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The use of GIS-based digital morphometric techniques in the study of cockpit karst

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Abstract

Cockpit karst landscapes are among the most distinctive landscapes in the world, and have been the focus of long-standing scientific interest. Early researchers used largely descriptive techniques to categorize the terrain, and subsequent work has not attempted to critically re-evaluate descriptions of landscapes using more sophisticated methods. The distinctive surface topography of cockpit karst areas can be characterized in order to compare them with other karst as well as non-karst areas, and to determine geological and/or climatic conditions that are responsible for the observed terrain. Process models of the rate of karst denudation or evolution can only be accurate if the contemporary morphology of the landscape is quantitatively and unambiguously defined. A detailed analysis of cockpit karst terrain is carried out using the latest GIS-based digital morphometric techniques in order to assess the nature of such terrain and provide further information for subsequent modelling, as well as other non-geomorphological applications, such as environmental management and conservation issues. The paper presents the methodology used for the digital analysis of terrain and landforms in the distinctive Cockpit Country area of Jamaica and its environs. The results indicate that cockpit karst may be categorized based on its vertical, horizontal and shape characteristics, as well as by looking at the semivariogram, slope characteristics, and landscape relief scale, which combine measures of vertical and horizontal scales. Copyright © 2006 John Wiley & Sons, Ltd.

Keywords: cockpit karst; Jamaica; GIS; digital morphometry

Introduction

Robust, quantitative descriptions of landscape form are essential ingredients for mapping and classifying terrain, interpreting its origins, and testing mathematical models of landform genesis. Yet, despite recent and rapid improvements in the resolution, quality and availability of digital terrain data, there have been relatively few attempts to develop morphometric indices that are diagnostic enough to reveal essential differences between landscapes. Many of those that have been introduced are intended specifically for fluvial environments. For instance, metrics such as drainage and valley density (e.g. Montgomery and Dietrich, 1989; Tucker *et al*., 2001), the slope–area–elevation relationship (e.g. Willgoose, 1994), the area–aggregation index (e.g. Moglen and Bras, 1995), and hydrologic 'moisture indices' (O'Loughlin, 1986) do not apply to landscapes that lack coherent stream networks. This focus on fluvial environments excludes a wide variety of terrain types, including, for example, dune fields, many tundra environments, and internally drained karst landscapes. In this paper, morphometric indices are developed for internally drained karst topography, and applied to the cockpit karst region in north-central Jamaica. We show that a simple set of metrics based on relief and its horizontal scaling properties can reliably distinguish between landform types in this region, and provides a useful basis for testing the predictions of process-based models.

For hundreds of years, cockpit karst landscapes, unique to the tropics, have intrigued scientists and others who are fascinated by the stunning scenery and the associated development of endemic flora and fauna. The early descriptions of cockpit karst landscapes were qualitative and based largely on field observations alone. Quantitative karst morphometric research has been conducted since the early 1970s, and has led to improved understanding of the nature of such terrain, enabling more precise description and comparative analysis, and assisting investigation of the relationships between morphology and the controls on the karst environment. However, most analyses to date have relied on fairly limited sets of measurements obtained from field surveys or from printed topographic maps. Vast improvements in technology and data available – such as the Global Positioning System (GPS), digital elevation models (DEMs) and high-resolution satellite imagery – now enable a comprehensive reanalysis of cockpit karst terrain. Using such technology, cockpit karst terrain, first described in 1869, may be redefined according to robust, objective criteria derived from high-resolution terrain data.

There has been much disagreement over the last century about the cockpit karst phenomenon, and this is reflected in the confusing terminology. For instance, Lehmann (1925) was the first to describe the karst topography of southern China as *kegelkarst*, and the term has been used since then to describe tropical karst landscapes. However, Sawkins (1869) was the first to describe a terrain as having cockpit topography, noting the resemblance of these karstic depressions to arenas used for cock-fighting. Furthermore, there is confusion over what exactly *kegelkarst* is. Lehmann (1925) used *kegelkarst* to describe tropical karst topography in general; Sweeting (1972) regarded *kegelkarst* as the same as cone karst, where both residual hills and depressions equally dominate the landscape. However, Corbel and Muxart (1970) regarded *kegelkarst* as being tower karst (Sweeting's (1972) *turmkarst*), where isolated residual hills are separated by extensive, often alluviated plains. Nevertheless, Day (1978, p. 117) maintained that 'of all the recognized tropical karst styles, that termed cone karst has attracted by far the greatest interest, research and discussion'. However, some confusion remains, as the cockpit karst of the Cockpit Country of Jamaica does appear, in some respects, different in morphology from the cone karsts of Asia. Moreover, the very appellations of 'cockpit karst' and 'cone karst' denote two very different landforms, with cockpit karst being characterized by deep enclosed cockpits which are distributed throughout the terrain, while cone karst is typified by hemispherical hills separated by narrow interconnected depressions. Morphometric analysis of karst is needed in order to unambiguously characterize different karst landscapes and to more adequately describe and model such areas.

Cockpits are irregular, star-shaped hollows in the landscape through which water is conducted underground. They are distinct from dolines in being deeper and not being circular in plan. On a contour map of a doline area, circular contour lines indicate the locations of negative relief elements (depressions), whereas on a contour map of cockpit karst terrain it is the positive relief features (the conical hills) that are shown by circular contour lines. In cockpit karst, unlike other karst forms, enclosed depressions and residual hills attain approximately equal prominence (Day, 1978, 1982; Miller, 1998). Sweeting (1972) described cockpit karst as a landscape consisting of a succession of cone-like hills with alternating enclosed depressions (see Figure 1). She described the uniformity of the terrain, in terms of both the apparent uniformity in the summit levels of the hills, as well as the apparently uniform areas of both the hills and the depressions, and the slopes of the landforms. Cockpit slopes are generally between 30° and 40° and mantled by weathered debris, but some are bare and cliff-like (exceeding 70°).

Figure 1. Classic cockpit karst landscape of the Cockpit Country, Jamaica.

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GIS and cockpit karst

An attempt is described in this paper to redefine the morphology of cockpit karst terrain using geographic information systems (GIS)-based morphometric techniques to quantify the landscape and landforms of part of the Cockpit Country of Jamaica. This provides a clearer picture of the landscape, and prompts a re-evaluation of many assumptions about the morphology of such landscapes, most of which were originally devised before sophisticated computer-based tools became widely used in geomorphology. We analyse terrain on both a regional scale (tens of kilometres – referred to as 'general' morphometry) and at the scale of individual landforms (hundreds of kilometres – referred to as 'specific' morphometry). Vertical, horizontal, shape and scaling properties of karst areas are digitally analysed and used to distinguish different types of karst areas. The morphometric techniques we describe provide a basis for analysing other karst regions around the globe. A quantitative examination of cockpit karst morphology also allows an evaluation of the influence of geology and other morphogenetic factors.

