An automated method to extract typical karst landform entities from contour lines on topographic maps

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Abstract— **Mapping specific landform entities in the past is mainly achieved by manually examining contour lines on topographic maps. Automated delimitation of specific landform from digital elevation data remains difficult in geomorphologic mapping. This paper presents a method to automatically identify five common surface features of karst landscapes: isolated karst hill or sinkhole, clustered karst hills or sinkholes, and clustered hills with sinkholes. These landform entities have their own singular geomorphometric characteristics and thus could be identified from digital elevation data. In this study, boundary of individual landform entity is defined by an outmost closed contour line (CCL), which contains at least another CCL but not contained by any other CCLs. The innermost CCL with a local extreme elevation value represents either a peak or a sink of that specific landform. Between the innermost and the outmost CCLs, several intermediate CCLs may exist, depending upon relief of the landform and contour interval of the topographic maps. The aforementioned surface karst landform entities were then delimitated and identified by examining the spatial relationships among these CCLs and the change of their elevation values. The method was applied to delimitate these landform entities in Oolitic, IN and Florida, PR. Comparison of the distribution of these surface features in these two areas provides new insights into karst development processes and landscape evolution.**

I. Introduction

The Earth's surface is covered by different types of landforms, which can be recognized and distinguished from their distinct dimensions and the statistical frequency of their geomorphometric attributes [1]. The topography of a specific landform type usually defines its geomorphic form and represents the interactions of climatic, geological, and other surface processes that have acted on it over time [2]. Extraction of different types of landforms and examining their distinct geomorphometric characteristics thus can play an essential role for geomorphologist to understand their origins and evolution processes.

Automated extraction of specific types of landforms from digital elevation data remains a challenge in geomorphologic mapping [3]. One of the possible reasons might be the lack of operational definitions of specific types of landform entities and it is usually hard or even not possible to crisply define their boundaries [3]. This might not be the case for some typical karst landform entities, such as isolated karst hill or sinkhole, clustered karst hills or sinkholes, and clustered hills with sinkholes (Fig. 1). Geometrically, an isolated sinkhole is a small to intermediate enclosed depression which is formed by the dissolution of surface carbonate rocks typically at joint intersections. Sinkholes are actually deemed as the diagnostic karst landform as karst is always developed in the areas where sinkholes are found [4]. As dissolution of surface carbonate continues, isolated sinkholes gradually grow and coalesce with adjacent ones and consequently clustered sinkholes are developed. In many cases, isolated or clustered sinkholes are widely found on temperate plains. Carbonate residual hills are developed when most carbonate has been removed by dissolution processes. These residual hills might be isolated or share a common base (clustered karst hills). The last type of landform entity, clustered hills with sinkholes, is well developed in humid tropical areas and is characterized by occurrence of deep sinkholes within a cluster of karst hills. Obviously these landform entities have their own geomorphologic significance as they are developed in different hydrogeological circumstances [4]. These landform entities are also the representative products of different karst evolution stages [4]. Therefore, mapping these landform entities will help karst geomorphologists better understand their origins and development. Currently these types of specific landforms are mainly identified for a few small areas by visual examining topographic maps and/or remote sensing images [6]. With digital elevation data more accessible today, an automated method thus is needed to map these landform entities at a broad scale.

