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HURRICANE CRAWL CAVE: A GIS-BASED CAVE MANAGEMENT PLAN ANALYSIS AND REVIEW

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With the goal of minimizing impact to rare, fragile, and significant cave resources, this paper compares the location of such features in Hurricane Crawl Cave, Sequoia National Park, California, to the open and unrestricted areas of the cave as defined by the Hurricane Crawl Cave Management Plan. geographic information systems (GIS) analysis provided statistical data on the relationship of chosen key features and resources to caver travel corridors and open areas, and thus, allowed an unbiased assessment of the appropriateness of travel closures and management restrictions. Using buffer analysis around these features, we determined that the existing plan for the cave addresses the protection of cave speleothems and paleontological features, but is not adequate in the protection of areas of biological significance.

Nearly pristine Hurricane Crawl Cave lies in a roof pendant of Mesozoic marble in the Sierra Nevada of California (Sisson 1994). The cave is one of 212 documented in Sequoia and Kings Canyon National Parks. Hurricane has 3132 m of surveyed passages, a depth of 72 m, and lies between 1320 and 1400 m msl. Its two entrances formed near the cave stream's resurgence and insurgence, respectively (Despain 2000). Hurricane developed through the piracy of a surface stream that recharges on plutonic rocks in areas of coniferous forest rising as much as 850 m above the cave (USGS 1993). The piracy occurred beneath a ridge that provides the cave with more than 150 m of overburden. The cave features breakdown, anastomotic and branchwork mazes, and paleo-phreatic upper levels 18 - 27 m above the existing vadose streams. These streams have created thousands of meters of deep, narrow canyons (Fig. 1) (Despain 2000).

The cave was found in 1988, 98 years after the area was set aside as part of Sequoia National Park. This has allowed Hurricane to be managed carefully since its discovery. The cave was closed in 1990, pending a biological evaluation, and the first management plan for Hurricane was completed in 1992. This plan was revised in 1998. Hurricane Crawl contains exceptional resources including large and delicate examples of unusual cave formations, likely endemic species, and paleontological remains. Currently, the cave has 17 closed areas and 15 sections of flagged trail as well as additional restrictions in numerous areas concerning clothing and footwear. Also, two areas considered in the subsequent analysis are restricted to one trip per year as an extra measure to protect these areas' features (Despain 1998).

The speleothems in Hurricane are exceptional. The Star Chamber upper level contains 0.3-m long vermiform and filamental helictites in profuse displays. Folia have been noted in five areas. One location is currently active at base level while another lies 25 m above the cave stream. Approximately 30 shields occur in groups in several areas of the cave. Most of these areas are in upper-level phreatic passages. The largest shields are more than 3 m in diameter (Fig. 2).

Many GIS applications in cave and karst studies examine surface relationships to karst hydrology or cave passage relationships to surface features (e.g., Szukalski & Yocum 1998; Stokes *et al.* 1999; Call *et al* 1999; Glennon & Groves 1999; Pfaff *et al* 2000). The dataset used in this paper examines the spatial relations of in-cave features to caver travel areas and trails. The detailed mapping and analysis that follows is probably not appropriate or necessary in most caves. This study focuses on a cave with a high level of protection, management focus, and a large number of rare and fragile features and endemic species (Despain 1998). The vast majority of caves do not have this abundance of rare formations or unique animals. However, similar analysis could be helpful in the sensitive and appropriate development of new commercial caves or the adjustment of existing trails, utilities and other infrastructure components at current commercial caves. In addition, caves with particularly rare and sensitive features or animals might also benefit from this type of GIS analysis. Such analysis could ensure that a cave's most fragile and significant features lie within closed or restricted areas.

Three types of features in Hurricane Crawl will be examined in the following analysis: 1) rare and delicate mineralogical features; 2) paleontological features, which constitute bones of unknown age and species; 3) biologically significant locations and areas of key habitat.

