First Approach to Implementing Search Theory in Mexico: Lessons Learned, Future Perspectives, and Public Policy Implications

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Abstract

For the first time in Mexico, a large-scale search for a missing person was conducted using a Search Theory–based methodology. A strong Incident Command structure and effective inter-agency coordination allowed for detailed coverage of the search area. This framework enabled the calculation of key parameters—search effort, coverage, and probability of detection (POD)—which in turn provided the first quantitative assessment of search effectiveness in the country. These data supported authorities' decision-making on whether to continue or suspend the search. After three weeks, operations on the mountain concluded, and the case transitioned into a police investigation. The experience also revealed significant deficiencies in the current search and rescue system, highlighting the urgent need to improve training and methodologies to strengthen national search capabilities.

KEY WORDS: *Search Theory, Search and Rescue (SAR), Probability of Detection (POD), Incident Command System, Ajusco, Mexico*

Introduction

Search has been a fundamental challenge since the earliest stages of humankind, from locating animals for hunting to searching for missing people and objects. The formal mathematics of search theory, however, was only developed during World War II to support the search for enemy submarines. The pioneering works of Koopman (1946, 1980) laid the theoretical foundations of the field. These concepts were rapidly adopted and incorporated into search and rescue (SAR) manuals, such as the *International*

Aeronautical and Maritime Search and Rescue Manual (IAMSAR, 1999) and continue to inform contemporary SAR practices.

Despite this, Cooper et al. (2003) reported that ground SAR groups have sometimes struggled to apply search theory effectively in real-world operations. Complementing the mathematical approach, Koester (2008) introduced a behavioral perspective, offering insights into how individuals typically react and make decisions when lost. This line of research opened new possibilities for ground SAR, enabling more detailed operational planning and a deeper understanding of human behavior in survival situations.

While many countries have incorporated search theory into standard SAR training, Mexico still faces delays in both formal instruction for SAR teams and in implementing search theory. In México, there is no formal program to train SAR groups. In fact, SAR operations primarily focus on Urban Search and Rescue and involve groups from the Navy, Army, and Police, as well as volunteer organizations such as the Red Cross. In the backcountry, Search and Rescue is more informal, with each group determining what training its members need. The absence of a national doctrine of SAR makes it highly heterogeneous in terms of knowledge and capability, and sometimes difficult to manage during incidents involving multiple groups. In that sense, Search Theory is one of the forgotten subjects of SAR teams in México. It is worth noting that few individuals are knowledgeable about Search Theory because they have sought training abroad, but implementation has so far been a long way off.

In México, SAR operations in the backcountry are led by two volunteer associations, Socorro Alpino and the Red Cross, as well as several other groups (mainly volunteers) that conduct mountain rescue and, in some places, are supported by mountain police (responsible for mountain safety against criminal acts). Despite the extensive experience of mountain rescue teams in Mexico, the implementation of clear incident command systems remains incomplete, while formal search theory and search cartography are absent. Groups usually use experience-based search methods, which solve most cases with relatively low complexity.

Ajusco volcano is one of the favorite places to hike in Mexico City, with high weekend attendance and incident rates. Most incidents can be classified as delayed people who underestimate the difficulty of the routes. Usually, searches in the Ajusco area do not pose a challenge for planning because routes are relatively clear and people are found within a few hours on or near alternative trails.

A milestone occurred on July 12, when AAMG, a 19-year-old student, was reported missing at the Ajusco volcano in Mexico City. This incident marked a turning point in searches in Mexico, resulting in the largest search in the country and the first to be based on search theory.

This was possible because of the adoption of the Conjunct Incident Command, along with the requisite knowledge and willingness to conduct research based on this methodology. In this sense, also for the first time, government authorities were able to use reliable statistical data for decision-making, highlighting the usefulness of search theory and the need for its routine implementation.

The main objective of this paper is to present a case study of the pioneering application of Search Theory during the largest search operation conducted in Mexico and to assess how this experience influenced authorities' recognition of the need to implement search theory in SAR operations, as well as its potential implications for public policy and for search and rescue planning, training, and governance in the country.

Method

The search for AAMG involved an extraordinary deployment of resources, with more than 2,500 personnel participating over a three-week period. The present study is a quantitative case analysis based on operational search-and-rescue (SAR) data collected and processed daily to support planning for subsequent search operations. This data was compiled and analyzed throughout the three-week operational period. The dataset includes GPS tracks, search-area assignments, and deployment records compiled by the Conjunct Incident Command.