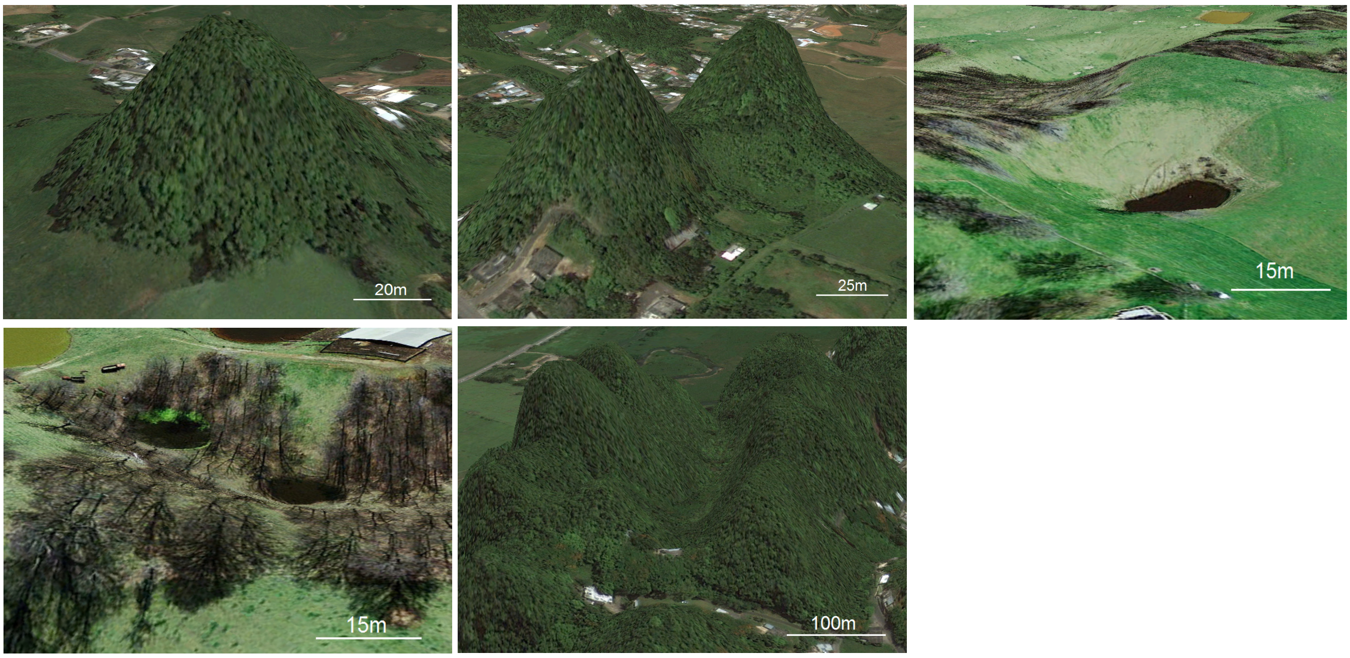

Figure 1. Google Earth screenshots showing A) isolated hill, B) clustered hills, C) isolated sinkhole, D) clustered sinkholes, E) clustered hills with sinkholes. Scales are approximate.

II. Study area and data

This study examined the typical surface karst landforms in Oolitic, Indiana (38.90N, 86.52W) and Florida, Puerto Rico (18.36N, 66.55W). Landscapes in the first area are mainly characterized by small size isolated and clustered sinkholes scattered on a rolling plain. By contrast, isolated or clustered karst hills and cluster hills with sinkholes are very common in Florid, PR. Landforms in these two areas represent the most typical temperate and humid tropical karst landscapes respectively.

The contour interval is 10 feet and 10 meters on the 7.5 minute Oolitic and Florida quadrangles respectively. Digital Line Graph (DLG) of these 7.5 topographic maps have some contour lines left open due to aesthetic reason in cartography though they should be closed, particularly in the areas with high relief. Therefore, the DLG data were not used in this study. Instead, contour lines were generated from the 30-m USGS DEMs at the same contour intervals as the corresponding topographic maps. The DEM-derived contour lines well match those on the 7.5 minute topographic maps. As this study mainly focuses on surface karst landscapes, geologic maps of these two study areas were also acquired and used to mask out non-karst landscapes.

III. Methodology

This study delimitates these five types of landform entities by examining the spatial relationships of the closed contour lines (CCLs) that represent each specific landform. The boundary of a landform entity to be delineated is defined by an outmost CCL, which contains at least another CCL but not contained by any other CCLs. Thus a specific landform entity is represented by a cluster of CCLs, including the outmost CCL and all other CCLs within it. The CCL cluster is then converted to an acyclic graph, with a node representing a specific CCL. The outmost CCL is represented by a root node. The innermost CCL, which contains no other CCLs but is contained by at least another CCL, is represented by a leaf node. If a CCL contains at least two other CCLs with same elevation, it is defined as a branch node in the acyclic graph. Any other CCLs within the outmost CCL are represented by middle nodes. Given that, the aforementioned landform entities can be described by following representative scenarios (Fig.2).