The Study Region

The Cockpit Country of Jamaica is the type area for cockpit karst landforms. First described in 1869 by Sawkins, the region has attracted geomorphologists for well over a century. Sweeting (1956, 1958) conducted the first detailed geomorphological survey of the Cockpit Country, while Day (1978) carried out the first detailed quantitative study of the karst terrain and landforms there. Since then, most of the scientific work in the Cockpit Country has been carried out by biologists studying the endemic flora and fauna of the region. An exception to this is a GIS-based biogeomorphological study of a part of the Cockpit Country by Chenoweth and Day (2001).

Six areas were selected for study in this research (Figure 2): three of largely cockpit karst terrain within the Cockpit Country (Barbecue Bottom and Windsor in the parish of Trelawny, and Quickstep in St Elizabeth), and three of largely non-cockpit karst terrain outside the Cockpit Country (Elderslie, St Elizabeth, with mixed doline and cockpit topography; and Nassau Valley, St Elizabeth, and the Queen of Spain's Valley at the border of St James and Trelawny, which are poljes (interior valleys) containing karst towers). These areas were chosen in order to compare and contrast the morphology of the landscape and landforms of cockpit karst and non-cockpit karst. All the areas were chosen based on site accessibility and availability of data, as well as their overall representativeness of the wider region. An area of 25 km^2 was selected for each location; this sample size is large enough for meaningful statistical and spatial analysis, yet small enough for thorough fieldwork to be carried out.

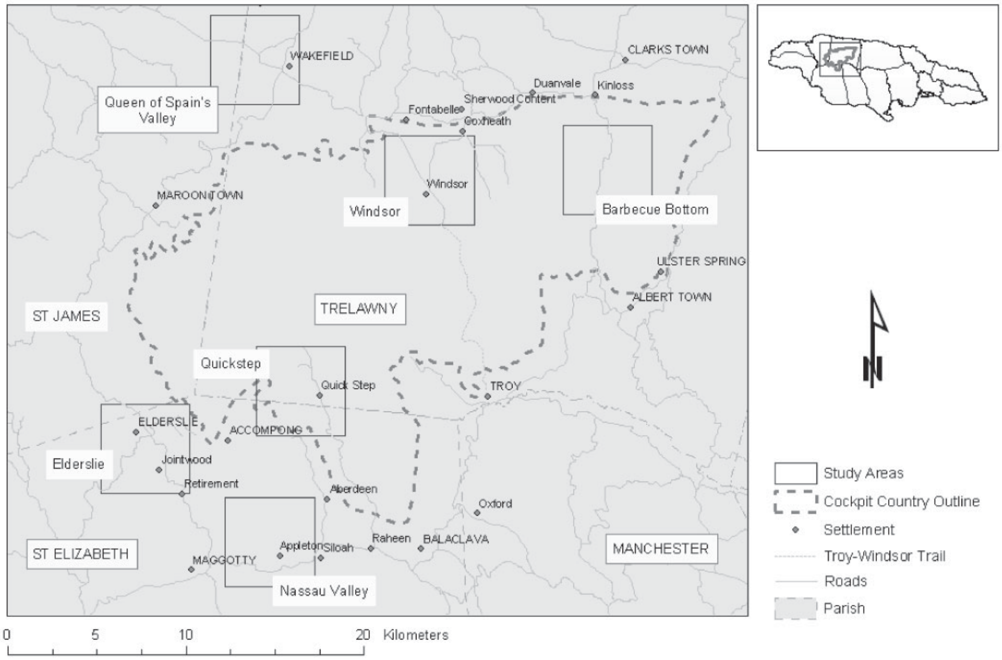

Figure 2. Location of the study areas.

Methodology

Methodology is described here in detail since most of the morphometric techniques have never before been applied in the field of karst morphology. Some methods are entirely new, while others have been adapted from other areas of geomorphology and landscape ecology. Morphometric analysis of the cockpit karst areas using GIS required the assembly of several data sets. Crucially, topographic data were required. Contours of the study region at a scale of 1:12 500 were acquired from the Jamaican Survey Department and digitized using AutoCAD. In addition, GPS spot heights collected during fieldwork also served as topographic inputs to the analysis. The digitized contours were decomposed into hundreds of thousands of vector spot height points and integrated with the GPS data in order to construct a digital elevation model (DEM). The use of imagery to create DEMs was not feasible due to cost and technical issues, particularly the problem of cloud cover over the study region.

The GIS software programs *ArcView 3·2* and *ArcGIS 8·2* were used for the morphometric analyses. Further software customization, necessary to enhance the functionality of the GIS to perform specific analyses, was also carried out.

Data analysis was divided into two main sections: digital terrain analysis, which uses general morphometric techniques to analyse the entire surface (Evans, 1990), and digital landform analysis, which involves specific morphometric methods (Jarvis and Clifford, 1990) to examine particular landforms in the terrain.

Digital terrain analysis

Geostatistical investigations of the variography of the elevation data were used both to construct a DEM and to characterize terrain statistics in each of the study areas. The first step in investigating this variography involved the creation of a semivariogram (Johnston *et al.*, 2001), measuring the strength of statistical correlation between points as a function of distance between them. The semivariogram of elevation, γ, is defined by:

$$\gamma_{(si,sj)} = {}^{1}\!/\!_{2}\sigma(z_{si} - z_{sj})$$

where σ is the variance of elevation, z is elevation, and s_i and s_j are the pairs of points being analysed. As s_i and s_j become farther apart, the difference in their values ($Z_{si} - Z_{sj}$) becomes larger as the points become less similar.

The geostatistical analysis was performed on the input spot heights after removing the overall directional trend in the data. The spherical model was used, based on the shape of the semivariogram cloud and on cross-validation of the predictive model. The semivariogram not only provides inputs for kriging interpolation of the spot heights to create DEMs, but also provides useful information on key topographic properties. The degree of vertical variation in the terrain is indicated by the sill, while the range describes the extent of spatial autocorrelation.

DEMs were created using kriging interpolation of the spot height data. Based on the dense coverage of spot heights and their spacing, 2-m DEMs were created for each of the study areas. Primary topographic attributes, such as mean elevation, slope and aspect, were calculated within the GIS. Other measurements of the general morphometric properties of the landscape included determination of the relative and local relief characteristics.

The determination of the relative relief of the landscape – the difference between the highest and the lowest points within a terrain – involved creating summit surfaces, representing the highest parts of the terrain, and sink surfaces, representing the lowest parts of the landscape. Sinks and summits themselves were identified using hydrological modelling techniques. In conducting hydrological modelling experiments involving DEMs, sinks (closed depressions) are often removed, as they may represent artefacts from the interpolation process. However, in karst areas they may represent actual sinks, a fact verified in the field using GPS. The sink points in each data set were identified using a standard hydrologic sink-detection algorithm. Summit points were identified by inverting the DEMs and rerunning the sink-detection algorithm. The sink and summit points were then interpolated separately using tension splining, in order to generate surfaces representing the lower and upper limits of the terrain, respectively. Map algebra was then used to subtract the sink DEM from the summit DEM to create a relative relief surface.