For the initial search phase, we interviewed the missing person's parents and obtained the last known location of the subject's cellphone. Based on this information, we classified the case using Koester's (2008) general statistics and behavioral categories with the *Lost Person Behavior* application.
For cartographic analysis, we employed CalTopo in SAR mode. Several teams also used mobile applications such as Avenza, Wikiloc, and Strava for tracking purposes. Their data was exported in KML format and subsequently imported into CalTopo for integrated analysis.

The rapid initial search focused on the main hiking routes of the Ajusco area. Teams of six searchers were deployed to cover these trails as well as areas with a documented history of accidents and locations commonly associated with lost hikers.

Assumptions of the Detection Model

Several assumptions were made for the detection model. First, we assumed that the subject remained within the containment boundary defined by the Circuito Ajusco Road during the search period. This assumption was considered reasonable because the area is bordered by a heavily trafficked road, and it is likely that a missing person who reaches the road would be quickly detected.

Second, the model assumes independence of detection events across repeated passes. In this case, the probability of detection for one search party is treated as independent from that of another, since the teams consisted of different groups with varying levels of training and operational conditions.
Finally, sweep width was treated as constant across the search area.

In the initial modelling stage, criminal activity was excluded as a causal factor because information obtained from interviews and authorities did not suggest such a scenario.

Selection of Sweep Width

A constant spacing of 5 m between searchers was selected based on studies by Mansfield et al. (2020), previous operational experience in the area, and the clothing worn by the missing person. The planning team agreed to maintain the same spacing across different terrains because it was easier for searchers without SAR training to maintain consistent spacing and for team leaders to supervise alignment.

We also decided not to modify the spacing in terrain without vegetation. Although alpine grasslands and rocky summit areas appear visually open, they contain terrain features such as cracks and gaps between rocks that create blind spots and may reduce detection probability.

Search teams were organized into groups of seven people. Six members performed the line search at 5 m spacing, while the team leader supervised the process and ensured proper spacing and parallelism. Under these conditions, the statistical sweep width used in the model was 30 m.

Probability of Containment (POC) Assignment Process

The Probability of Containment (POC) assignment was based on the consensus of four search experts familiar with the area. These experts included experienced mountain guides and members of mountain rescue organizations who have participated in numerous SAR operations in the region. Two of them regularly guide mountaineering groups in the area, typically leading one or two excursions per week.

For the analysis, the experts used historical data, terrain analysis, and were briefly trained in the use of the *Lost Person Behavior* framework and the LPB application.

During a group meeting, the search area was divided into five smaller zones based on terrain characteristics and common patterns of recreational use. Each expert independently assigned a probability to each zone. The values were then averaged, followed by a group discussion to review the results and reach a final consensus.

Coverage (C) and Probability of Detection (POD) Calculations

Coverage (C) is defined as the ratio of search effort to search area and is dimensionless. For communication with authorities, coverage was presented as a percentage because it was easier to interpret during operational briefings. However, when calculating POD using the exponential search model, coverage was expressed as a proportion, consistent with standard search theory.

Because many tracks overlapped, we limited the count to a maximum of three overlapping tracks in the coverage calculation. This approach allows cumulative POD estimation while avoiding the overestimation of search effort due to excessive track overlap.

Given the relatively small size of the search area (11.62 km²) and the fact that tracks often covered different selected areas, we calculated the total effective coverage for the operation.

To estimate POD, we applied the exponential model (Koopman, 1946):

$$POD = 1 - e^{-C}$$

where C represents the coverage.

For comparison purposes, we also retrospectively applied the Cubic model, calculating the cumulative POD for three repeated searches:

$$POD_{cum} = 1 - (1 - POD_1)(1 - POD_2)(1 - POD_3)$$

Rest of the World (ROW)

The Rest of the World (ROW) was intentionally excluded from the initial modelling because the area is bounded by a heavily trafficked road (Circuito Ajusco), which serves as a containment boundary. Additionally, the case received significant attention on social media, making it unlikely that the subject could reach the road and remain undetected.

Data Limitations

Some data limitations resulted in conservative estimates of coverage and POD. The primary limitation was the lack of cartographic training among some participating search groups, which prevented the consistent recording of GPS tracks. To avoid calculation errors, we excluded all data with inaccurate or incomplete coordinate information. This decision resulted in the removal of approximately two-thirds of all recorded search tracks.

Similarly, drone and K9 searches were excluded from the quantitative analysis because reliable spatial records of their search paths were not available. Consequently, the calculated coverage and POD values likely underestimate the actual search effort.

General description of the area

The Ajusco is the highest mountain in Mexico City, reaching an elevation of 3,930 meters above sea level (masl) at 19.21235°N, -99.25743°W (Fig. 1). Two main hiking destinations dominate the area: *Cruz de Marquez* (3,923 masl) and *Pico del Águila* (3,839 masl). Hikers often traverse a connecting route between these two peaks. Access is possible from three primary points—*El Abrevadero, Albergue Alpino*, and *La Cantimplora*—with secondary trails linking these entry routes (Figure 1).