METHODOLOGY - DETERMINATION OF FEATURES TO BE INCLUDED IN THE ANALYSIS

This paper attempts to recognize the key Hurricane Crawl features deserving protection and to determine what percentage of these features are close to approved travel routes

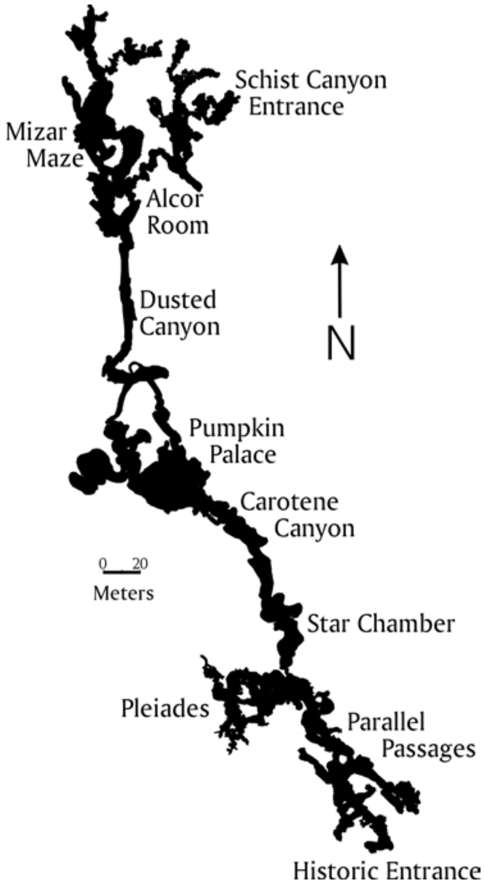

Figure 1. Hurricane Crawl Cave map, plan view.

through the cave, thus in danger of being broken or disturbed. To do this requires placing qualitative values on cave features and resources.

The relative rarity of cave formations is difficult to determine, yet this remains an important factor in assigning cave passage closures and restrictions in Sequoia, Kings Canyon, and other protected areas. Very few caves have undergone careful resource inventory and very few of these data have been published. Available for potential comparison and analysis are data from a few other caves located across the United States, including Carlsbad Caverns National Park, Jewel Cave National Monument, and Wind Cave National Park (DuChene 1997; Horrocks 2002; Ohms 2002). However, even these data present information on only a few chemically unusual caves (Palmer 1999; Jagnow *et al* 2000) and provide no comprehensive information on caves across the nation or a region. While a cave-by-cave comparison is possible using the results at these National Parks, no overall determinations of speleothem rarity are possible.

Hill and Forti (1997) make inferences concerning the relative commonness of cave features on a global scale, but provide little specific data based upon cave inventories and resource assessments. Comparison of commonness may also be inferred from local data. Inventory work within Sequoia and Kings Canyon provide data for an overview of the features in many park caves, including Crystal Sequoia, Soldiers, Cirque, Clough, Weisraum, Carmoe Crevice, White Chief, and, to a more limited extent, Lilburn caves (Despain & Stock 1998; Vesely & Stock 1998; Despain 2001; Fryer 2001). These data also include all examples of many features (shields and helictites) that have been documented in all known park caves (Despain & Fryer 2001). In light of the lack of data on national and global occurrences of features, the study made comparisons and the determination of relative rareness using local data from the inventory of other Sequoia and Kings Canyon National Parks caves.

The determination of rareness also considered the size of individual cave mineral features in Sequoia and Kings Canyon, because larger examples of many speleothems are less common (Despain & Stock 1998; Vesely & Stock 1998; Despain 2001; Fryer 2001). Thus, the analysis included only individual larger examples of some features (such as shields).

Features determined to be rare for this analysis and the reason for that determination are below. Out of the 212 caves in the two parks, folia are found only in Hurricane Crawl, which qualifies all of these speleothems as locally rare. Pendulites occur as only poor examples in two locations in two other park caves and were, thus, included for proximity analysis in the rare category. Filamental helictites (Hill & Forti 1997) are known from only one location in the park outside of Hurricane Crawl. They were also included (Fig. 3). Raft cones, known from one other park cave, and dogtooth spar crystals, known from three other park caves, but with only one or two examples each, were included. Gypsum and hydromagnesite, found in two and three other park caves, respectively, are locally rare and, thus, included. Shields, known from six park caves, including at least 96 in Crystal Cave, were not included. However, Hurricane's largest shields, more than 2 m in diameter and the largest in the parks, were included. Other features included due to size are vermiform helictites longer than 10 cm, which are only found in Hurricane within the parks; stalactites longer than 3 m, found only in Hurricane Crawl; curtains longer than 3 m, found in two other park caves; rimstone dams more than 2 m across, found in three other park caves and soda straws longer than 1 m, currently found only in Hurricane Crawl (Table 1).