Local relief and its variation with measurement scale were also examined. Here, local relief at a point is defined as the maximum height difference between points falling within a window of specified dimensions, centred at the point in question. This was conducted using the neighbourhood analysis function with the *ArcGIS* extension *Spatial Analyst*. The neighbourhood size was varied in order to examine the relief-scaling properties of the terrain. An ideal neighbourhood size could be determined after investigating the relief-scaling properties of the terrain.

By looking at the range of elevation at multiple horizontal scales, the relief-scaling properties of the landscape may be determined. Previous studies (e.g. Weissel and Pratson, 1994) have shown power-law scaling in topographic relief, such that $y = cx^m$, where y represents vertical relief (average maximum height difference between points within a window of width *x*) and *x* represents horizontal scale, while *c* represents the amplitude factor (or *y* intercept), and *m* represents the scaling exponent, or slope. Both *c* and *m* are required for a 'complete characterization of surface topography', according to Weissel and Pratson (1994). Topographic roughness may be determined using both *c* and *m* by calculating the area beneath the lines on a log–log plot by the equation:

$$r(X_1, X_2) = \left(\frac{c}{m+1}\right)[X_2^{m+1} - X_1^{m+1}]$$

where r is relative roughness, X_1 is the initial horizontal scale (which may be zero, or may represent a scaling break), and X_2 is the upper scale range considered. Total area is calculated by adding the area beneath the plot before and after any scaling breaks. Terrain with a large area under its log–log plot would be 'rougher' than areas with smaller area values.

On the basis of the relief scale investigations, an appropriate neighbourhood size for determining local relief can be selected. Intrinsic differences between cockpit karst and non-cockpit karst terrain can also be identified, and from this cockpit karst terrain may be identified from an area that is morphologically mixed.

Digital landform analysis

Individual features of the landscape may be described, and their distributions, patterns and forms may be used to characterize an entire landscape. Indeed, a landscape may be described by the assemblage of its constituent landforms.

Sink and summit delimitation has already been outlined. The degree of randomness in the distributions sinks and summits may be described using nearest-neighbour analysis, which examines point spacing. This is done by comparing the mean observed distance between nearest neighbouring points with that of a known pattern. If the mean observed distance (r_a) is more or less equal to the value generated by an equation designed to indicate randomness (r_e), the observed pattern of points is said to be random, and the nearest-neighbour statistic (*R*) is around 1·0. As the ratio of r_a to r_e gets larger, the pattern of points is deemed to be trending towards uniformity, and as it gets smaller, the observed point distribution is said to be trending towards clustering. *R* values can range from 0 (absolute clustering), where all points are in the same location, to 2·1491 (absolute dispersion), where the points are distributed in a hexagonal pattern. A significance test allows a positive conclusion to be drawn as to whether the departure from randomness in either case is significant. This significance test involves calculating the score, *z*.

Both the *R* statistic and *z* depend on both the number of points in the distribution and the size of the area under study. Since all the study areas in this research are the same size (25 km^2), the number of points in each area was the main factor determining whether their distribution within each study area was clustered, uniform or random.

Nearest-neighbour analysis was performed within the GIS using methods described by Lee and Wong (2001). The observed and expected nearest-neighbour distances were calculated, as were the nearest-neighbour (*R*) value and score.

Delimiting individual landforms requires strict adherence to geomorphological criteria and a clear objective method. Hills are defined here as positive relief features in the landscape, while depressions are defined as negative relief features. This avoids complications of actually defining different particular landforms, such as ridges, uvalas and glades. Several methods were attempted for the delineation of hills and depressions. These included determining the portions of the landscape above (hills) and below (depressions), the mean elevation of the terrain, manual digitizing of landforms, and supervised classification of IKONOS imagery. Identifying portions greater than or below the mean elevation of the terrain results in the bases of hills and the rims of depressions having similar uniform elevations – an unrealistic assumption. Manual digitizing, using IKONOS imagery and a series of DEMs and shaded relief models, still has an element of subjectivity and human error. Supervised image classification was not feasible due to similarities in vegetation cover in depressions and hills, cloud cover, and the fact that this method did not consider many geomorphic variables, such as breaks in slope.

Eventually, landforms were delimited using the compound topographic index (CTI). Originally termed the topographic wetness index, and developed by Moore *et al.* (1991), this is a useful topographic variable in terms of water and sediment transport (Köberle and Köberle, 2002). It was renamed the compound topographic index (Gessler *et al.*, 1995) (or aggradation index) in order to broaden its use beyond hydrology and to incorporate pedological and other applications. It is defined by the equation:

$$\mathrm{CTI} = \ln(\alpha/\tan\,\beta)$$

where α represents the catchment area per unit width (in this case, one pixel) and β refers to the slope (in degrees). Those parts of the DEM with steep slopes and small catchment areas represent hills, while areas with gentle slopes

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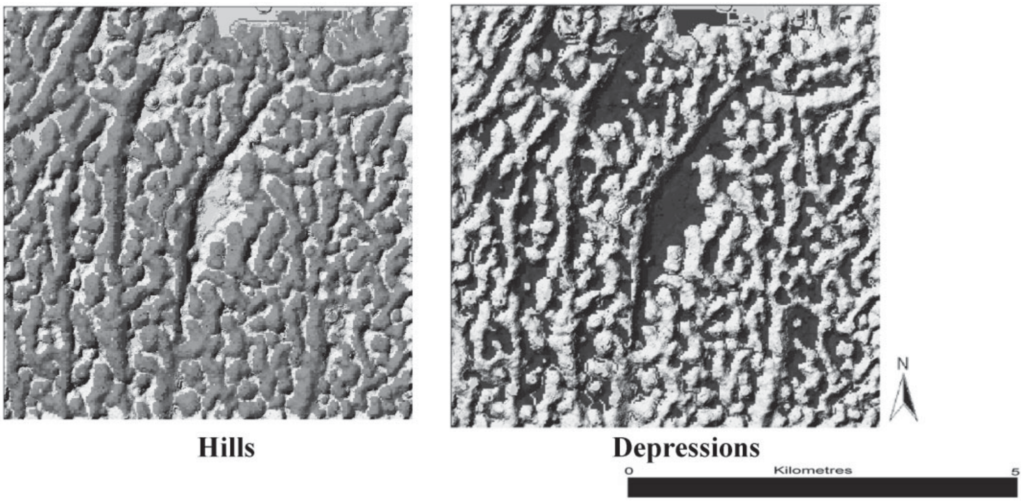

Figure 3. Delimited hills and depressions in the Barbecue Bottom study area.

and large catchment areas are depressions. (Note that the cockpit karst terrain lacks integrated drainage networks, so in this case there is no risk that the delineation procedure will misidentify river valleys as closed depressions.) This method of delineation of specific landforms in the study areas is far less ambiguous than using sink-normalized surfaces to define hills or depressions, using supervised classification of IKONOS imagery, or manually digitizing particular features. Figure 3 shows the delimited hills and depressions at Barbecue Bottom, using a threshold CTI of 1·8 to differentiate between the two (this figure was derived from the bimodal distribution of CTI frequency values, with a peak below 1·8 representing hills, and another peak beyond this value representing depressions).