Both isolated sinkhole and karst hill have no branch nodes but only one leaf node connecting to the root node. From the root node to the leaf node, elevation gradually increases for the isolated karst hill (Fig.2A) while decreases for the isolated sinkhole (Fig.2C). An acyclic graph with at least one branch node represents a specific landform of clustered hills (Fig.2B) if the elevation gradually increases from the root to the leaf node and clustered sinkholes (Fig.2D) if the elevation is gradually decreasing. If there are at least one leaf or middle node having elevation higher and another one having elevation lower than the branch, middle, or root node that right connects to them, this scenario defines the clustered hills with sinkhole (Fig. 2E). An algorithm was developed to automatically label these five scenarios and consequently identify these five types of landform entities.

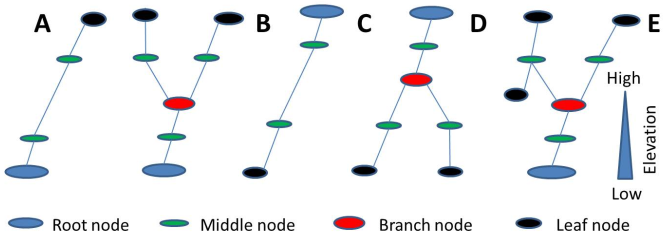

Figure 2 Representative acyclic graphs showing the typical types of surface karst landform entities. A) isolated hill, B) clustered hills, C) isolated sinkhole, D) clustered sinkholes, E) clustered hills with sinkholes

IV. RESULTS AND DISCUSSIONS

Delimitation results are shown atop of hillshaded DEMs of our two study areas (Figs. 3 and 4). Totally 175 and 2079 specific landform entities were delineated in Oolitic, IN and Florida, PR respectively (Table 1). These entities account for 21.9% and 37.8% of the total area of these two regions respectively.