Individual cave feature data points in the proximity analysis for rare features included pendulites, raft cones, and all size-dependent features, except pools larger than 2 m. Data points for folia, filamental helictites, gypsum, and hydromagnesite deposits denote areas where the features exist, not specific individuals. In this instance, data points were created throughout the area of occurrence and have overlapping proximity buffers. Polygons represent pools larger than 2 m across due to their large size and location on the floors.

The protection of fragile features constitutes another concern in the management of Hurricane Crawl. Analysis reveals the relationship between travel corridors and the location of

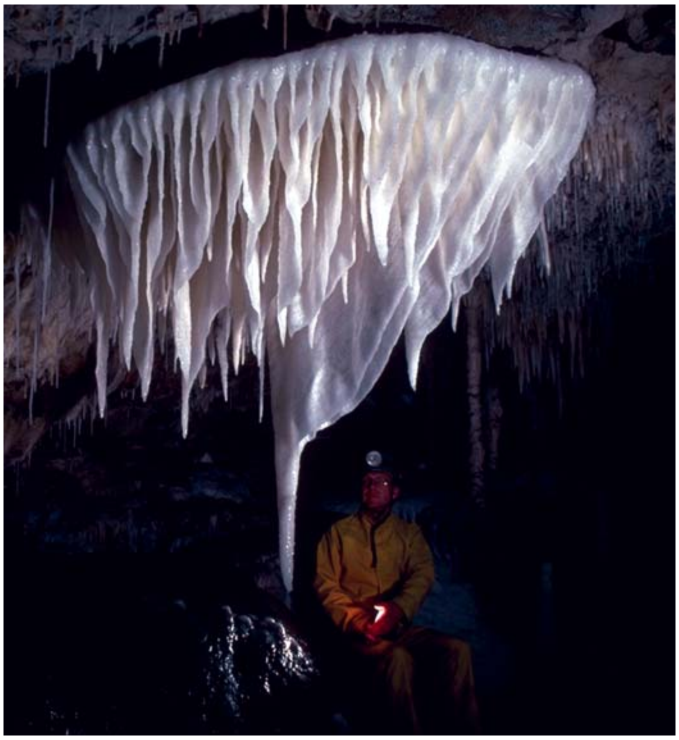

Figure 2. Large shield in the Star Chamber area of Hurricane Crawl Cave. This speleothem was included in the GIS analysis due its large size.

Figure 3. Filamental and vermiform helictites in the Pleiades area of Hurricane Crawl Cave. Filamental helictites were included in the GIS analysis due to their rarity in Sequoia and Kings Canyon, while vermiform helictites were included due to their fragility.

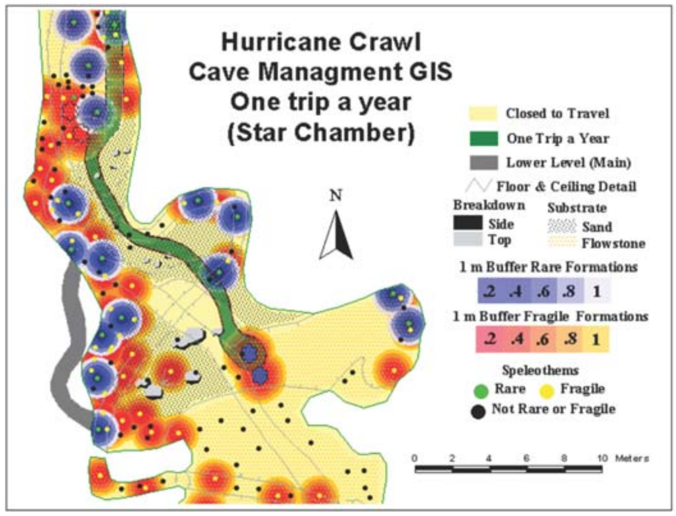

Figure 4: The upper-level Star Chamber area of Hurricane Crawl showing a segment of one-trip-per-year trail. Notice how the trail generally avoids both rare and fragile features.