Before measuring individual morphometric properties of the derived landforms, the spatial relationships between similar landform features were assessed. Specifically, the degree of isolation of hills and depressions was determined using functions commonly applied to landscape ecology (McGarigal and Marks, 1995). The degree of isolation of the features may be considered to be the tendency for hills or depressions to be isolated in space from other hills or polygons. This may be calculated using a proximity index (PI) measure, as defined by the equation:

$$\mathrm{PI} = \Sigma(a_j/h_{ij}^2)$$

where a_j represents the area (m^2) of feature j within a specified distance (m) of feature i, and h_{ij} represents the distance (m) between features i and j based on nearest edge-to-edge distance. This considers the nearest edge-to-edge distance between features of the same class (hills and depressions are separate classes in this analysis), and considers the size and proximity of other features of the same class within a specified distance (in this case, the mean edge-to-edge distance between features) of the feature being examined.

This is repeated for all landforms, and a mean proximity index for all classes is determined. The proximity index increases as the neighbourhood, defined by the search radius, is increasingly occupied by features of the same class, which may be described as being more contiguous, or less fragmented, in distribution. If a feature has no neighbours of the same class within the search radius, then the proximity index is zero – that feature is completely isolated.

Once delineated, individual hills and depressions were measured for their morphometric properties of area, lengths of their long and short axes, orientation of the long axis, height or depth, and perimeter length. Other derived measures include the shape index of the landform, which measures its planar complexity. The three-dimensional forms of the patches were analysed by determining the ratio between the total surface area of the feature (determined using the original DEM) and the area of its footprint. The mean slope of each feature was also determined.

Cockpit karst terrain was then described using attributes calculated from general morphometry, which considers the entire surface, and by the assemblage of the landforms that make up the landscape.

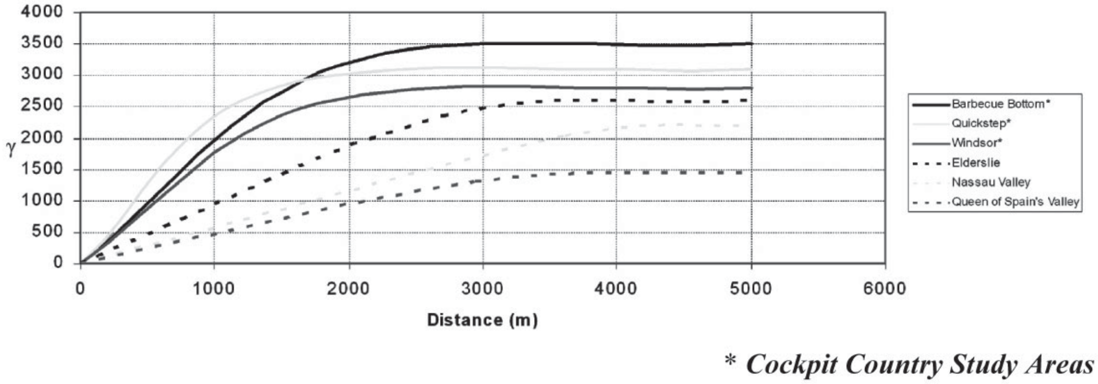

Figure 4. Semivariograms of DEMs of the study areas.

Table I. Summary table of geostatistical results

	Barbecue Bottom*	Quickstep*	Windsor*	Elderslie	Nassau Valley	Queen of Spain's Valley
Total sill	3164·3	2831·98	2559·3	2346·2	2042·75	1320·12
Isotropic range (m)	1934·9	1478·0	1772·6	2701·2	3613·1	2942·1
Major range (m)	4623·5	3170·3	4765·1	3501·8	4375·3	4692·0
Minor range (m)	1906·9	1368·8	1660·2	2229·2	2672·4	2004·4
Angle of anisotropic direction (degrees)	026·5	349·2	062·3	283·3	059·3	322·9

* Cockpit Country study areas

Results

Digital terrain analysis

From the digital terrain analysis of the study areas, key properties of cockpit karst landscapes emerged. There are distinct morphological differences between the Cockpit Country study areas and the other areas, quantitatively describing visually obvious differences between cockpit topography and that of surrounding areas.

Geostatistical results Geostatistical investigations of the topography of the study areas revealed much about the spatial variation of elevation in cockpit karst areas *vis-à-vis* other types of terrain. The results are shown in Figure 4 and Table I.

The sill values, which indicate the degree of spatial variation in the data, show higher values for the Cockpit Country study areas, indicating greater relief. These areas also have lower isotropic ranges, suggesting a narrower field of spatial autocorrelation. Elsewhere, larger ranges suggest that spatial autocorrelation continues at greater horizontal distances, and that points remain fairly similar over greater distances, than within the Cockpit Country. Where the range is large, long-range variation dominates (Burrough and McDonnell, 1998). This is especially true of the study areas outside the Cockpit Country. Based on their respective geostatistical properties and the shape of their semivariograms, the differences between the Cockpit Country landscapes and those in the other study areas may be compared with differences between the morphologies of upstream river channels and downstream channels. For example, Chappell *et al.* (2003) found greater variation in upstream channels, with lower ranges than in downstream regions, in a geostatistical analysis of drainage basins.

Where there is more variation in one direction than in another, anisotropy can be measured, as shown in Table I. Directional effects responsible for this phenomenon are due to structural influences in the study areas. The degree of anisotropy can be estimated by examining the difference between the major and the minor ranges. Barbecue Bottom has the highest degree of anisotropy (2716·6); its angle of anisotropic direction is 26·5°, which correlates strongly with known structural trends.

Primary topographic attributes For the purposes of identifying cockpit karst areas, we compare the primary topographic attributes of each of the study areas. The three Cockpit Country study areas are visually distinct from the other

