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MORPHOMETRIC CLASSIFICATION AND SPATIAL DISTRIBUTION OF DOLINES IN SOUTHERN SLOVENIA

Sašo Stefanovski, Mateja Ferk, Timotej Verbovšek, Uroš Stepišnik

Dolines of the Rajndol corrosion plain.

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Sašo Stefanovski[1], Mateja Ferk[2], Timotej Verbovšek[3], Uroš Stepišnik[1]

Morphometric classification and spatial distribution of dolines in southern Slovenia

ABSTRACT: Dolines have traditionally been classified based on qualitative descriptions. This research presents the first attempt to connect a morphometric classification of dolines with existing morphological typologies in Slovenia. Using an automatic detection algorithm on a digital elevation model, we identified 179,288 standalone dolines and classified them into four classes based on morphometric characteristics. The classes were interpreted using statistical and spatial analyses. Dolines in Slovenia can be grouped into bowl-, funnel-, well-shaped, and elongated types. The type and distribution of dolines reflect the properties of karst, particularly sediment coverage and cone karst features. This research marks an initial step toward the systematic study of dolines, laying a foundation for further research.

KEYWORDS: karst, typology, data clustering, digital terrain model, Slovenia

Morfometrična klasifikacija in prostorska razporeditev vrtač v južni Sloveniji

POVZETEK: Vrtače so bile tradicionalno razvrščene na podlagi kvalitativnih opisov. Ta raziskava je prvi poskus povezave morfometrične klasifikacije vrtač z obstoječimi morfološkimi tipizacijami v Sloveniji. Z uporabo algoritma za samodejno zaznavanje vrtač na podlagi digitalnega modela višin smo identificirali 179.288 samostojnih vrtač in jih razvrstili v štiri razrede glede na njihove morfometrične značilnosti. Razrede smo interpretirali s statističnimi in prostorskimi analizami. Vrtače v Sloveniji lahko po obliki razvrstimo v skledaste, lijakaste, vodnjakaste in koritaste tipe. Tip in razporeditev vrtač odražata lastnosti krasa, zlasti prekritost s sedimentom in prisotnost kopastega krasa. Ta raziskava pomeni začetni korak k sistematičnemu preučevanju vrtač in postavlja temelje za nadaljnje raziskave.

KLJUČNE BESEDE: kras, tipizacija, podatkovno razvrščanje, digitalni model višin, Slovenija

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1 Introduction

Karst is a distinctive geomorphic system characterised by the predominance of subterranean water flow. The primary geomorphic process governing karst development is chemical denudation of bedrock, primarily via dissolution. Dissolution also extends deep within the subsurface, resulting in the formation of cavities with high effective permeability (White 1988). The heterogeneous nature of surface denudation, which is predominantly influenced by dissolution and supplemented by other mechanical processes that facilitate the transfer of material across the surface and into the subsurface, leads to the development of a complex karst landscape. This landscape is marked by a diversity of geomorphological features, including both positive and negative topographical forms (Jennings 1985; Habič 1986; Ford and Williams 2007). A very common surface landform in karst areas within the temperate climate zone is a doline or a sinkhole (Sauro 2003). This term refers to circular depressions, typically up to 100 m diameter and around 10 m deep (Gams et al. 1973; Jennings 1985; White 1988; Gams 2003; Ford and Williams 2007; Mihevc and Mihevc 2021; Stefanovski et al. 2024). Due to their prevalence, dolines are often considered the most typical or even diagnostic landform of karst landscapes (Sweeting 1973; Ford and Williams 2007; Sauro 2019). These landforms exhibit a wide variety of shapes and sizes, making their classification both challenging and crucial for understanding karst dynamics. Despite this, classification and typification of dolines are mostly based on their formation processes (e.g., Cramer 1941; Waltham and Fookes 2003; De Waele and Gutiérrez 2022) rather than on morphometric or morphographic characteristics (e.g., Cviji 1893; Gams et al. 1962; Jeanpert et al. 2016). The morphogenesis of certain dolines has been well-documented in previous studies, leading to the widespread adoption of classification systems centred on their morphogenetic mechanisms. Cvijić (1893) was among the first to categorise dolines by their formation processes. Cramer (1941) upgraded the findings of Cvijić (1893) and introduced a systematic morphogenetic typology that remains largely relevant today, distinguishing dolines into types such as collapse, subsidence, solution, suffosion, and alluvial dolines.