The Ajusco features a temperate climate, with mean annual temperatures ranging from 5°C to 12°C, and minimum down to -3°C. Precipitation varies between 200 mm and 1,800 mm, peaking in July (Arriaga et al., 2000). Vegetation follows an altitudinal gradient: dense forest at the base, transitioning to alpine grasslands, and ultimately giving way to sparsely vegetated zones near the summits.

Results

SAR teams were activated after receiving a report that a young woman had begun descending from *Pico del Águila* toward *Albergue Alpino* during the night. At some point, her light was reported to have disappeared. This information could not be confirmed through a direct interview, as the individual who informed *Albergue Alpino* provided no personal details and could not be located. This represented the first difficulty in compiling reliable information.

The case quickly gained wide visibility on social media, where multiple and sometimes contradictory versions obscured the facts. Narratives ranged from her being alone on the mountain to joining a hiking group to waiting for a friend at the summit until 20:00 hours before starting her descent, after someone allegedly advised her that it was too late and too dark.

The only verifiable information came from the last position of her phone, retrieved by her brother at *Pico del Águila.* This point was established as both the Last Known Point (LKP) and the Initial Planning Point (IPP) for the search. The suspected ascent route was *La Cantimplora – Cruz de Marquez – Pico del Águila* (Figure 1)

For the initial operational phase, the Search Area was delimited by the Ajusco circuit road, which borders the volcano and served as a containment zone. The planning assumption was that the missing person's disappearance was not related to criminal activity.

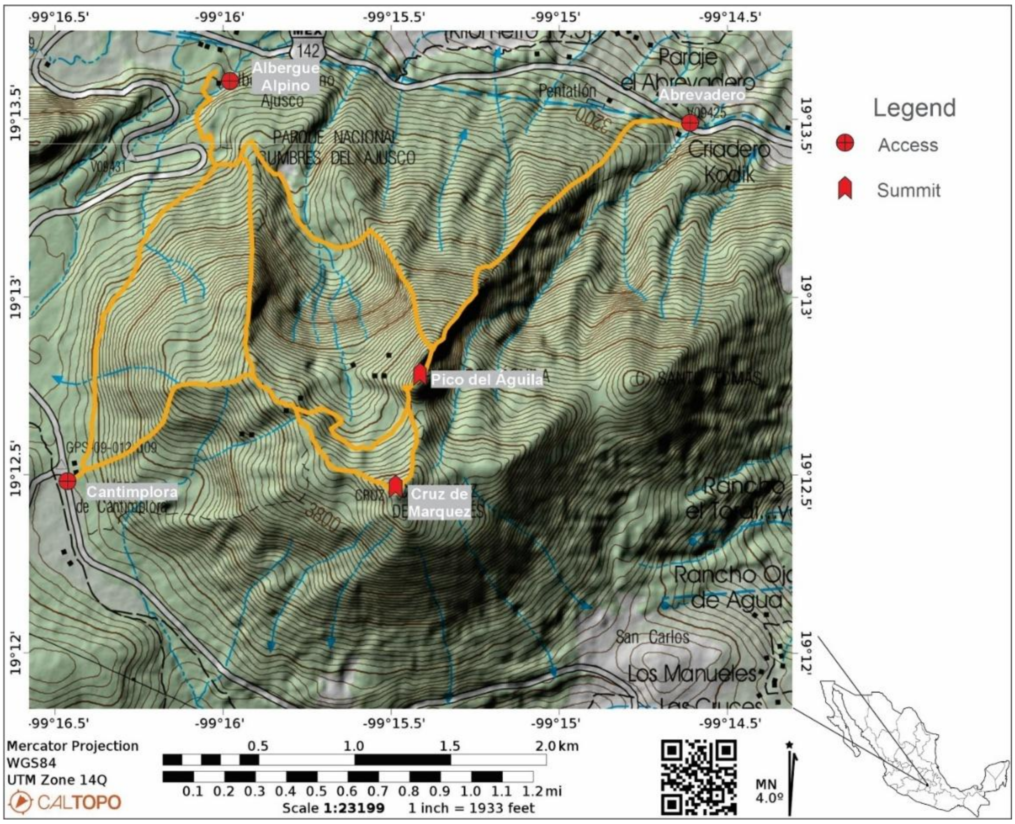

Figure 1: Location of the Ajusco Volcano in Mexico City. Three main access points are commonly used for hiking: Abrevadero, Albergue Alpino, and La Cantimplora. The volcano features two principal summits—Cruz de Márquez and Pico del Águila—each served by distinct trails.

