Rene Ohms and Matthew Reece - Using GIS to manage two large cave systems, Wind and Jewel Caves, South Dakota. *Journal of Cave and Karst Studies 64*(1): 4-8.

USING GIS TO MANAGE TWO LARGE CAVE SYSTEMS, WIND AND JEWEL CAVES, SOUTH DAKOTA

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The length and complexity of Wind and Jewel Caves offer unique challenges for cave managers. Determining the location of specific cave passages in relation to surface features is a key management tool, which is now greatly facilitated by Geographic Information Systems (GIS). This has been particularly useful at Wind and Jewel, where the complexity of the caves and their lack of obvious relation to the overlying surface make visualization of their locations difficult. GIS has also been used at both Wind and Jewel to display data tied to cave survey stations (such as feature inventories and control points). At Jewel Cave, GIS has been used to aid in management decisions regarding the use of herbicides above cave resources, and to better identify where the cave crosses political boundaries. At Wind Cave, GIS has been used to plan a parking lot replacement project and to create a model of the cave's potential extent.

South Dakota's Wind Cave, over 160 km, and Jewel Cave, over 200 km, are complex network mazes with several distinct levels of passage in a vertical extent of just over 190 m. Wind Cave is more complex than Jewel, averaging 150 survey stations per kilometer to Jewel's 105 stations per kilometer (Fig. 1). Both caves have over 21,000 total survey stations.

Prior to the use of GIS, the location of the caves in relation to surface features was roughly determined by processing the cave survey data, printing a scaled line plot, then overlaying the print-out on a topographic map or aerial photograph. Known locations of the caves' entrances were used to correctly align the overlay. This provided important information about the relation of the caves to surface features, but provided little flexibility to work with multiple layers or to change the scale of the overlay.

Overburden for specific survey stations could not easily be calculated or visualized with the two-dimensional overlay. Calculations for particular stations of interest could be made by adding the Z value in the cave survey software (the vertical relationship with the survey origin) to the known elevation of the origin, then subtracting this value from the elevation of the surface above the station (as determined by the rough overlay). This was a time-consuming process, and could not easily be done for all 21,000+ stations.

A wealth of data associated with cave survey stations has been collected over the years at both caves. Survey teams also collect cave feature inventory information. Each recorded feature (speleothems, biological resources, etc.) is associated in the database with the nearest survey station. Queries of the inventory databases can return a list of all stations near designated items or combinations of items, but this list is not particularly useful without the ability to put these relationships in a broader context.

Cave radiolocations have tested survey accuracy at both caves, and are also associated with the nearest survey station.

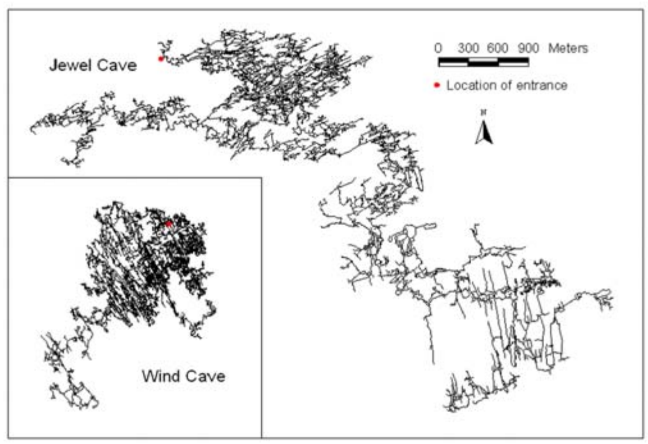

Figure 1. Line plots of Wind Cave (161.91 km) and Jewel Cave (203.20 km), illustrating complexity and passage density.

These data have been used to adjust the cave survey by entering control points into the cave survey software, but in the past there had been no easy way to graphically compare corrected and uncorrected data.

GIS technology has provided the link between these databases of information, the cave survey, and surface features. These combinations have provided managers with the ability to view and analyze spatial relationships of features located inside the caves, as well as accurate spatial distribution of the cave passages with respect to overlying surface features.

