

Path	Start	Near Feature	Intended Destination	Scenario	Divergence Point?	Rescue Method
20000942	Road	Taft Point	Taft Point	Lost but walked out	No	Walkout
20001009	IPP Not on Road or Trail	Tilltill Valley	Tiltill Valley	Severe Injury	No	Helicopter
20001416	IPP Not on Road or Trail	Swan Slab	Unknown	Not Lost	No	Other
20001433	**Trail**	**Near John Muir Trail**	**Yosemite Valley**	**Lost**	**Yes**	**Helicopter**
20001505	**Trail**	**Young Lakes Trail**	**Young Lakes**	**Lost**	**Yes**	**Helicopter**
20001719	Trail	Porcupine Flat Campground	Unknown	Not Lost	No	Other
20002715	Trail	Lodge Overflow Parking	Lower Yosemite Falls	Not Lost	No	Other
20002764	**Road**	**Ottoway Creek**	**Lower Ottoway Lake**	**Lost**	**Yes**	**Walkout**
20003134	Trail	Inspiration Point	Inspiration Point	Not Lost	No	Other
20010852	Trail	Glacier Point Road	Sentenel Dome Parking	Lost	No	Walkout
20011458	Trail	Four Mile Trail	Glacier Point	Lost	No	Walkout
20011968	Trail	Emerald Pool	Unknown	Not Lost	No	Walkout
20012531	Road	Bridalveil Creek	Pools Above Bridalveil Fall	Not Lost/ Overdue	No	Walkout
20012670	Off trail	Vogelsang Peak	Uknown	Not Lost/ Overdue	No	Walkout
20020367	**Parking Lot**	**Tamarack Creek**	**Foresta Road**	**Lost/ Stranded**	**Yes**	**Technical**
20020983	**Trail**	**Deer Camp**	**Alder Creek Loop**	**Lost**	**Yes**	**Helicopter**
20021197	Trail	Glen Aulin Trail	Uknown	Separated	No	Walkout
20021633	**Trail**	**Mt. Watkins**	**Yosemite Valley**	**Lost/ Stranded**	**Yes**	**Helicopter**
20022605	Trail	Ten Lakes Pass	Unknown	Lost	No	Walkout
20022977	Trail	Mono Meadow Trail	Yosemite Valley via Panorama Trail	Lost	No	Walkout
20023834	Trail	Red Peak Pass	Clark Range	Lost	No	Helicopter
20030346	Lodge	Upper Yosemite Falls Trail	Unknown	Not Lost/ Overdue	No	Walkout
20031175	**Trail**	**Half Dome - Subdome Steps**	**Unknown**	**Lost**	**Yes**	**Other**
20031696	**Trail**	**Kuna Creek**	**Small Lake Below Donohue Pass**	**Lost**	**Yes**	**Helicopter**
20031821	**Point of interest**	**Tenaya Canyon**	**Curry Village Taco Stand**	**Lost**	**Yes**	**Helicopter**
20031868	**Trail**	**Snow Creek Trail**	**Yosemite Valley**	**Lost/ Heat Illness**	**Yes**	**Helicopter**
20033063	Trail	Sunrise Lake Trailhead	Sunrise Lakes	Not Lost/ Overdue	No	Other