Interviews with AAMG parents revealed that she had only recently begun participating in hiking activities and had limited experience in the Ajusco area. However, she had visited the mountain at least twice before. According to Koester’s (2008) classification, she falls into the “Hiker” category. This group is characterized by a tendency to make errors at decision points, representing 56% of recorded cases. Based on this classification, we considered three initial scenarios:

1. Descent with navigation errors. AAMG may have begun her descent and become lost at one or more decision points. Within this scenario, two possibilities were identified: (a) taking the route toward *Abrevadero*, or (b) heading toward *Albergue Alpino*. Both alternatives involve multiple decision points but a general downward path.
2. Disorientation and re-ascending. AAMG may have become disoriented and attempted either to relocate the main trail or to regain cell phone coverage by ascending to higher ground. This scenario would involve retracing portions of the ascent route and encountering several decision points along the way.
3. Accidental fall. AAMG may have fallen into a ravine adjacent to the trail.

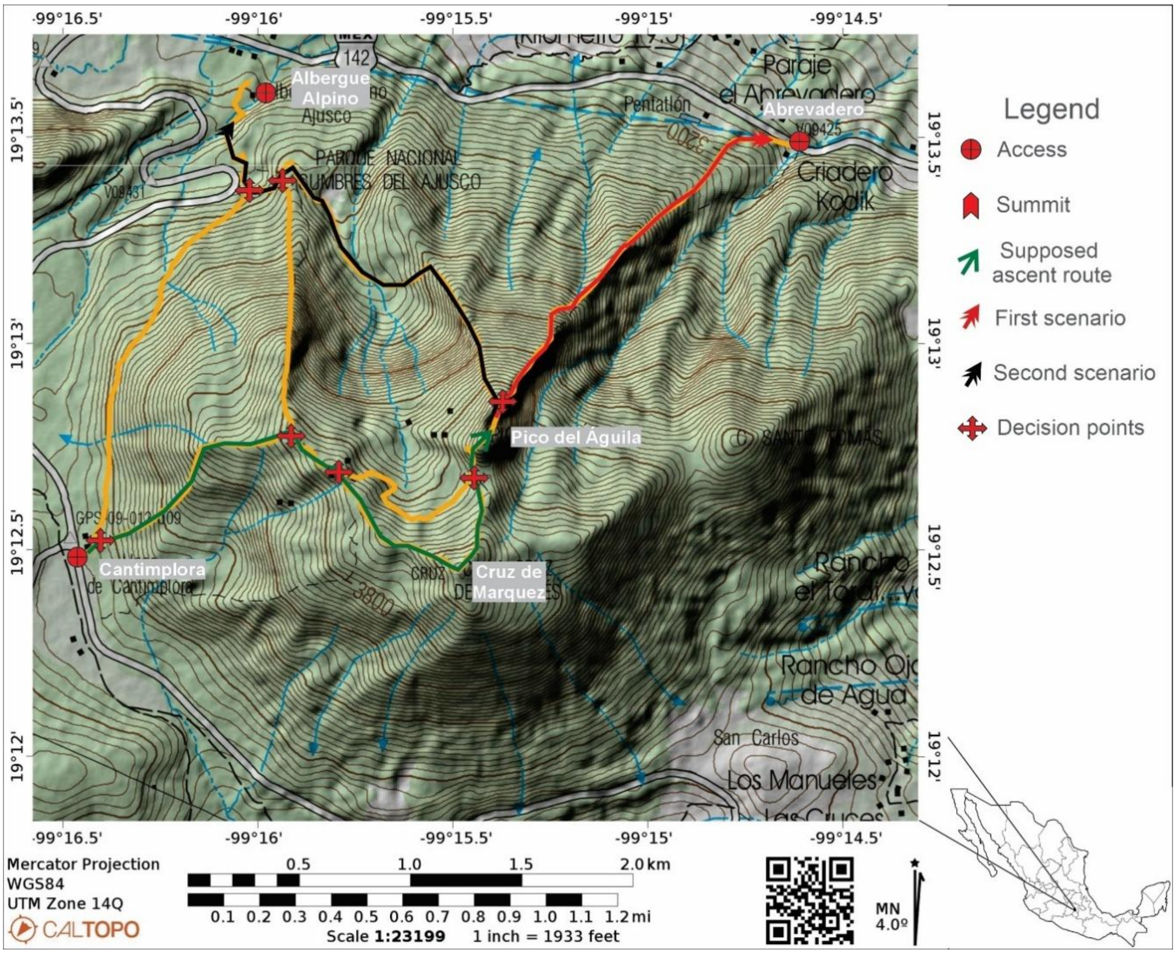

Figure 2: Analysis of routes and decision points. The presumed ascent route from La Cantimplora to Pico del Águila, including the Last Known Position (LKP), is shown in green. The path toward Abrevadero is shown in red, and the route to Albergue Alpino in black. Blue arrows indicate the location of ravines and watercourses.