CAVE-SURFACE RELATIONSHIPS

The first step to determining a cave's location in relation to other GIS layers is to export the cave survey data to GIS software and register (or tie) the data to a known location. At both Wind and Jewel, ArcView GIS 3.2 is used, in conjunction with CaveTools 5.0 (an ArcView extension), and COMPASS 3.01 cave survey software.

CaveTools imports a COMPASS plot file, then creates ArcView shapefiles representing the cave line plot and the cave survey stations. Two or three-dimensional shapefiles can be created. The line plot shapefile provides a more pleasing graphic representation of the cave, whereas the stations shapefile is more suited to querying data tied to specific survey stations.

The line and point shapefiles can then be registered separately to a known location (such as the cave entrance) using CaveTools. Geographic coordinates in the appropriate projection are needed for a specific survey station. These can be determined by Global Positioning Systems (GPS) or by a survey run from a known benchmark

At Jewel Cave, a surface transit survey to the cave entrance was done in 1997, but by this time the survey station at the entrance (originally set in 1936) had been obliterated. The 1997 surface survey also included a monumented radio location point above station 40. To register the cave survey as accurately as possible in the GIS, these X and Y coordinates for station 40 were used, and the Z coordinate was determined by using the elevation of the entrance and correcting with the appropriate Z value from the cave survey (station 40 is 25.2 m below the entrance). At Wind Cave the registration point is AU!4, at the natural entrance. The coordinates for AU!4 were determined by GPS, as well as a surface survey from known control points.

Once the caves were correctly registered in the GIS, they were combined with other layers representing hydrography, roads, political boundaries, and topographic contours. They were also overlain on images supported by ArcView, such as Digital Raster Graphics (DRGs) and Digital Orthophoto Quadrangle (DOQs) (Figs. 2 & 3).

CaveTools can add the geographic coordinates of every survey station to the data attribute table. The X and Y coordinates for any station can then be input in a GPS unit and used to navigate to the point on the surface directly above that station. The interpretation division at Wind Cave has used this tool to provide new opportunities for park visitors, offering them a "surface hike to the water table," which follows the in-cave route to Wind Cave's Calcite Lake. This technique has also been used by the cave management staff to locate potential blowholes in an area where the cave is very near the surface. At Jewel Cave, GPS was used to find the approximate surface location above a chosen site for a new radiolocation. This made it easier to locate the magnetic signal.

SURVEY ACCURACY AND CONTROL POINT ADJUSTMENT

When surface land use, such as construction of roads, installation of sewer lines, or chemical treatment of vegetation, is influenced by the known extent of the cave, such management decisions need to be based on an accurate cave survey. To check the accuracy of the Jewel Cave survey, radio-located control point data were brought into the GIS. A total of 34 monumented radiolocations above Jewel Cave have been surveyed from benchmark locations. To display these, a spreadsheet of surface coordinates was first converted to a database file (.dbf), then added to ArcView as an Event Theme.

The corresponding in-cave radiolocation points (survey stations), were selected from the attribute table for the survey stations shapefile and converted to a new shapefile. Displaying both the surface control point locations and the corresponding in-cave locations showed the distance and direction of offset between the points determined by the cave radio and those determined by the cave survey (Fig. 4a).

As expected, the surface and in-cave points closest to the entrance overlap almost perfectly. The offset between the radio-located points and the survey-determined points increases as the survey moves farther from the entrance, becoming as great as 60 m at the far southeastern end of the cave. This suggests a compounding survey error. The direction of the offset is nearly the same for all points, however, which could point to an as-yet-undetermined systematic error rather than survey error.

In COMPASS, the X and Y coordinates from the radiolocations were entered as control points. The depth determined by the radiolocation was not used to calculate a control Z coordinate (elevation) because this measurement is subject to large, non-systematic errors (Mixon & Blenz 1964). Instead, the elevation determined by the cave survey was used as the Z value. The cave was then re-plotted with the fixed control points and brought into ArcView. A portion of the unadjusted cave line plot is shown in Figure 4b, together with the plot adjusted for the radiolocations.