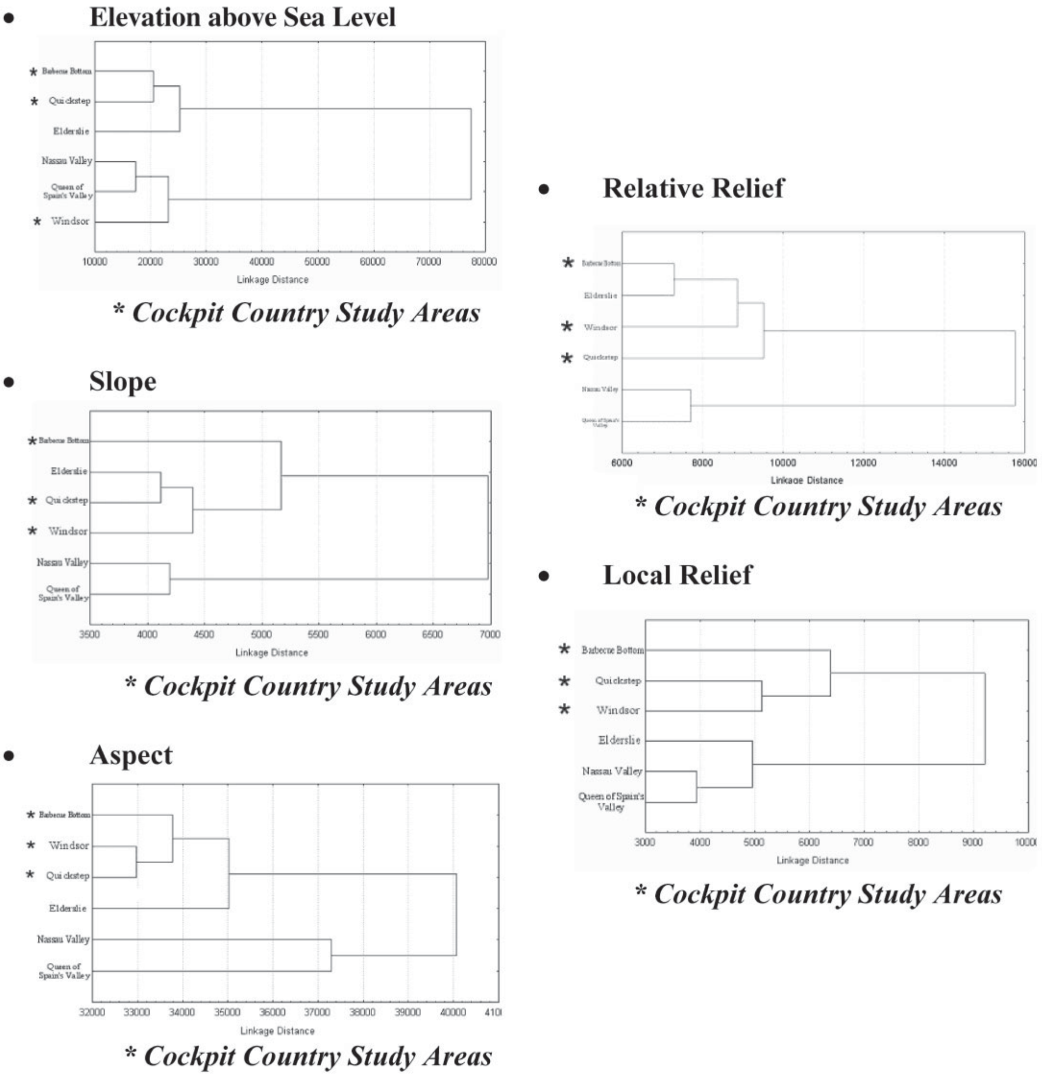

Figure 5. Results of cluster analysis of the primary topographic attributes of DEMs of the study areas.

areas, and any morphometric property that quantifies this distinctiveness can be used to identify cockpit karst areas and to distinguish these areas from the rest of the landscape.

Cluster analysis of the different map properties (slope, aspect, relative relief and local relief) showed local relief to be the best discriminator between the Cockpit Country areas and the other study areas, which all clustered separately (see Figure 5).

Relief-scaling characteristics The relief-scaling characteristics of the terrain are revealed by a log–log graph of local relief versus window size (Figure 6). Terrain should typically exhibit scaling characteristics where there is increasing vertical relief with increasing horizontal scale. This pattern is observed in all the study areas. However, there is a major scaling break at around the 100 m horizontal scale for all the study areas; at length scales >100 m, the slope of the graph (scaling exponent) becomes gentler. In the Cockpit Country study areas, however, the topography shows a greater degree of vertical relief development.

In order to examine the scaling properties of the landscapes in greater detail, the scaling characteristics of each study area below and above the 100 m scaling break were analysed.

10 m to 100 m. Table II displays the values of c (amplitude factor) and m (scaling component), as well as topographic roughness calculated by determining the area beneath the respective plots. For the area calculations, X_1 is defined as 10 m, while X_2 is defined as 100 m. The scaling exponents for all areas except the Queen of Spain's Valley were similar, ranging from 1·32 to 1·45. The Queen of Spain's Valley had a slightly higher scaling exponent (1·6).

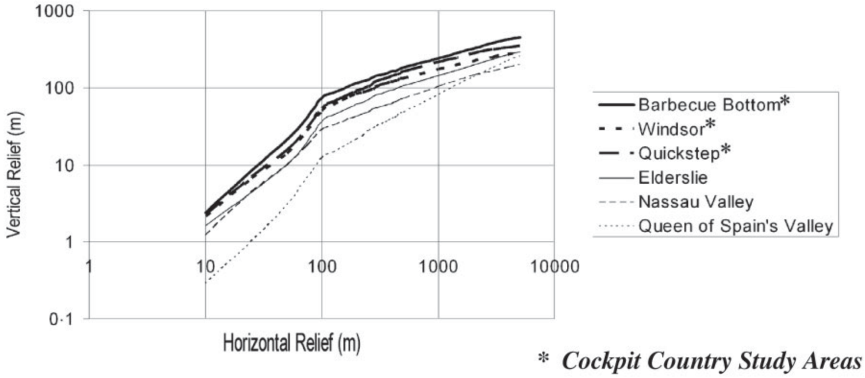

Figure 6. Log–log plot of relief scale.

Table II. Scaling properties of the study areas before the scaling break

Study areas	Vertical relief at scale break (m)	Amplitude factor, *c*	Scaling exponent, *m*	Topographic roughness (m^2)
Barbecue Bottom*	73·08	0·080	1·45	2584·52
Windsor*	50·54	0·097	1·32	1965·70
Quickstep*	54·40	0·099	1·33	1816·35
Elderslie	36·68	0·070	1·32	1310·77
Nassau Valley	28·44	0·056	1·34	1140·20
Queen of Spain's Valley	11·99	0·006	1·6	364·83

* Cockpit Country study areas

Table III. Scaling properties of the study areas beyond the scaling break

Study areas	Amplitude factor, *c*	Scaling exponent, *m*	Topographic roughness (m^2)
Barbecue Bottom*	11·21	0·44	1 645 143·55
Windsor*	9·77	0·41	1 430 101·86
Quickstep*	9·01	0·45	1 133 634·00
Elderslie	4·68	0·49	1 016 823·63
Nassau Valley	3·16	0·49	686 573·22
Queen of Spain's Valley	0·36	0·78	775 600·58

* Cockpit Country study areas

There is no statistically significant difference between the scaling exponents of the Cockpit Country areas and the other study areas. This suggests that, for all the study areas, there is a similar increase in vertical relief over increasing horizontal scale. The Cockpit Country study areas, however, have a greater area beneath their respective plots than the other study areas, suggesting greater topographic roughness in the former.