Five search areas were identified, and for each, we calculated the Probability of Containment (POC) and Probability Density (Pden). The total search area covered 11.63 km². (Figure 3)

Area 1 (2.37 km²; POC = 60%; Pden = 25.3): The most popular hiking zone in Ajusco, with numerous small trails leading to both *Abrevadero* and *Albergue Alpino*. Historically, most incidents of lost hikers have occurred here, often when individuals follow side paths descending into deep ravines. This area also corresponds to witness testimony suggesting that AAMG was descending toward *Albergue Alpino* before disappearing.

Area 2 (1.0 km²; POC = 15%; Pden = 15): This scenario assumes AAMG attempted to reorient herself or find cell phone coverage by ascending. The parents reported that her last message originated from *Pico del Águila*. However, given the demanding ascent, this area was considered less probable than Area 1.

Area 3 (1.46 km²; POC = 10%; Pden = 6.8): Characterized by multiple firebreak gaps that can cause navigational errors if hikers attempt to return via the ascent route toward *Cruz de Marquez*. Accessing this area requires a strenuous climb from *Pico del Águila* to *Cruz de Marquez*, with a positive elevation gain of more than 166 m and slopes ranging from 30° to 60°.

Area 4 (4.67 km²; POC = 10%; Pden = 2.14): This zone offers direct visibility of populated areas and roads. It begins with an alpine grassland and includes trails and firebreaks that could be used for descent.

Area 5 (2.13 km²; POC = 5%; Pden = 2.34): A difficult-to-access area with steep terrain and deep ravines. No established trails or historical SAR incidents exist in this zone, though an unintended descent is possible.

At this stage, the “Rest of the World” (ROW) category was not included in planning, as the search area was bounded by a road encircling the volcano. In any direction, a descent would eventually intersect this road, where detection would be highly likely. This assumption excluded criminal activity. As the search evolved, however, the ROW concept gained greater importance.