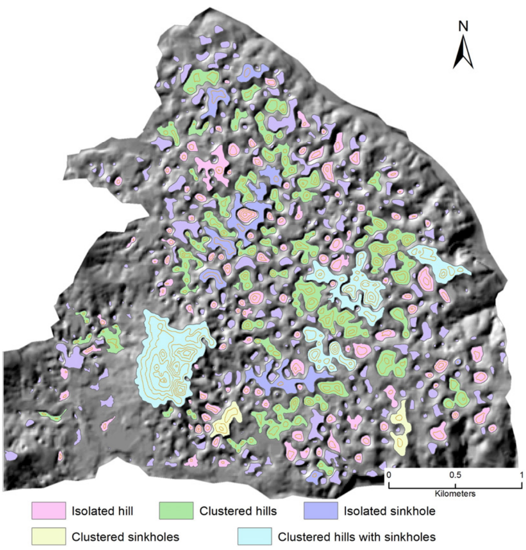

Figure 2. Delimitation results of Oolitic, IN

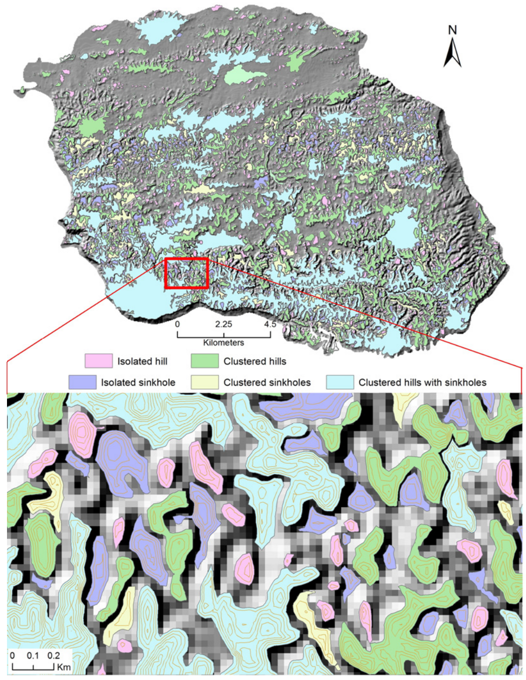

Figure 4. Delimitation results of Florida, PR

Dominant types of landform entities in these two areas are not the same in our two study areas (Tab. 1). The clustered hills with sinkholes type occupies 18.06% of the total area in Florida, PR while the dominant type of landform entities in Oolitic, IN is the clustered sinkholes. Residual hills, either isolated or clustered, are more developed in Florida while isolated or clustered sinkholes outnumber hills in Oolitic in terms of both occurrence frequency and area. Karst geomorphologists have noticed the different dominant karst landforms types in these two areas based on their field observations and subjective interpretation. To our knowledge, this study is the first one to provide an indicator to quantitatively describe the difference. Tectonic uplifting and climate seem to be the main reason that why these two study areas are dominated by different types of landform entities. Both vertical and lateral dissolution of limestone is more intense in the tropical Florida PR than the temperate Oolitic IN. More intense vertical dissolution resulting from tectonic uplifting in Florida PR significantly enhanced the development of deep sinkholes and removed more carbonate formation, producing more isolated and clustered residual hills. By contrast, slower vertical and lateral dissolution processes remove less carbonate and thus mainly produce isolated or clustered sinkholes in Oolitic IN.

TABLE 1. FREQUENCY AND AREA PERCENTAGE OF DIFFERENT TYPES OF LANDFORM ENTITIES DELIMITATED IN OUR TWO STUDY AREAS

Study areas		Oolitic, IN	Florida, PR
Total area (km²)		*9.72*	*278.72*
Isolated hill	Number	9	822
	Area (%)	*2.29*	*3.06*
Clustered hills	Number	2	524
	Area (%)	*0.67*	*10.82*
Isolated sinkhole	Number	114	461
	Area (%)	*5.4*	*2.6*
Clustered sink-holes	Number	45	175
	Area (%)	*8.23*	*3.26*
Clustered hills with sinkholes	Number	5	97
	Area (%)	*5.28*	*18.06*

Number of isolated hill and sinkhole is always more than that of their clustered counterparts in both areas. However, size of isolated hill and sinkhole is much less than the clustered hills or sinkholes respectively. For example, in total 45 clustered sinkholes were delimitated in Oolitic and they account for 8.05% of the total study area while the 114 isolated sinkholes occupy only 5.40% of the total area. In Florida, the 822 isolated hills account for only 3.06% while the 524 clustered hills occupy 10.82% of the total area.

These landform entities probably are developed in different stages of karst development though dissolution of carbonate is the dominant driving force. Isolated sinkholes are usually the first surface karst feature that are developed once subsurface conduits were established [4]. Once a sinkhole commences to form, the centripetal focusing of runoff and hence further dissolution of carbonate encourages the enlargement of initial isolated sinkholes. Given enough time, this self-reinforcement process leads to the coalescence of adjacent sinkholes thus clustered sinkholes are developed within a larger enclosed depression.

With more carbonate being removed by the focusing dissolution within sinkholes, original carbonate block is subdivided into smaller chunks. Within these chunks, clustered hills with sinkholes or clustered hills are developed, depending on different hydrogeological settings. New isolated sinkholes may commence to form and existing sinkholes continue to grow in these chunks, from which isolated hills then are developed as the next sequential products. Yet some isolated hills could also be directly derived from the continuous growth and enlargement of isolated or clustered sinkholes [4], [7]. Nevertheless, the isolated residual hills tend to represent the final stage of karst development as solution activity has removed most of the carbonate formation.

A similar study was conducted to discriminate tower karst and cockpit karst landforms in Guilin, China [5]. The former type includes isolated and clustered karst hills while the latter literally the same as the clustered hills with sinkholes in this study. This study classified karst landscapes from a different perspective, delineating the sequential evolution products of karst development.

V. CONCLUSIONS

Typical types of surface karst landform entities were automatically delimitated in Oolitic IN and Florida PR by examining the spatial relationships among closed contour lines on topographic maps. All these five types of landform entities are found in these two areas while they occur at different frequencies and account for significantly different areas. The delimitation results show that isolated or clustered sinkholes are the dominant landforms in Oolitic IN. By contrast, type of clustered hills with depressions accounts for the larges area among all these five types of landform entities in Florida, mainly due to different conditions of climate and hydrogeology in these two areas. Further examination of morphometric characteristics of these specific landforms in these two areas may provide new insights on the development processes of karst landscapes. It would be also of great value if these types of landform entities are identified in more study areas and further comparison definitely helps geomorphologists better understand the controls on karst development. This method, with appropriate modification and improvement, also provide a new approach for landform classification.

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