OVERBURDEN DETERMINATION

Determining the depth of cave passages beneath the surface is an important cave management tool. Prior to the use of GIS, depths beneath the entrance could easily be calculated from the cave survey, but overburden could not. GIS provides the means to find the elevation of the surface above any point in the cave, as well as the elevation of every cave survey station. Subtracting the in-cave elevation from the surface elevation yields the overburden.

The method used by both Wind and Jewel to match each station with its corresponding surface elevation is known in ArcView as a spatial join. Digital Line Graphs (DLGs) of 20-foot (~6 m) topographic contours were used to determine surface elevations. The Shape field from the DLG attribute table was joined to the Shape field of the cave survey stations attribute table. The resulting table lists, for each station, the record from the topographic attribute table located closest to the station (i.e., the closest contour line). The surface elevation above the station is listed in one of the fields, in feet. The ArcView field calculator can then be used to convert this ele-

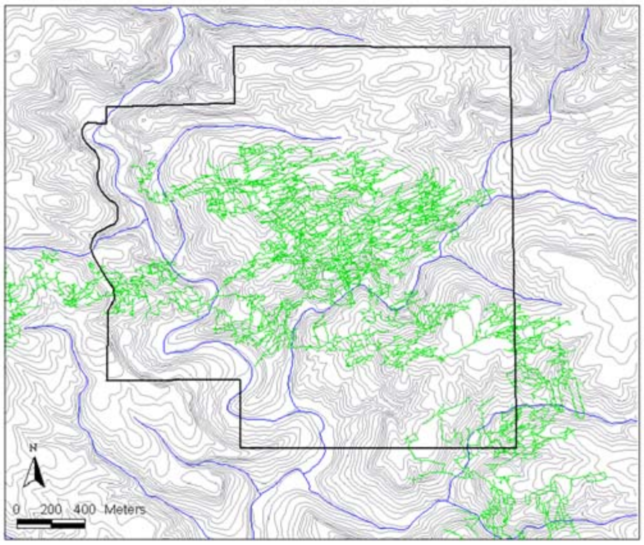

Figure 2. A portion of the Jewel Cave line plot, overlain on Digital Line Graphs representing the Monument boundary, surface elevation contours, and surface drainages.

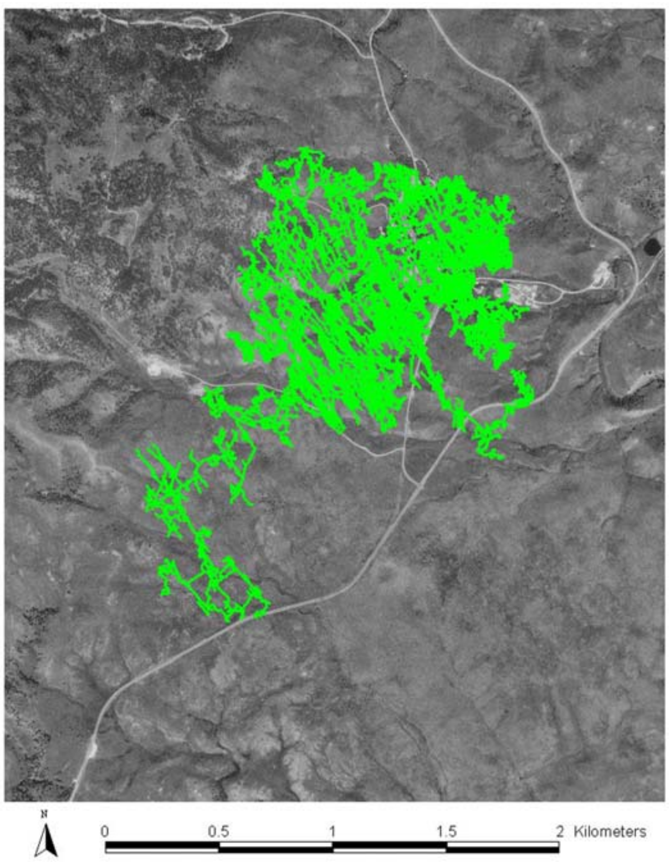

Figure 3. A view showing the location of Wind Cave relative to surface features. The surface feature image is a DOQ (Digital Orthophoto Quadrangle).