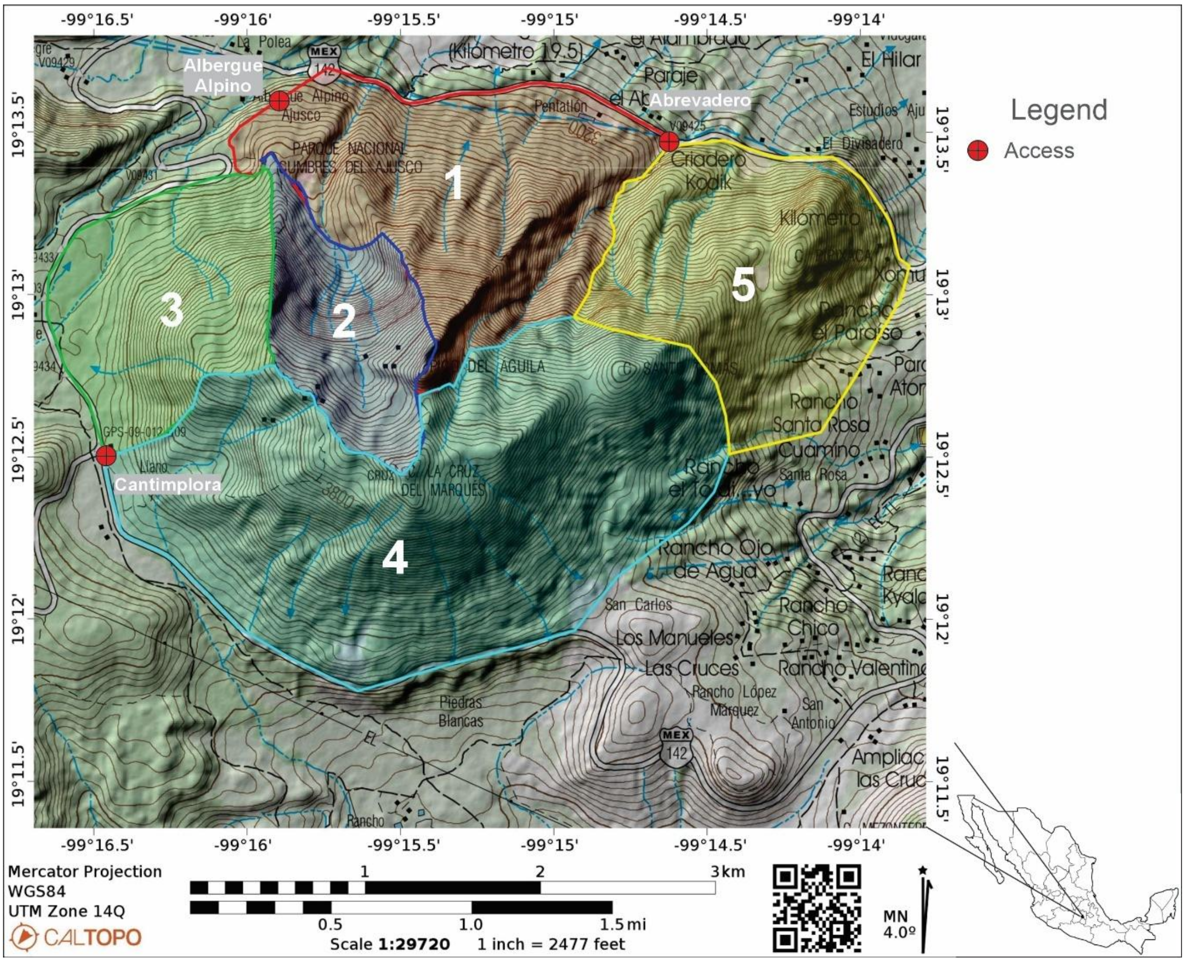

Figure 3: Delimitation of the five search areas. Areas are labelled 1 through 5 according to descending

Probability of Containment (POC)

On the second day, all possible trails had been searched at least twice, prompting a shift to a more detailed strategy with larger groups. The operation extended over three weeks and involved more than 2,500 people, three K9 teams, multiple drones, and helicopter coverage. Despite these efforts, no positive results or clues were obtained.

Subsequent statistical analysis provided insights into the quality and effectiveness of the search. This information served as a critical decision point for determining whether to continue with additional resources and strategies or to suspend operations.

Statistics of the Search

As Frost (1997) states: “The goal of search planning is to maximize the probability of success.” Following this principle, we analyzed the Probability of Success (POS) in relation to two key variables and a measurement that not only estimates the likelihood of success but also reflects the effectiveness of the search. This last element became especially relevant in the final stages of the mission.

POS=POD×POC

Where:

POS: Probability of Success

POD: Probability of Detection

POC: Probability of Containment

Figure 4: Details of the search in the Ajusco. (A) Three levels of vegetation cover. The upper zone is almost barren, exposing bare rock. The middle zone features alpine grass interspersed with trees. The lower zone consists of dense forest. (B) Systematic search formation with a 5 m separation between searchers.

POD depends on multiple factors, including sweep width, search effort, and environmental conditions. For this search, we selected a sweep width (W) of 5 meters, following the studies of Mansfield et al. (2020), our previous operational experience in the area, and the high-visibility clothing worn by the missing person (as confirmed by the last available photograph at *Cruz de Márquez*, shared on Facebook by other hikers).

The vegetation gradient in Ajusco complicated this estimation: dense forest at the base, alpine grasslands above the tree line, and bare rock near the summit. In our mapping, each track corresponds to a 30 m sweep width (a team of six searchers spaced 5 m apart) (Figure 4). As previously noted, the Ajusco is encircled by a road (*Circuito Ajusco),* which served as the containment boundary.

The total search area (A) was 11.63 km², and the cumulative search distance (L), based on recorded tracks, was 370.23 km. Since the area is relatively small, several tracks crossed more than one designated search zone. (Figure 5)