Path	Start	Near Feature	Intended Destination	Scenario	Divergence Point?	Rescue Method
20033118	Trail	Sunrise Lakes	Yosemite Valley	Not Lost	No	Other
20033240	Trail	Sunrise Lakes Trail	Uknown	Lost	No	Walkout
20033679	Trail	Cathedral Trailhead	Unknown	Lost	No	Other
20033854	Trail	Staircase Falls	Ahwahnee Hotel	Lost/ Medical	No	Other
20040633	**Building**	**Church Bowl**	**Loop Hike Awhahnee Hotel**	**Lost**	**Yes**	**Walkout**
20041002	Campground	Clark Point	Uknown	Lost/ Darkness	No	Walkout
20041652	**Trail**	**Crescent Lake Drainage**	**Unknown**	**Lost**	**Yes**	**Helicopter**
20041708	Trail	White Wolf Interp Office	Uknown	Lost/ Overdue	No	Other
20042012	Trail	Four mile trailhead	Four mile Trailhead	Lost/ Separated	No	Other
20042940	Trail	May Lake Trail	Unknown	Lost	No	Other
20043082	Trail	Happpy Isles	Little Yosemite Valley	Lost/ Separated	No	Other
20043237	**Trail**	**John Muir Trail**	**Tuolumne Meadows**	**Lost**	**Yes**	**Walkout**
20043902	**Trail**	**Lost Lake**	**Unknown**	**Lost**	**Yes**	**Helicopter**
20043928	**Trail**	**Union Point**	**Uknown**	**Lost**	**Yes**	**Helicopter**
20043987	Trail	Vernal Falls Footbridge	Half Dome	Lost/ Darkness	No	Walkout
20050901	**Road**	**Marble Point**	**Hite's Cove**	**Lost**	**Yes**	**Walkout**
20051044	Trail	Yosemite Lodge	Unknown	Not Lost	No	Other
20051614	**Trail**	**Tueeulala Falls**	**Lake Vernon Loop**	**Lost**	**Yes**	**Helicopter**
20052170	trail	Murphy Creek Trail	Murphy Creek Trailhead	Lost/ Overdue	No	Walkout
20052281	**Trail**	**Trail at top of El Capitan**	**Uknown**	**Lost/ Overdue**	**Yes**	**Walkout**
20052555	Trail	Delaney Creek	Young Lakes	Lost	No	Walkout
20052608	Water	Tenaya Canyon	Mount Whitney	Drowning	No	Trail
20053965	Trail	Unnamed Trail	Unknown	Lost	No	Walkout
20053979	Trail	Tuolumne Visitor's Center	Unknown	Lost/ Overdue	No	Other
20054044	Road	Murphy Creek - Tioga Road	Unknown	Lost/ Injured	No	Other
20054089	Road	Upper Pines Campground	Unknown	Lost/ Overdue	No	Other
20054356	**Lake**	**Yosemite Lodge**	**30 Mile Loop Hike**	**Lost**	**Yes**	**Other**
20061717	**Road**	**Taft Point Trail**	**Unknown**	**Lost/ Separated**	**Yes**	**Walkout**
20062046	Trail	Rafferty Creek Trail	Vogelsang High Sierra	Not lost	No	Walkout
20062805	Road	Glacier Point Road	Sentinel Dome Parking	Not Lost	No	Other

Path	Start	Near Feature	Intended Destination	Scenario	Divergence Point?	Rescue Method
20063924	**Trail**	**Little Yosemite Valley Campground**	**Unknown**	**Not Lost**	**Yes**	**Other**
20064539	Trail	Grizzly Peak	Unknown	Above ground level fall	No	Found Dead On Arrival
20064938	Trail	MirrorLake Road	Unknown	Not Lost	No	Walkout
20070526	**Trail**	**Vernal falls Bathroon**	**Unknown**	**Sparated**	**Yes**	**Walkout**
20070559	Building	Mirror Lake Trail	Mirror Lake Loop Trail	Lost	No	Walkout
20070616	Road	El Cap Straight	Unknown	Not Lost	No	Other
20070916	Trail	Mirror Lake Trail	Unknown	Lost	No	Walkout
20071026	Road	Sentinal Dome Paking	Sentinel Dome Parking	Lost	No	Other
20071057	**Trail**	**Mono Meadow Trail**	**Unknown**	**Lost**	**Yes**	**Walkout**
20071376	**Road**	**Sentinel Creek**	**Sentinel Dome Trailhead**	**Lost**	**Yes**	**Walkout/ Injured**
20072917	Trail	Echo Creek	Unknown	DOA/ Drowning	No	Helicopter
20073223	Trail	Backpackers Camp - Horse Trail	Yosemite Lodge	Not Lost	No	Walkout
20074148	**Trail**	**Taft Point**	**Unknown**	**Lost/ Heat Illness**	**Yes**	**Helicopter**
20074225	Trail	Yosemite Lodge	May Lake	Not Lost	No	Other
20074316	**Trail**	**Kendrick Creek**	**Hetch Hetchy Backpacker Camp**	**Lost**	**Yes**	**Helicopter**
20074355	Trail	Curry Village	North Dome	Lost/ Overdue	No	Other
20080603	Road	Hazel Green Dip	Big Oak Flat Road	Not Lost	No	Other
20080696	Trail	Silver Apron Footbridge	Unknown	Not Lost	No	Other
20081012	Trail	Visitor Center	Unknown	Not Lost	No	Other
20081237	Trail	Wawona Trail	Unknown	Lost	No	Walkout
20081633	Trail	Hodgdon Meadow Campground	Lembert Dome	Not Lost	No	Other
20081746	Trail	Yosemite Lodge	Unknown	Lost/ Separated	No	Other
20082579	Trail	John Muir Trail	Sunrise High Sierra Campground	Lost	No	Walkout
20083153	Trail	May Lake High Sierra Camp	May Lake High Sierra	Lost	No	Other
20084101	**Drainage**	**Conness Creek**	**Unknown**	**Lost**	**Yes**	**Walkout**
20084485	**Trail**	**Red Peak Pass**	**Unknown**	**Lost**	**Yes**	**Helicopter**
20084520	Trail	Pohono Trail	Tunnel View Parking Lot	Not Lost	No	Walkout
20085029	**Trail**	**Upper Yosemite Falls Trail**	**Upper Yosemite Falls**	**Lost**	**Yes**	**Technical**
20090652	Road	Tuolumne Grove Parking	Unknown	Separated	No	Walkout
20091134	**Trail**	**Indian Ridge**	**Loop back to Yosemite**	**Lost**	**Yes**	**Helicopter**