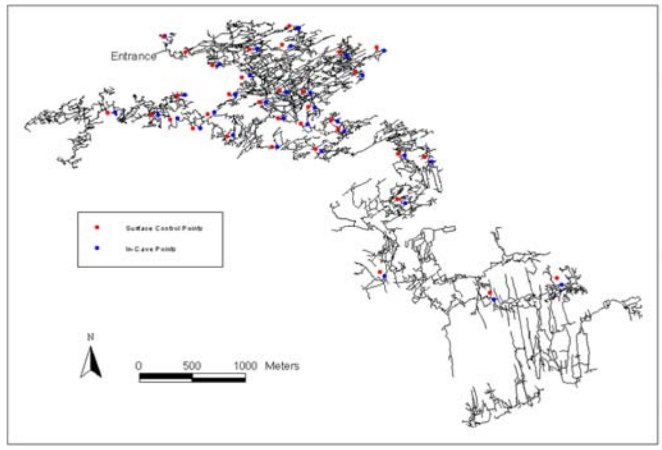

Figure 4a. Figure shows a portion of Jewel Cave, with surface control points (red) and corresponding in-cave locations (blue).

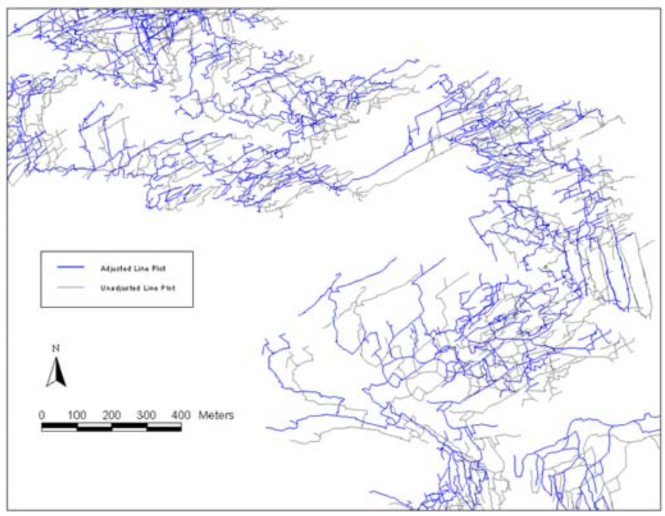

Figure 4b. Bottom figure shows a portion of the Jewel Cave line plot adjusted to fit radio location data (blue) and unadjusted (gray).

vation to meters and subtract from it the station's elevation. The resulting field gives the overburden for each station.

The accuracy of this depth determination is limited by the accuracy of the surface elevations and the accuracy of the cave survey. The DLGs used were digitized from USGS topographic maps, created from benchmark surveys, aerial overflights, and interpolation. By USGS Map Accuracy Standards, at least 90% of all tested points must be within ±10 feet of the actual elevation (for 20-foot contours). Therefore, with the exception of ≤10% of all points, the surface elevation can be determined within ±10 feet.

A high-resolution Digital Elevation Model (DEM) could have been used to determine surface elevations, and this may be attempted in the future. The surface data available were the

DLGs used, and the error range of these is acceptable for the broad management applications of the overburden determination. Wind and Jewel both hope to refine the methodology when better data are available.

Cave survey accuracy will also influence the overburden determination. At Jewel Cave, survey data corrected for cave radiolocations was used when calculating overburden. Although the survey can be corrected in the X and Y directions to match the radiolocations, the Z coordinate from the original cave survey was used (as discussed in the previous section). Using the surveyed elevations could introduce error to the depth determination, particularly in the far southeastern part of Jewel Cave, where known survey error is the greatest. Less work has been done at Wind to correct survey data with radio locations, primarily based on some question of the surface survey coordinates and some missing data. Once these issues are resolved, similar corrections will be made for Wind Cave.

