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Applications of LiDAR and field reconnaissance in the rapid assessment of karst-based surface morphology, Coconino National Forest, Arizona

Kyle Rowinski, Geological Society of America GeoCorps Program, Summer 2015

Subsurface analysis using data obtained from an aerial platform may be regarded as impractical, however recent advancements in Very High Resolution (VHR) remote sensing have rendered the collection of terrain data with a vertical resolution of up to 30 cm highly feasible. Obtained via a process termed Light Detection and Ranging (LiDAR), data collected provides a 3-dimensional representation of surface morphology with high resolution. Input of LiDAR data into geospatial analysis software such as ArcMap or ArcScene allows for the identification of subtle topographic changes across a land surface. Considering subsurface processes often have observable effects on the surface, a thorough examination of LiDAR terrain data may provide the basis for conclusions regarding subsurface dynamics. Of particular interest is the application of LiDAR in the investigation of karst topography; terrain characterized by sinkholes, surface depressions and areas of subsidence as a result of the dissolution and collapse of underlying soluble rock units. Karst features offer points of recharge or discharge for associated aquifer systems, and are therefore considered important geologic resources. Geospatial analysis of LiDAR data is a preliminary step in the examination of karst topography; potential karst feature locations may be identified and input into a geodatabase. Subsequent field assessment of potential karst features may involve a rapid, broad-scale inventory, or require an in-depth, localized geologic analysis of a specific feature. The former is both time and resource conserving, and allows for a high number of features to be surveyed in a relatively short timeframe. Thus, federal agencies such as the United States Forest Service may incorporate a rapid karst inventory and assessment into a forest resource management and conservation project. Such is the case on the Coconino National Forest, where LiDAR data was used to facilitate a recent cave and karst survey, conducted by participants of the Geological Society of America’s GeoCorps America program.

The Coconino National Forest exists within North-Central Arizona and contains numerous physiographic and geologic provinces. The Mogollon Rim, in the Southern part of the forest, is of particular interest due to a variety of forest and geologic resources. The area is topographically elevated from surrounding arid regions of the Verde Valley by as much as 2500 feet. The project location receives on average 31 inches of annual precipitation. Underlain by limestone/dolostone and basalt bedrock, caves, sinkholes, and other karst features are common and occur with high density. The karst terrain provides a high recharge rate to the regional karst aquifer. Therefore, surface water resources on the Mogollon Rim are abundant, some of which have been allocated to previously groundwater-dependent towns and cities.
Cragin Reservoir is a prominent resource, with an available 15,000 acre-feet of water recharged by a 72 mi² watershed. Protection of the reservoir is of high importance; a primary concern is the potential for a stand-replacing wildfire to occur in the ponderosa pine and mixed conifer forest, which would have adverse effects on water quality.

Established in 2015, the Cragin Watershed Protection Project (CWPP) is based out of the Blue Ridge Ranger Station, a relatively remote area within the Coconino National Forest approximately 40 miles south of Flagstaff. Designed to reduce stand-replacing fire risk, the CWPP provides forest thinning and fuels reduction while taking into the effects of such actions on the unique biologic, archeologic, and geologic resources prevalent in the 64,000 acre² project area. Survey teams from respective disciplines analyzed resources within the area throughout the summer of 2015. The Geology team was comprised of GeoCorps participants, who completed a cave and karst survey in the project area with the intent of developing karst feature protection buffers to mitigate ground disturbance from project activities. Considering the specific niche of karst within the geologic discipline, a thorough review of both karst and pseudokarst processes was necessary prior to beginning the project. Additionally, the project area was physically observed through aerial imagery and scouting from fire towers.

Preliminary LiDAR data analysis via ArcMap manually established 284 potential karst features in the project area with subsequent spatial analyst techniques providing details concerning area, maximum depth, volume, and the contributing area of such features. Specifically, a hillshade layer was rendered from a LiDAR-derived DEM to visualize areas of subsidence. Raster analysis, primarily via hydrology tools, provided quantitative data regarding subsidence areas. Following preliminary identification, a geodatabase for data collection was created. In the planning stages of the cave and karst survey, it was thought that a geodatabase and methods existed to facilitate the rapid field inventory and assessment of karst terrain in a national forest. However it was discovered that no pre-existing template met the unique needs of the Cave and Karst survey, thus a geodatabase was designed to allow for rapid field assessment and data collection. The geodatabase was input into ArcCollector and installed on a tablet for field use. Also available within ArcCollector was a LiDAR hillshade raster, providing high-resolution terrain data for geologic analysis of potential karst features on site.

Inventory and assessment was completed through the visual analysis of each potential feature in the field and recording of data through both field notes and the geodatabase within ArcCollector. Field notes consisted of a brief sketch of the location, including cross sections and dimensions. A geologic analysis of the feature was also completed, taking into consideration fluvial activity, rock type, and
surrounding geomorphology. Attributes entered into the geodatabase included Karst type, feature type, surface and subsurface geologic data, airflow presence, and more. From this data, features were ranked from minor to major importance, to aid in the establishment of protection measures. ArcCollector also allowed for the attachment of several photos to the attribute data of each location. Wirelessly syncing the geodatabase and photographs to ArcGIS OnLine provided a secure on-line service from which GIS data could be downloaded and manipulated in ArcMap, in the office.