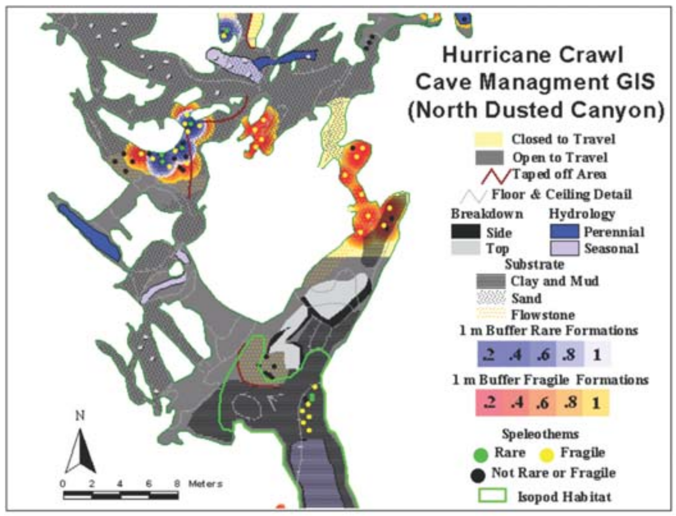

Figure 5. The north end of Dusted Canyon and the beginning of Mizar Maze. Notice the closed areas with fragile speleothems and open areas both with and without flagging but with fragile and rare speleothems. These locations are possible places for new closures and restrictions. Also notice the terrestrial isopod habitat (area with food sources) and the lack of closures or restrictions to protect these endemic animals. Finally, an area of fragile formations was removed from the study because they occur in the ceiling of the passage and are in no danger.

fragile, potentially breakable cave features. As avoiding damage to rare features is particularly important, certain routes through the cave may minimize damage and be the most appropriate to use. Formations were considered fragile if they can be damaged or destroyed through a single interaction with a caver. Formations used in proximity analysis for their fragility include all helictites, soda straws, frostwork aragonite, calcite ice, all rimstone dams, and cave pearls (Table 1). All data points in the fragility analysis represent groups or clusters of the same type of feature. Points are distributed across an area

Table 1: Secondary speleothems included for analysis, the reason for that inclusion, and how features are represented in the GIS. Rare determinations are based upon park-wide occurrences.

Included Feature	How represented	Number of points or polygons in the analysis	Category and reason for inclusion
folia	points represent groups of individual features	15	Rare - occurs only in Hurricane Crawl
pendulites	points represent each feature	32	Rare - occurs in two other park caves
filamental helictites	points represent groups of individual features	30	Rare - occurs in one other location in another park cave
raft cones	points represent each feature	8	Rare - occurs in one other park cave
dogtooth spar	points represent groups of individual features	10	Rare - known from three park caves with one occurrence each
gypsum	points represent groups of individual features	17	Rare - occurs in two other park caves
hydromagnesite	points represent groups of individual features	20	Rare - occurs in three other park caves
shields more than 2 m in diameter	points represent each feature	4	Rare due to size - occurs only in Hurricane Crawl

of occurrence so that the features have overlapping proximity buffers. Points or polygons included in the analysis that represent rare or fragile speleothems totaled 1252.

Paleontological features consist of individual skeletons in alcoves along narrow canyons and at least six skeletons in the Alcor Room. All skeletons appear to be small mammals up to 40 cm long (Table 2) (Despain 2000). They may reveal the previous presence of now extinct animals in the area near the cave, or may illuminate animal behavior that led to these individuals deaths underground. In addition, all paleontological remains in National Park areas are to be protected and carefully managed. (NPS 1994: 156) Thus, all 8 skeletons known in the cave make up points in this analysis.