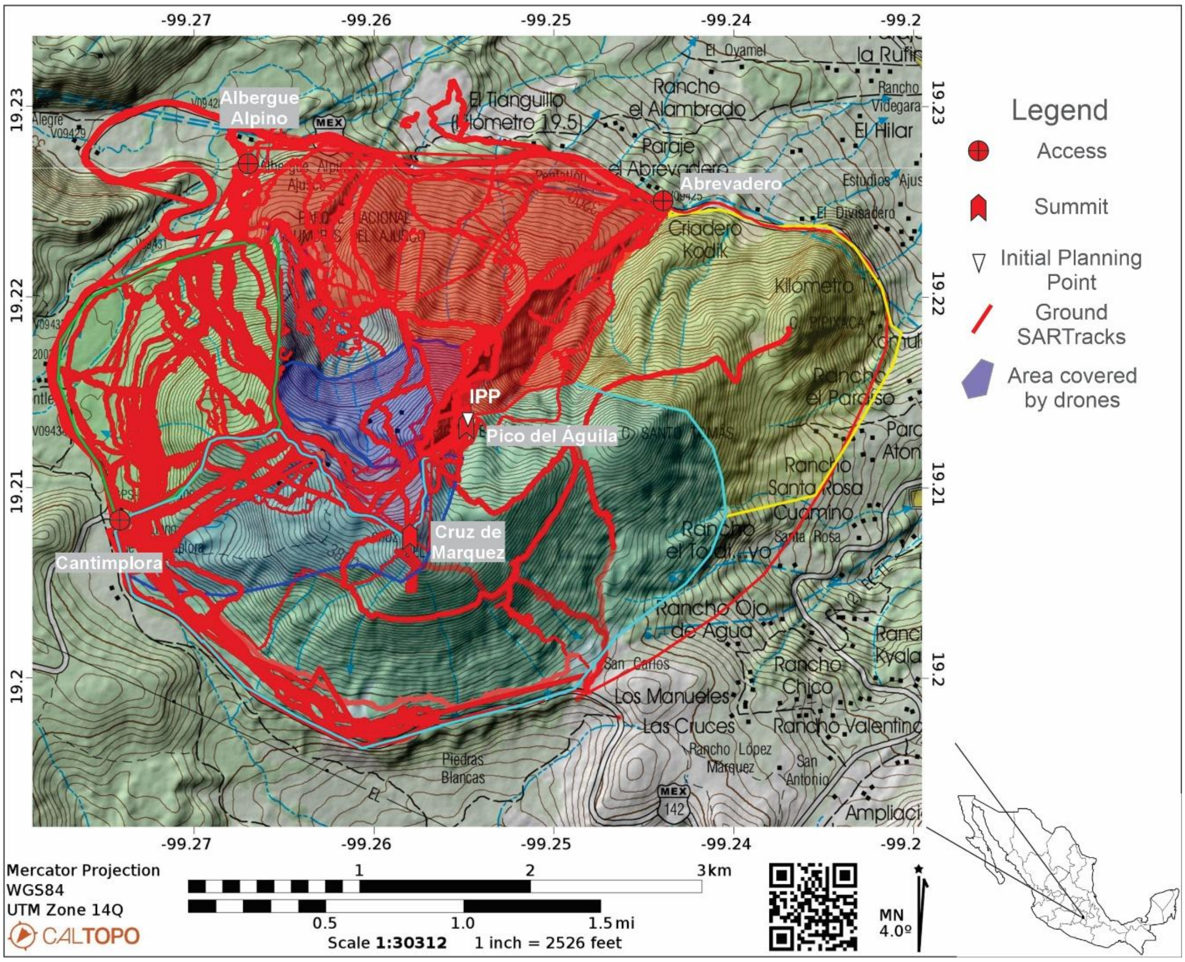

Figure 5. The cartographic base of the AAMG search shows plotted tracks of the main SAR groups and drone coverage. Approximately two-thirds of the tracks are missing from the map, as several groups were unable to record their routes.

Search effort (Z) was calculated as (Cooper, 2003):

Z= W*L

W= 0.03 km

L= 370.23 km

Thus Z=11.1069 km^2

Coverage (C) was estimated as:

C= (L(m)*W(m))/A*100

C: Coverage

L: Search distance

W: Sweep width

A: Search area

Resulting in a coverage of 94.6%

According to Frost (1999), the POD is defined as “the conditional probability of detecting the search object if it is in the area (segment) searched at the time of the search.” POD was therefore calculated using the equation:

$POD=1-e^{-C}$

Yielding a POD of 61.18%.

Discussion

The search for AAMG lasted three weeks, mobilized approximately 2,500 people, and became the most extensive search ever conducted in Mexico City—and, to our knowledge, in the country. Following a detailed analysis, the case was transferred to a police investigation. Nonetheless, the joint efforts of multiple entities operating under a strong Incident Command structure, together with the first application of search theory in Mexico, provided valuable insights for strengthening the national search and rescue system and informing the development of more effective public policies.

The application of search theory provided, for the first time, reliable data on coverage and probability of detection (POD) for decision-making authorities. This allowed authorities to determine whether to continue the search within the defined area or to expand the scope to include the "rest of the world," focusing on the possibility of criminal involvement.

It should be noted, however, that the calculated POD values are likely underestimated. Only one-third of the search tracks are represented on the final map, excluding several K9 searches, specialized drone missions, and aerial operations. These teams provided only approximate search areas, which prevented their inclusion in the calculations despite the substantial effort involved. Similarly, although Areas 4 and 5 were intensively searched, the absence of recorded tracks required us to estimate POD values by consensus, as recommended by Frost (2000) and Mansfield et al. (2020).