100 m to 5000 m. Beyond the 100 m horizontal scale, there is an overall decline in the slopes of plots of relief scale for all six study areas (Figure 6). The plots of all the study areas approximate a straight line, and can be described by a power law. Table III displays the values for the scaling exponent, amplitude factor and topographic roughness of each study area. For the determination of topographic roughness, $X_1 = 100$ m and $X_2 = 5000$ m.

As before the 100 m scale break, the scaling exponents for all areas except the Queen of Spain's Valley are similar, although the values are lower than before the scaling break, ranging from 0·407 to 0·495. These are comparable to observed scaling exponents of topographic profiles (e.g. Weissel and Pratson, 1994), and similar to the Brownian noise scaling exponent $m = 1/2$. The scaling exponent of 0·78 at the Queen of Spain's Valley indicates a greater rate of increase in vertical relief over horizontal scale than in the other karst areas beyond the scaling break.

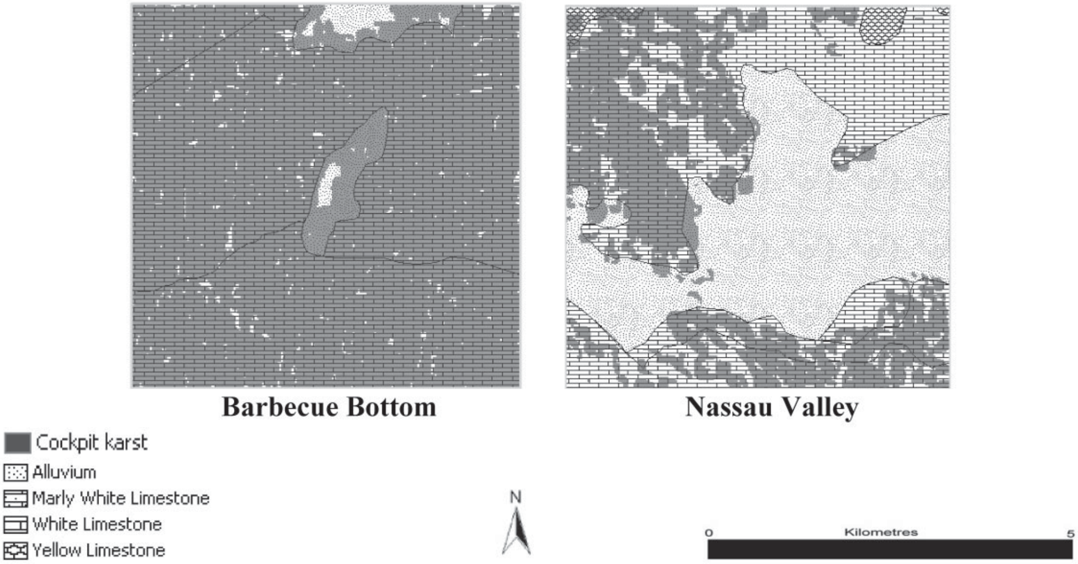

Figure 7. Cockpit karst coverage in Barbecue Bottom (within the Cockpit Country) and Nassau Valley.

The Cockpit Country areas, as before the 100 m scale break, have greater overall topographic roughness, as defined by the larger area beneath their respective plots. Total roughness for the areas before and after the 100 m scale break shows the Cockpit Country areas having the greatest degree of roughness.

Identifying discrete cockpit karst areas The 100 m horizontal scale was used to specify the size of the neighbourhood area in order to examine local relief, and to identify cockpit karst regions from the terrain. One of the problems with general morphometry is that, since it measures the entire continuous surface, it may overgeneralize the landscape. Terrain may not be morphologically homogeneous, and different types of terrain may, and do, exist within one study area. In karst landscapes, cockpit karst may give way abruptly to a polje/tower karst terrain due to the presence of faults or a different geological formation that does not support cockpit karst development. It is necessary to identify and isolate the different types of terrain present, and to carry out morphometric measurements in these areas to evaluate their morphological differences.

Visually, the Cockpit Country study areas appear to be relatively homogeneous morphologically, while in the other study areas there are clearly at least two types of terrain. Essentially, two types of terrain were searched for: cockpit karst and non-cockpit karst. Those parts of the DEM which met the criteria for cockpit karst were isolated, their proportions of the total landscape identified, and their morphological properties described. Similarly, those areas which did not meet the criteria for cockpit karst terrain were identified as belonging to the non-cockpit karst region. Examination of these areas against the background of geological maps and aerial/satellite imagery indicates that cockpit karst is found predominantly in the pure White Limestone lithologies of the study areas, with less development of cockpit karst in the impure Yellow Limestone, as illustrated at Elderslie and in the polje/tower karst areas, where cockpit karst has developed largely along the periphery.

Figure 7 and Tables IV and V give the results of morphometric analyses of the cockpit and non-cockpit karst regions of the study areas. Not surprisingly, cockpit karst dominates the Cockpit Country study areas, ranging from 96·4 per cent at Barbecue Bottom to 76·2 per cent at Windsor. In contrast, about half (49·7 per cent) of the topography at Elderslie is cockpit karst, while only 28·1 per cent of Nassau Valley and 13·2 per cent of the Queen of Spain's Valley are occupied by cockpit karst terrain.

The morphometric properties of the cockpit and the non-cockpit karst parts of all the study areas are similar; cockpit karst areas in the Cockpit Country resemble cockpit karst areas outside it, while non-cockpit karst areas in the Cockpit Country are also similar to non-cockpit karst areas outside the region. The main difference between the Cockpit Country study areas and the other areas is the proportion of the overall terrain occupied by cockpit karst. It is proposed here that any landscape with greater than 75 per cent cockpit karst may be considered to be a cockpit karst landscape. These landscapes would be dominated by cockpit karst, but they would not be exclusively cockpit karst, due to the presence of elongated glades and other enlarged depressions.

Table IV. Statistics for the cockpit karst regions of the study areas

	Barbecue Bottom*	Quickstep*	Windsor*	Elderslie	Nassau Valley	Queen of Spain's Valley
% of total area	96·44	83·7	76·22	49·27	28·13	13·18
Surface area: planar area ratio	1·34	1·45	1·36	1·35	1·31	1·37
Mean slope (°)	32·63	26·04	27·45	23·46	22·99	21·86
% Flat	0·01	0·6	0·0	0·3	0·1	0·0
Mean range of elevation of 100 m × 100 m neighbourhood area (m)	74·20	57·11	57·08	47·46	45·97	43·54

* Cockpit Country study areas

Table V. Statistics for the non-cockpit karst regions of the study areas

	Barbecue Bottom*	Quickstep*	Windsor*	Elderslie	Nassau Valley	Queen of Spain's Valley
% of total area	3·56	16·30	23·80	50·73	71·87	86·82
Surface area: planar area ratio	1·03	1·04	1·02	1·02	1·02	1·03
Mean slope (°)	5·48	8·36	4·25	6·81	3·48	2·21
% flat	22·1	4·67	41·5	17·7	39·42	44·37
Mean range of elevation at 100 m × 100 m neighbourhood area (m)	14·34	20·67	13·40	15·46	7·58	4·72