Two biologists who work with invertebrates visited Hurricane Crawl in 1991. W. Calvin Welbourn, from Ohio State University collected 24 invertebrates in the cave in July 1991. From this collection, he reported that the cave had both aquatic and terrestrial troglobitic isopods, a troglobitic millipede, and an eyeless centipede. All of these species are possible endemic and potentially new to science (Welbourn 1991). Taxonomy on these species has not been completed. In September 1991, Ubick (1991) reported a *Pimoa* sp. spider from twilight areas of the cave and possibly *Nesticus silvestrii* spiders throughout the cave. In 1999 and 2000, biological inventory plots were established in the cave and were assessed during the summers of 1999, 2000, and 2001 using the protocol of Poulson & Kane (1977) (Despain & Fryer 2002).

While these limited biological investigations provided important information concerning the biology and ecology of Hurricane Crawl, comprehensive information on the variety of species, habitat requirements and ecology is lacking. Nevertheless, while more comprehensive work is pending, management decisions and plans to protect the cave's features went forward. For endemic cave species, the need to protect these animals in a national park setting is clear (NPS 1994: 137). Food inputs into Hurricane Crawl, as in most cave environments, are very limited. Very few bats have been seen in the cave and no bat guano piles exist. Rodent feces are only in passages adjacent to entrances. However, roots are in areas over 100 m from entrances and in the Pleiades area of the cave. The cave streams also flood annually and transport organic matter into the cave. This organic material accompanies fine, flood-deposited sediments in wide passages and coarser-grained sediments on stream bottoms. Flood deposition is most common in Pumpkin Palace, the largest room in the cave, and in the Mizar Maze complex at the north end of Hurricane (Despain 2000). The cave's two species of isopods are closely associated with these food sources. Welbourn noted aquatic isopods in sections of the cave stream floored by cobbles, sediments and organic matter, but not in sections of streams flowing across areas of clean-washed bedrock or flowstone (Welbourn 1991). In over 1000 m of stream passage in Hurricane, <10% are floored by sediments, primarily in Pumpkin Palace. Terrestrial isopods have been found in streamside plots with organic matter in Pumpkin Palace and the Mizars, but never in any other location, even by casual observations.

With the limited information available on these species and their habitat requirements, areas in the cave defined as biologically significant for this study are those locations with the potential food sources described in Table 2. Disturbance of these areas could lead to the trampling of the animals and the destruction of their food supply. These areas were incorporated in the GIS analysis as 16 polygons.

GIS DATA

Data for this project have been gathered through more than ten years of fieldwork. The cave's original survey included a specific effort to document all features, particularly mineralogical features. Information from the cave's original survey notes was augmented by field checking existing maps and during visits by biologists and geologists. Maps of the cave were originally created using the CorelDraw! 7 graphics package. These maps were converted into .dxf files and imported into ArcView, where they were organized, converted to ArcView.shp files, and geographically referenced.

The Hurricane Crawl GIS consists of eleven themes expressed on four levels including an upper level, with many heavily decorated rooms and passages, an extensive main level, and two small underlying levels. The themes include wall location and composition data; a floor theme expressing the cave's total extent; a detail theme showing slopes, dropoffs and changes in ceiling height; a sediment theme for floor composition; a hydrology theme for streams and pools, and a breakdown and cobble theme. Additional themes include a speleothem theme composed of 44 types of secondary speleothems. A route theme shows travel corridors as polygons, and flagging tape and closed areas from the implemented Hurricane Crawl Cave Management Plan (Despain 1998). Additional themes developed for this analysis include point data for paleontological features and polygons for areas of key food availability within the cave.

Initial review of the GIS images revealed limitations to the two-dimensional rendering of the three-dimensional cave. In the cave's tall canyons, travel corridors that lie many meters below fragile speleothems were shown to intersect those deposits' buffers. In these cases, these formations were removed from further analysis (Fig 5). This problem did not apply to any of the paleontology points or biology polygons.

An additional concern with this data set was the size of the proximity buffer. How far should a given feature be from a trail and open areas to be considered not at risk and, therefore, protected? For this analysis, a 1-m buffer was used around speleothem and paleontologic points. We believe that this area around a feature will protect it from breakage or disturbance from passing cavers. No buffers were used around polygons denoting biologically significant sites.