While POD was calculated using the classical exponential model during the operation, recent studies (Koester, 2020) suggest that the inverse-cube model provides greater accuracy for daytime ground searches. Using this approach, the estimated POD increases from 61% to 74%. Moreover, cumulative POD was calculated only for the hasty searches conducted on main trails, which were independently searched at least three times in accordance with Koester (2008).

Similarly, variations in sweep width may affect coverage and POD results; for example, a −20% variation yields a POD of 53.4%, while a +20% variation yields a POD of 68.2%.

It is also important to note that, in the exponential model used in the present study, if coverage (C) equals 1 (100%), the POD is approximately 63.2%. This reflects the fact that the model accounts for imperfections in real-world detection.

Beyond the quantitative results, the operation revealed critical weaknesses in the Mexican search system. Most groups lack formal training in SAR, including search theory, not only in planning but also in executing systematic search patterns, navigation, and basic cartography. This deficiency often resulted in inaccurate or misplaced area assignments. Furthermore, the lack of proper training prevented several groups from accurately recording search tracks or plotting them on the operational map. As a consequence, approximately two-thirds of the search paths could not be used in the modeling process or in the calculation of search quality.

In addition, several groups lack basic training in the Incident Command System (ICS), which resulted in confusion and operational difficulties during the incident.

Perhaps the most serious obstacle was related to group dynamics. Some teams distrusted the work of others, insisted on re-searching areas that had already been covered multiple times, and followed personal intuitions about the possible location of the missing person. For example, the route from Pico del Águila to El Abrevadero was searched by eleven different groups—always along the same trail—resulting in an oversaturation of effort without generating new operational information.

The search for AAMG represents an unprecedented attempt in Mexico to combine all available resources with a scientific search methodology. At the same time, it revealed significant weaknesses within existing SAR groups. Based on the data obtained during the operation, we initiated discussions with national authorities to promote the implementation of several public policy measures. Perhaps the most important of these is the urgent need to establish a National SAR System capable of coordinating efforts across institutions and volunteer groups. Another key issue currently under discussion is the need for formal training programs and for the development of a ground SAR manual in Spanish that would allow rescue groups to apply the basic principles of search theory and operational coordination.

Finally, as a direct outcome of the search and the detailed cartographic work conducted during the operation, authorities have begun developing a management plan for the Ajusco area. This initiative seeks to improve safety conditions by enhancing trail signage, strengthening cell phone and radio communication coverage for hikers, and improving operational capabilities for future rescue missions.

Limitations

The present study has several limitations. Only about one-third of the participating groups were able to record their routes. Thus, only this portion was available for analysis, excluding important contributions from drone operations, K9 teams, and aerial searches, resulting in underestimates of coverage and POD. Additionally, the lack of formal training in Search and Rescue groups diminished the accuracy of the assigned segments and areas.

Future Research

We are developing a formal training program for Search and Rescue groups in Mexico, and we expect that improved training will facilitate the application of search theory in future operations.

Conclusion

The search for AAMG marked the first large-scale application of Search Theory in Mexico. The implementation of a strong Incident Command structure, collaboration among multiple agencies, and full access to government resources enabled the most extensive search ever conducted in the country and expanded collective knowledge of SAR practices. For the first time, it was possible to calculate search parameters, such as search effort, coverage, and probability of detection (POD) and to use them in assessing both search areas and overall effectiveness. These parameters provided decision-making authorities with reliable data to determine whether to continue or suspend the operation.

High levels of coverage, search effort, and POD were decisive in shifting the operation beyond the Ajusco and into a police-led investigation. Although the calculated POD values were underestimated due to incomplete track recording, the operation still yielded valuable insights.

The aforementioned results demonstrate to the authorities the potential of the Search Theory to improve SAR effectiveness and its usefulness as a powerful tool in the decision-making process and in communicating with interagency and to the public.

After the operation, several meetings were held with the National Commission of Search and political authorities to conduct a detailed review of the results and deficiencies and to improve future operations.

Some of the opportunity areas were the need for a National SAR system to coordinate all efforts during an action. Also, the need for formal training of the groups in incident command, search theory, basic cartography, and land navigation. Another important conclusion derived from that is the need for a ground SAR manual in Spanish for national training.

While these aspects are being implemented, the authorities have begun a management plan for the Ajusco area that includes increased security, the implementation of rescue management plans, signage for routes to facilitate tourist navigation, and work to improve future telephone and radio signals.

The search for AAMG represents a turning point for ground SAR in Mexico. Beyond the unprecedented scale of the operation, it marked the first implementation of a scientific search methodology based on search theory and highlighted the importance of incorporating such approaches into the future development of a national SAR system.

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