The ease of use and feasibility of the rapid-assessment system ensured the project was completed within two months and with high accuracy. Post-fieldwork data analysis provided both numerical and geospatial data depicting the type and location of karst features. Results show a variety of karst mechanisms existing within the project area including solution, pseudo, and tectonic karst. For simplification purposes, tectonic-karst was noted as pseudokarst. See: Figure 1.

Figure 1: Karst Mechanism by Percent/Total.

![Karst Mechanism by Percent/Total](image)

Due to the high z-resolution of LiDAR data, non-karst was commonly preliminarily identified as potential karst. Examples represent depressions formed from downed trees and rock outcrops, the LiDAR-rendered appearance of which closely resembles a prominent karst feature. Field inventory ensured such features were classified appropriately. Assessed karst features include sinkholes, extensive cave systems, emerging and sinking streams, and possible collapsed lava tube. See: Figure 2.

Figure 2: Karst Feature by Percent/Total
It was discovered that the majority of karst features, predominantly bedrock collapse sinkholes, exist within the Miocene basalt flows of the region, a rock type not typically associated with karst due to relatively resilient chemical and physical properties. Such a conclusion offers motivation for further research.

Of particular geologic interest is a karst feature recognized by a substantial depression within Miocene basalt, with an associated sinkhole and talus slope existing in the zone of greatest subsidence. Air is emitted from a cave entrance within the talus slope; exploration revealed details pertaining to the stratigraphy of the feature. Specifically, 15’ of basalt unconformably overlies the highly fractured and karstified Upper Kaibab Formation. Thus, it can be stated with confidence that the primary karst mechanism is that of normal karst; the subsidence within basalt is a direct result of the dissolution and subsequent collapse of the underlying Kaibab limestone.

Hydrologically, the feature is found within a north-dipping basalt plateau, and is 1800 feet east from an incised fluvial system with both strike and dip to the north. LiDAR based DEM analysis with ArcScene suggests that the karst feature is within a shallow tributary channel, leading into the larger fluvial system to the west. Surface hydrology tools including flow direction and accumulation were used within ArcMap to delineate a watershed and contributing drainage area for the feature. See: Figure 3.

Figure 3: LiDAR hillshade, depicting the karst feature and associated drainage area. Note the fluvial system to the East.
The area spans 47 acres, with flow eventually accumulating at the karst feature. Additional calculations provided the water volume received by the drainage area annually, assuming a typical climate. Considering 31 total inches of precipitation, the area receives 5,293,843 ft$^3$ of water. It is realized that the presence of high-permeability alluvium at the surface allows the vast majority of such water to penetrate into the subsurface. However, an impermeable basalt unit underlying the vadose zone will likely constrict water flow into the karst aquifer and direct flow towards the feature sub-surficially. This concept may be applied to regional bedrock collapse sinkholes and offer a mechanism of formation for those existing within basalt.

At least three previously unknown caves were discovered and are pending mapping by the forest’s partners, the Arizona Cave Survey. The Forest Service maintains a volunteer agreement with the organization, allowing for the sharing of cave data and locations. Several cave reconnaissance trips were completed to assess surficial entrances and sub-surficial cave systems. The largest, previously unknown, cave system explored with the Arizona Cave Survey was a large underground chamber, accessible through a narrow surficial entrance. Vertical gear was required for navigation through first the entrance and then a 40’ cliff found shortly thereafter. It is likely this cave opens up into a large system, however some excavation is necessary. This trip was of particular interest due to the fact that numerous bones were discovered within sediment at the bottom of the cave feature, possibly from a small mammal. Images were captured and will be sent to a paleontologist for analysis. Over time, the Arizona Cave Survey will investigate and map all potential cave features discovered through the Cave and Karst Survey.

Developing resource protection buffers for the karst features was achieved through the downloading of data from ArcGIS Online and editing through ArcMap. An accurate footprint for each feature was manually digitized from a LiDAR raster and assigned a level of importance: no, minor, intermediate, and major. Footprints were buffered to 0, 50, 100 and 300 feet, respectively. Fluvial systems leading into features were considered of major importance and were buffered to a width of 100 total feet, for a distance of 1000 feet upstream, and will be managed as Aquatic Management Zones. The karst feature buffers serve as a zone of exclusion from forest thinning logging equipment, thereby protecting the microclimate and ecology that has developed over time and minimizing sedimentation into the karst features. Fuels reduction using low-intensity prescribed burning may occur within the karst terrain while meeting resource objectives developed for the karst features.
The utility of LiDAR in the analysis of sub-surficial processes, specifically those processes occurring in karst terrain, was realized through the completion of the Cave and Karst survey. Preliminary identification of karst features via LiDAR and geospatial analysis techniques provide data to facilitate a rapid field inventory and assessment, one which may cover a large area in a relatively short timeframe. As such, a rapid karst assessment system was integrated into the Cragin Watershed Protection Project by the USFS to provide zones of protection for karst features. Due to the feasibility of the system, the Cave and Karst Survey met all pre-established goals and was termed a success. Additionally, personal goals were met, with geologic and geospatial analysis skills developed that will prove highly useful in future research projects. The personal desire to work within an earth science based research field was also realized; this will provide incentive for further research. The methodology and results from the Cave and Karst survey, working under the Cragin Watershed Protection Project, will provide a template for future surveys on additional National Forest lands and allow for further research regarding the Karst terrain on the Mogollon Rim, possibly utilizing GeoCorps participants.