At Jewel Cave, the deepest point was determined to be nearly 230 m below the surface. Due to the errors described above, one survey station was found to be 2.5 m above ground! At Wind Cave, the deepest point (at the level of the water table) is 161 m, and some survey data points are as much as ~7 m above the surface. Overall, Wind Cave is much closer to the surface than Jewel, and has much greater potential for multiple surface connections (Fig. 5).

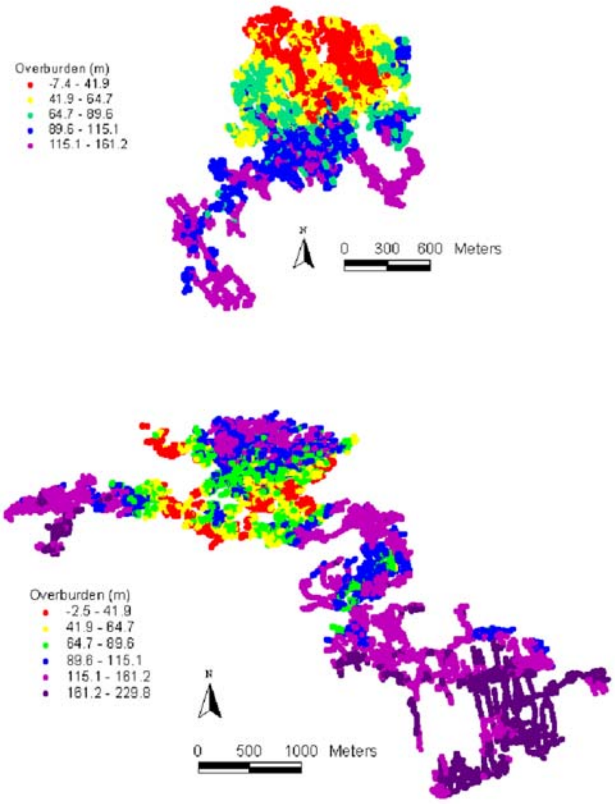

Figure 5. Wind and Jewel Caves, shaded by ranges of overburden. Wind Cave is shallower than Jewel.

DATABASE LINKAGES

Both SMAPS and COMPASS include utilities to graphically display information from databases, such as feature inventories, on the cave line plot (Nepstad 1991; Knutson 1997). Integrating these data with other GIS layers and searching for relationships between them, however, is only possible with more powerful GIS software such as ArcView.

Feature inventory data has been collected at both Wind and Jewel. While the parks use slightly different techniques in collecting data, the fundamentals are the same: features such as speleothems, hydrologic items of note, geologic items of note, cultural artifacts, and the like are recorded with reference to the nearest survey station. These data can then be linked to attribute tables in ArcView. The inventory is now a fully-functional spatial database, and all of the functionality of ArcView is available for use on these data. Relationships between features, which may not intuitively exist, can be discovered.

It is important to note that not every surveyed passage in Wind and Jewel has been inventoried. The inventory program at both caves is relatively young, and complete coverage has not yet been achieved. Wind has much better coverage than Jewel, with over 20,000 inventoried survey stations. Over 6,000 survey stations have been inventoried at Jewel Cave.

In both Wind Cave and Jewel Cave, bat scratches have been found on the ceilings of many cave passages. The GIS inventory linkage at Jewel Cave has shown that many of the inventoried bat scratch locations are very far from the cave entrance. One rather isolated bat scratch site is near the Big Duh, ~8 km (travel distance through the cave) southeast of the natural entrance. Another isolated site is in the western extent of the cave, a travel distance of ~5 km from the entrance. The overburden of these areas, as determined by the GIS analysis described in the previous section, is >125 m (Fig. 6). These