Path	Start	Near Feature	Intended Destination	Scenario	Divergence Point?	Rescue Method
20091345	Road	Bank 3 Way	Top of Yosemite Falls	Overdue	No	Other
20091583	Road	Glacier Point Road	Loop	Lost	No	Vehicle
20091755	**Trail**	**Grizzly Peak**	**Half Dome**	**Lost**	**Yes**	**Helicopter**
20092078	**Trail**	**Mildred Creek**	**Sunrise Trailhead**	**Lost**	**Yes**	**Walkout**
20092164	Trailhead	Columbia Point	Unknown	Overdue	No	Walkout
20093168	**Road**	**South Fork Tuolumne River**	**Loop**	**Lost**	**Yes**	**Helicopter**
20093531	**Water**	**Vogelsang Trail**	**Vogelsang Pass**	**Lost**	**Yes**	**Walkout**
20093725	Trailhead	Murphy Creek Trail	Crane Flat Gas Station	Lost	No	Helicopter
20094115	Trail	Lyell Canyon	Tuolumne Campground	Lost	No	Walkout
20094519	Trail	Merced Lake	Unknown	Not Lost	No	Walkout
20094603	Trail	Ten Lakes Pass	Ten Lakes	Not Lost/ Injured	No	Walkout
20094894	Trail	Vernal Falls Viewing Platform	Happy Isles	Lost	No	Walkout
20101824	Trail	Tuolumne Campground	Tuolumne Campground	Lost	No	Other
20101842	**Trail**	**Lost Lake**	**Unknown**	**Lost**	**Yes**	**Walkout**
20102047	**Trail**	**Lost Lake**	**Yosemite Valley**	**Lost**	**Yes**	**walkout**
20102496	Wilderness	Columbia Point	Unknown	Lost	No	Helicopter
20102498	Trail	Orchard Parking Lot	Unknown	Separated	No	Other
20102587	Trail	Glen Aulin High Sierra Camp	Unknown	Separated	No	Other
20102786	Trail	Mount Broderick	Unknown	Lost	No	Other
20103110	Trail	Glen Aulin High Sierra Camp	Unknown	Separated	No	Other
20103475	Trail	Lower Pines Campground	Nevada Falls	Not Lost	No	Other
20104030	**Woods**	**Cethedral Creek**	**Unknown**	**Lost**	**Yes**	**Helicopter**
20104201	Trail	Sentinel Dome Parking	Sentinel Dome Parking	Not Lost	No	Other
20104385	Trail	Wilderness Parking Lot	Merced Lake	Not Lost	No	Other

Appendix C Links to Project Data on ArcGIS Online

Least Cost Paths:
https://services1.arcgis.com/ZIL9uO234SBBPGL7/arcgis/rest/services/All_Hiker_Paths/FeatureServer

Path Divergence Points:
https://services1.arcgis.com/ZIL9uO234SBBPGL7/arcgis/rest/services/Hiker_Divergence_Points/FeatureServer

Stream Order:
https://services1.arcgis.com/ZIL9uO234SBBPGL7/arcgis/rest/services/Strahler_Stream_Order/FeatureServer