GIS ANALYSIS

The analysis for this paper was done as grid analysis of the trail and open areas of Hurricane Crawl Cave compared to biology polygons and to 1 m proximity buffers around rare and fragile formation and paleontology points. Grid resolution in the analyzed areas was 5 cm^2 creating 2,793,322 data points for analysis. The total two-dimensional floor area of Hurricane Crawl Cave is 7023 m^2. The trail and open areas are 2454 m^2 or 35% of the cave.

The area of open trails in the cave that lie within 1 m of fragile mineral deposits is 11.9%, while the area of the cave trail that lies within 1 m of rare speleothems equals 2.3% of the open trail area. Risks threaten 10.8% of the cave's total fragile mineralogical resources and 7.1% of rare features because they lie within 1 m of the open trail (Table 3).

Areas of the cave limited to one trip per year contain a larger percentage of rare and fragile features. One-trip-per-year trails make up 5.2% of open areas in Hurricane Crawl. Of the areas of the cave open to one-trip-per-year, 16.7% are within 1 m of fragile speleothems, and the 1-m analysis buffer around rare features occupies 4.9% of the same section of the cave. In this case, 2.1% of the cave's total fragile mineralogical resources and 2.1% of rare features are at possible risk because they lie within 1 m of the one-trip-per-year trail (Fig. 4). These statistics imply that areas selected for one trip per year are more sensitive with a higher percentage of proximal rare and fragile features. Thus, these areas should be managed using greater restrictions compared to open trail areas.

At any given point throughout the entire cave, there is a 33.7% chance of being within 1 m of a fragile speleothem and a 10.2% chance of being within 1 m of a rare speleothem. For the trail as a whole (one-trip-per-year and open), 12.5% lies within 1 m of fragile speleothems and 2.6% is within 1 m of rare features. Thus, the trail lies in areas that are generally more free of rare and fragile formations than the cave as a whole. This implies that the total trail (including both once per year and open areas) was well chosen to avoid both fragile and rare features.

One-meter buffers around points denoting paleontological remains overlap 0.17% of the trail. This compares to 0.49% of the cave as a whole that lies within 1 m of paleontological resources. A total of 16% of the cave's paleontological resources lie within 1 m of open trails.

Food source and key habitat polygons for cave-adapted animals fell within 14.2% of the trail area (Fig. 5). This compares to 6% that these areas occupy within the cave as a whole. Thus, one is more likely to be encounter a biologically significant area while traveling the designated trail compared to simply wandering through the cave as a whole. In addition, a total of 84% of the areas of the cave recognized to be biological significant fall within the total trail and open areas of Hurricane Crawl (Table 4). Only 16% of the cave's biologically important sites are protected by the existing management plan.

DISCUSSION

Overall, the travel corridors and open areas within Hurricane Crawl Cave generally avoid rare and fragile cave formations. Slight adjustments to the trail routes may improve the percentage of rare and fragile features found within 1 m of the trail. Changes or alterations to existing management plans often require visits to areas under consideration for management changes, creating the potential for damage to the cave's features. However, using the existing GIS we can test other possible trail routes and open areas simply through the use of the database. Uncertainty about plan changes and trial-and-error alterations to the management of the cave might also be minimized.

Routes through the cave infringe more strongly upon currently recognized areas of biological concern and paleontological features. Based on our findings, future management of the cave will require that trails and closed areas be reconsidered. Some key biological areas, such as the north end of Dusted Canyon, and passages near both entrances may be closed in the future. In other areas, trails may be narrowed or shortened. In addition, biological work in the future may reveal other areas of concern that should be considered in the management of Hurricane Crawl. While the work of Welbourn, Ubick, and the park inventory plots do identify key areas of biological concern, these should be considered a minimum of what might be appropriate to protect in the cave. Additional data will likely reveal other areas of concern. In addition, travel routes near paleontological features may be moved or animal remains may be carefully and obviously flagged to encourage cavers to avoid them.

In this instance, with detailed inventory data available, GIS proved to be an effective tool for the objective review of a specific cave management plan. Since this analysis examined the spatial relationships of more than 1200 cave features compared to caver travel routes, GIS was the only option available for a complete analysis of the data. We hoped and believed that the existing management plan delineated appropriate rules, restrictions, and closures to protect the cave's key features. The GIS analysis revealed that this is only partially true. We will review and examine other existing management plans for park caves using this same analysis in the future.

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