* Cockpit Country study areas

Table VI. Results of proximity analysis of hill and depression patches in the study areas

Study area	Hill proximity index	Depression proximity index
Barbecue Bottom*	32 099·83	83·09
Quickstep*	28 592·16	1 300·68
Windsor*	15 771·58	4 147·39
Elderslie	3488·95	13 866·96
Nassau Valley	1515·72	16 171·79
Queen of Spain's Valley	241·16	22 519·03

* Cockpit Country study areas

Digital landform analysis

Points Sinks and summits were evaluated jointly as points; their combined distributions better characterize the entire landscape than looking at their separate distributions. Nearest-neighbour analysis showed that these points are significantly (at the 0·05 level) clustered in the polje/tower karst areas, while they are significantly uniform in the Cockpit Country study areas. While sinks and summits are uniformly dispersed throughout cockpit karst terrain, in the polje/tower karst areas, they tend to be clustered even within the delimited cockpit karst regions, along the periphery of these study areas. At Elderslie, an intermediate area, there is a significantly random distribution of sink and summit points.

Landform morphometry Landform isolation. Proximity analysis calculates the degree of isolation of each landform type, and the results are shown in Table VI. High proximity index values indicate a low degree of isolation, while low proximity index values indicate a greater degree of isolation. From Table VI it can be seen that hills in the cockpit karst areas have a lower degree of isolation than their counterparts in the polje/tower karst areas and, to a lesser extent,

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at Elderslie. Hills within the Cockpit Country are more interconnected; saddles between what appear to be separate hills actually form part of a single larger hill. These hills surround and isolate the cockpits, which have low proximity index values within the Cockpit Country study areas. In the polje/tower karst areas, depressions are more interconnected, with isolated towers scattered throughout the terrain.

Hill morphometry. Although fewer in number than in the other study areas, hills dominate the landscape in the Cockpit Country study areas, occupying more than 60 per cent of the terrain. These hills are significantly larger than their counterparts in the other study areas. The heights of hills (calculated relative to the interpolated sink surface used to compute relative relief) in the Cockpit Country are also significantly greater than those of hills in the other study areas. There was no statistical difference between Cockpit Country hills and hills in the other study areas on the basis of elongation. The mean slopes of hills within the Cockpit Country were greater than those of hills in the other study areas.

The number of summits per hill is one measure of hill complexity. Theoretically, complex hills would have several summits, while simpler hills, such as perfectly conical hills, would have only one summit. The Cockpit Country study areas had the highest frequency of hills with multiple summits, the average at Barbecue Bottom, for example, being 12·9 summits per hill. In contrast, the Queen of Spain's Valley averages just 1·04 summits per hill. There is a strong positive correlation between the number of summits per hill and hill area ($R^2 = 0{\cdot}85$), indicating that larger hills have more summits than smaller ones.

The planar complexity of hills can be described by determining their shape index. Hill elongation is inadequate in distinguishing Cockpit Country hills from hills elsewhere. Additionally, the long and short axes of landforms do not describe their shape. Two-dimensionally complex hills have high shape index values; simpler hills have a smaller shape index since their planar outline more closely approximates a circle. The Cockpit Country study areas have a high frequency of hills with low two-dimensional complexity.

The three-dimensional complexity of a hill is determined by calculating the ratio between the total surface areas of the hill and the area of its footprint. A simple hill would have a small ratio; a complex hill would have a greater surface area relative to the area of its base. There is very little statistical correlation between two-dimensional and three-dimensional complexity ($R^2 = 0{\cdot}027$), and the Cockpit Country study areas have a higher frequency of three-dimensionally complex hills than the other study areas. As such, hills may have a simple plan but may be more rugged, as noted by Aub (1964).

Depression morphometry. Depressions occupy far greater proportions of the landscape at Nassau Valley (63·8 per cent) and the Queen of Spain's Valley (77·2 per cent) than in the Cockpit Country areas or at Elderslie. The depressions in the polje/tower karst areas are also significantly larger than those at Elderslie or within the Cockpit Country.

However, depressions within the Cockpit Country are significantly deeper than their counterparts outside the region. Depression depths (calculated from the interpolated summit surface) range from an average of 83·1 m at Barbecue Bottom to 61·3 m at Quickstep, while the mean depression depth was as low as 23·3 m in the Queen of Spain's Valley. The areas outside the Cockpit Country also have a greater statistical variability in their depression depths, which is not surprising since these areas have deep depressions within their cockpit karst portions along their periphery; however, towards the large polje regions, these depressions become progressively shallower.

Depressions in the Cockpit Country, like the hills, are not significantly different from depressions in the other study areas on the basis of elongation. Elongation is controlled by local structural conditions which are not exclusive to cockpit karst areas. Elongation was an inadequate measure of shape since the long and short axes of features alone may not fully provide any idea about the full planimetric form of the landform.

However, depressions in the Cockpit Country are significantly steeper than depressions in the other study areas, with Barbecue Bottom having the steepest average slope (29·1°). This is a little less than indicated by Sweeting's (1958) comment that cockpits tend to have slopes between 30° and 40°, although digital morphometric determination of depression (and hill) slopes made it possible for a much larger number of landforms to be measured, and the high resolution of the DEMs used, reasonable accuracy of the delimitation criteria, and GPS-assisted ground-truthing provided greater confidence in the results.

The Cockpit Country areas have the largest number of sinks per depression, with Quickstep having the most (6·5 sinks per depression). Nassau Valley has the fewest (1·1) sinks per depression. It was expected that the polje/tower karst areas would have the most sinks per depression, with many sinks within the single coalesced depression, the polje surface. However, there is a high frequency of depressions with few sinks, resulting in the overall average number of sinks per depression being smaller than anticipated.

There is no significant (at the 0·05 level) difference in the planar complexity of depressions in any of the study areas. All areas appear to have depressions with similar levels of planar complexity, regardless of the landscape in which they are found. However, the Cockpit Country has a higher frequency of three-dimensionally complex depressions.

The Character of Cockpit Karst

On the basis of morphometric measurements of the terrain and its landforms, it is possible to begin to characterize the nature of cockpit karst. Cockpit karst may be categorized based on its vertical, horizontal and shape characteristics, as well as by looking at the semivariogram, slope characteristics and landscape relief scale, which combine measures of vertical and horizontal scales.

Measures of vertical relief can be used to identify cockpit karst areas. Measures of relative relief can be used, where the difference between surfaces created from interpolated sink and summit points can be determined. The cockpit karst areas have a greater degree of relative relief than the surrounding non-cockpit karst areas. Summits and hills are for the most part higher, and sinks and depressions deeper, within the cockpit karst areas.

Horizontal measures also characterize cockpit karst. Cockpit karst areas have a uniform distribution of sinks and summits. Sink and summit patterns in the non-cockpit karst landscape at Elderslie are random, while the pattern is significantly clustered at Nassau Valley and the Queen of Spain's Valley.