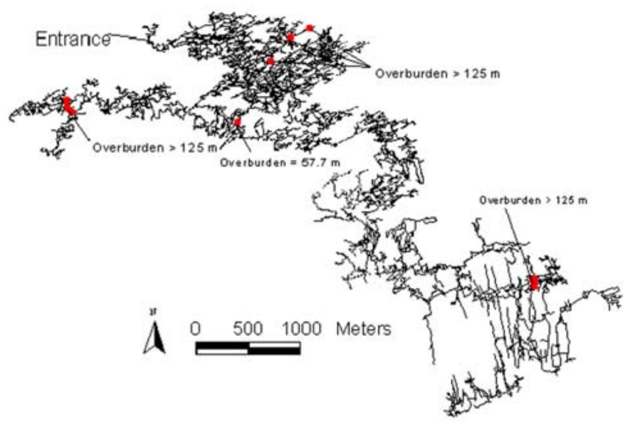

Figure 6. Locations of bat scratches in Jewel Cave (red) as determined by cave feature inventory linkage. These may be locations of old entrances that have since been naturally filled. Note overburden and distance from entrance for each area.

sites could be locations of past entrances that have since been naturally filled. Combining the feature inventory with other GIS layers has drawn attention to this mystery, which may have otherwise gone unnoticed.

Examples from Wind Cave include the location of water drip sites below surface drainages and the presence of helictite bushes along a distinct line across the cave. The geologic/hydrologic influences guiding the alignment of helictite bushes have not yet been understood, and the use of GIS analysis may soon help to explain this pattern.

The inventory linkage was only recently completed at both Wind and Jewel, but shows great potential to help unlock some of the secrets held, until now, by the caves. Once more data are included in the GIS, it is likely that more striking relationships will be discovered.

GIS AS A MANAGEMENT TOOL

Although GIS is in its infancy at Wind and Jewel Caves, the technology is already being used to guide management decisions. At Jewel Cave, GIS has been used to show the location of noxious weed sites relative to the cave, to calculate the depth of the cave below these sites, to evaluate their proximity to drainages and other potential infiltration zones, and to find locations of in-cave water drips near these sites. This analysis has helped the resource management staff make decisions regarding the use of herbicides to treat non-native plants.

GIS has also been used to more precisely determine where Jewel Cave leaves the National Monument boundary (Fig. 2). Currently, over 40% of Jewel Cave lies beneath U.S. Forest Service land.

A graduate student has used Jewel Cave's GIS to determine that cave passages trend beneath faults identified on the surface. He has then been able to look for evidence of faulting in those passages. This is the first step ever taken at Jewel Cave to assess surface/subsurface geologic relationships (Brian Fagnan, pers. comm., 2001).

At Wind Cave, the cave management staff has used GIS to show the relationship between the current parking lot and the cave. Plans are underway for a complete remodeling of the main parking lot at the Wind Cave Visitor Center, including a runoff treatment system. It was important to know the relationship of the cave to the overlying parking lot, particularly the amount of overburden in that area.

Likewise, the GIS has been used to create a "cave potential" model for Wind Cave (Horrocks & Szukalski 2000; 2002), in order to show the area of highest potential for cave development. This may help to guide continuing exploration, which will contribute to our knowledge of the cave and its extent. The GIS has also been used to show the relationship of Wind to other caves in the park.

ON THE HORIZON

As exploration of both caves progresses, more data will be collected, which will increase the knowledge base on these two world-class cave systems. At Wind Cave, researchers have already expressed interest in investigating the distribution of bat scratches, orientation of boxwork veins, and the arrangement and distribution of helictite bushes. All of these projects may be aided by use of the GIS.

A detailed geologic map of the area above Jewel Cave was recently created and will soon be digitized for use with GIS. Structural geologic contours of the top of the Mississippian Pahasapa Limestone, the cave-forming unit, were also determined and will be included as a GIS layer. The cave maps are currently hand-drafted and will be digitized in the coming years. Once this is done, passage shape, size, and orientation can be related to layers representing the surrounding geology.

The main benefit that managers have gained from the development of GIS at Wind and Jewel Caves is a way to combine datasets that were previously somewhat incompatible. This ability has allowed us to investigate relationships that would otherwise not have been apparent. As more data are made available, GIS will continue to aid in the understanding and management of these unique resources.

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