In cockpit karst areas the hills are largely interconnected, while the depressions are largely isolated. In contrast, the hills in the non-cockpit karst areas are more isolated and the depressions more interconnected.

The surface area of the cockpit karst landscapes is greater than that of the non-cockpit karst areas. The former also have a higher frequency of three-dimensionally complex hills and depressions than the latter. Cockpit karst areas also have a high frequency of hills with low two-dimensional complexity, but these tend to have a higher variability than their counterparts in the non-cockpit karst areas.

Finally, in addition to strict measures of vertical and horizontal forms of the karst areas, other techniques utilize both measures. The semivariograms produced from geostatistical investigation of the study areas and used as inputs for the kriging interpolation measured the extent of spatial autocorrelation of elevation in the terrain (range) as well as the amount of variation (sill). Cockpit karst areas have relatively high sills and small ranges, with a high degree of variation in elevation over a small horizontal area. The non-cockpit karst areas have lower sills (lower degree of variation) over a greater range, indicating that there is a larger degree of long-range correlation. The relatively low geostatistical range of the cockpit karst areas suggests that this may be the characteristic landscape scale for such areas. A study area that is smaller than this range would have all elevation values autocorrelated; all areas would be similar within that range. A larger study area would reveal more uncorrelated noise in the data set, and redundancy in data analysis.

The Cockpit Country study areas generally have steeper slopes than the study areas outside the Cockpit Country. However, this difference is not significant when comparing the overall slope characteristics of all the different study areas; the Cockpit Country areas and Elderslie, with its mixed cockpit and doline topography, are not significantly different from each other based on their respective slope characteristics. The slope properties of hills and depressions reveal that these features within the Cockpit Country are significantly different from their counterparts in the other study areas.

Analysis of the scaling properties of karst landscapes revealed that, while all the study areas have a similar horizontal scale (100 m), the cockpit karst areas have a greater degree of vertical relief development. The 100 m scaling break seems to represent the scale of individual landforms (hills and depressions), and suggests the maximum DEM resolution to be used if landform detail is to be captured. Both the semivariogram and the relief scale of the landscape may be used to distinguish cockpit karst from non-cockpit karst terrain, as well as to distinguish between karst and non-karst landscapes. Relief scaling plots may also distinguish between terrain with similar wavelengths and amplitudes. Table VII summarizes the unique morphometric properties of cockpit karst.

Cockpit karst areas may be isolated from a mixed landscape by measuring local relief within a particular search neighbourhood. This neighbourhood was defined from the relief-scale plot of all the study areas, where it was found that all the areas share a 100 m horizontal scaling break. This scaling break was used to specify the search neighbourhood. All areas with a local relief greater than 34·096 m are identified as cockpit karst areas. All the Cockpit Country study areas have greater than 75 per cent cockpit karst topography, and can be described as cockpit karst areas; these areas are dominated by cockpit karst, although they are not exclusively composed of it.

From the digital analysis of the morphometric properties of the landforms in the study areas, several key assumptions made by different authors over the past 50 years can be re-evaluated. Cockpit karst may not necessarily have an equal prominence of hills and depressions (Sweeting, 1972; Day, 1978, 1982; Mitchell *et al*., 2003); hills occupy more than 60 per cent of the terrain in the study areas. However, hills do appear to have a low variation in their heights, which supports the observations made by Sweeting (1958) and Versey (1972) that hills have concordant heights. Other descriptions of cockpit karst mention the fact that the depressions are isolated and are surrounded by outstanding residual hills. This is supported from the analysis of the degree of isolation of the hills and depressions. Hills are more interconnected than the isolated depressions in the cockpit karst landscape.

Table VII. Summary of the unique morphometric properties of cockpit karst

	Morphometric index	Comments relative to non-cockpit karst areas
Vertical measures	Relative relief	Cockpit karst areas have greater relative relief development
	Summit height/sink depth	Cockpit karst areas have significantly higher summits and deeper sinks
	Hill height/depression depth	Cockpit karst areas have significantly higher hills and deeper depressions, and less variation in hill heights
Horizontal measures	Nearest-neighbour	Cockpit karst areas have uniform sink-and-summit distributions
	Landform isolation	Cockpit karst areas have isolated depressions and interconnected hills
Shape measures	Terrain surface area	Cockpit karst areas have larger terrain surface areas
	Landform surface area	Cockpit karst areas have high frequency of three-dimensionally complex hills
	Landform shape index	Cockpit karst areas have high frequency of two-dimensionally simple hills, but also have high variation in planar complexity
Measures of vertical and horizontal characteristics	Geostatistical properties	Cockpit karst areas have high sills and low ranges
	Slope	Hill and depression slopes within cockpit karst areas are significantly different from non-cockpit features; cockpit karst areas have less variation in landform slopes
	Local relief	Cockpit karst areas have higher local relief
	Relief scale	Cockpit karst areas have similar horizontal scale to non-cockpit karst areas, but have greater degree of vertical development

Some researchers (Sweeting, 1972; Miller, 1998; Mitchell *et al*., 2003) have described cockpits as being star-shaped in plan. This is a very qualitative generalization. From the analysis of the planar complexity (i.e. shape index) of the depressions in the study areas, there is no significant difference between depressions in cockpit karst areas and depressions in non-cockpit karst areas.

Finally, Sweeting (1958, 1972) described cockpits as having slopes ranging from 30° to 40°. This was not explicitly supported from the analysis, where cockpits in the Cockpit Country study areas have average slopes ranging from 29.9° at Barbecue Bottom to 15.1° at Windsor. The depressions in the cockpit karst areas also show less variation in their slopes than depressions in the non-cockpit karst areas.

Conclusions

Jennings (1972) noted that any attempt to broadly categorize tropical humid karst would oversimplify the great variety of karst. Each may represent separate stages in the evolution of tropical humid karst, or may be independent of a particular evolutionary sequence (such as that proposed by Grund, 1914) altogether. Differences between landscapes cannot be based on a single or a few morphometric parameters. Only thorough analyses using both general and specific geomorphometric techniques would allow subtle differences in landscape character to be identified. It is hoped that, with sufficient morphometric examination of the different types of karst terrain, a revised scheme can be developed to distinguish doline karst, cone karst, cockpit karst and tower karst landscapes based on their different morphometric properties. According to Smith and Atkinson (1976, p. 398), morphometric studies ‘not only provide an adequate description of surface morphology and allow meaningful comparison between areas, but . . . they may give an insight into the evolution of forms within individual regions’. Although morphometric studies alone are incapable of determining how landforms or landscapes are formed (Day, 1978), they provide quantitative metrics against which to compare the results of simulation models (e.g. Ahnert and Williams, 1997; Groves and Howard, 1994; Kaufmann, 2003; Fleurant *et al*., in press). Similarly, morphometric data may be used in conjunction with geological and/or climate data to test different hypotheses about the nature of different karst landscapes and the manner in which different factors control this.

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