Geomorphological investigations involve various methods and steps. Morphological analysis describes dolines qualitatively, focusing on their shape, while morphometric analysis measures their numerical properties. The two are closely linked, as morphometric data provide exact values about the same features that morphological analysis describes (Pavlopoulos et al. 2009). Modern morphometric and morphographic typologies of dolines are relatively uncommon. Morphometric approaches mostly focus on the calculation and interpretation of general morphometric properties (e.g., Bondesan et al. 1992; Telbisz et al. 2009; Šegina et al. 2018; Verbovšek and Gabor 2019). Cvijić (1893) proposed the earliest typology, classifying dolines into bowl-shaped, funnel-shaped, and well-shaped types based on the depth-to-diameter ratio and slope inclination. Subsequent typologies have largely built upon Cvijić's findings (e.g., Gams et al. 1962; Gams et al. 1973; Gams 1974; Gams 2003; Sauro 2003; Ford and Williams 2007; Jeanpert et al. 2016; De Waele and Gutiérrez 2022). In the past, morphometric and morphographic classifications were less practical due to the time-consuming nature of field data collection through geomorphological mapping and measurements. Consequently, classifications of dolines were predominantly qualitative, with limited quantitative classifications (Péntek et al. 2007; Jeanpert et al. 2016). With the availability of high-resolution digital terrain models (DTMs) and advances in computer technology, manual geomorphological mapping is increasingly being complemented or replaced by advanced GIS-based delineation methods. Since dolines are one of the main features of karst surfaces, various methods for their delineation have been developed (e.g., Obu and Podobnikar 2013; Grlj and Grigillo 2014; Telbisz 2021; Ciglič et al. 2022). For instance, Mihevc and Mihevc (2021) created a comprehensive doline database for the karst areas of Slovenia using machine learning-supported U-Net segmentation. Their work also provides a valuable description of doline distribution, representing a significant contribution to karst research in Slovenia.

However, some limitations of the approach of Mihevc and Mihevc (2021) merit consideration. First, the delineation of dolines was not entirely precise, as the study did not define dolines as closed depressions, leading to the inclusion of false positives cases (gullies and other concave features) in the database. Second, the classification of dolines was based on genesis – categorised into collapse dolines, solution dolines, and suffosion dolines – primarily relying on the authors' terrain knowledge. While this approach offers valuable insights, it is inherently subjective, as it lacks explicitly defined quantitative or qualitative criteria for classification. The absence of such criteria or parameters makes it challenging to replicate or validate their classifications fully.

A recent study by Stefanovski et al. (2024) explored new approaches to doline delineation, comparing existing methods with a newly developed approach. Their findings suggest that the new method achieves higher accuracy in delineating dolines than previously employed methods (Obu and Podobnikar 2013; Zumpano et al. 2019; Mihevc and Mihevc 2021).

This study focuses on three main objectives. First, it aims to use the detailed spatial database based on the method provided by Stefanovski et al. (2024) to classify dolines in Slovenia based on their morphometric characteristics. Second, it seeks to connect the existing morphographic classifications and terminology to a new updated typology of dolines using this data, with the aim of bridging existing knowledge with current methods to ensure consistency and avoid unnecessary introduction of new terms or definitions. Instead, the study refines and enhances what has already been described, ensuring continuity and consistency in doline research. Third, it aims to analyse the relation between doline types, sediment presence, corrosion plains and cone karst areas. This analysis will help us better understand how dolines are distributed across various karst landscapes; however, it does not address their formation processes, as doing so would be overly speculative and require a dedicated, in-depth study focused specifically on these aspects.

2 Review of doline typologies: a theoretical overview

Dolines are typical geomorphological features of temperate karst landscapes. Some authors regard them as among the most characteristic karst landforms (Ford and Williams 2007) or even as diagnostic forms of karst surfaces (Sweeting 1973). However, it is important to note that dolines do not occur in all karst environments, but rather in areas where the vadose zone is developed. This type of karst is defined as deep karst (Šerko 1947; Bögli 1980; Šušteršič 1994). In other karst settings, such as fluviokarst, glaciokarst, or shallow karst, they are either absent or the karst depressions are not classified genetically as dolines (Stepišnik 2024). Due to the large number of dolines in karst areas of temperate geographic latitudes, early studies aimed to classify these landforms. Since the first detailed descriptions and studies of dolines, numerous typologies have been proposed by various authors (e.g., Cvijić 1893; Cramer 1941; Gams et al. 1962). Although these typologies are diverse, they can generally be grouped into four main categories. The first category includes morphometric and morphographic typologies (e.g., Cvijić 1893; Gams 2003; Sauro 2019), which are the focus of this research and are therefore examined in greater detail in the first part of the subsequent literature review. Dolines can also be categorised based on geological settings, morphogenetic and morphodynamic processes (e.g., Cramer 1941; Gams 2000; Čar 2001; Péntek et al. 2007; Verbovšek and Gabor 2019; De Waele and Gutiérrez 2022).

Morphometric typologies of dolines are relatively uncommon, even though most studies have included general morphometric analyses, such as depth, area and elongation, within their research (e.g., Bondesan et al. 1992; Telbisz et al. 2009; Šegina et al. 2018; Verbovšek and Gabor 2019; Ciglič et al. 2022). The sheer number of dolines can make data collection extremely time-consuming (Šušteršič 1994; Šušteršič 2006; Šušteršič 2017). Before the availability of LiDAR data in Slovenia, these measurements had to be collected manually in the field, or by examining large scale topographic maps (e.g., Čar 1982; Čar 2001; Frelih 2014; Čar 2018) further adding to the difficulty and effort required.

Morphographic typologies are more common, but are rarely supported by morphometric descriptions, which would make them more reliable and objectively comparable. The earliest morphographic typology of dolines was developed by Cvijić (1893) who used morphometric properties to provide a more precise description. He described the depressions we now define as dolines as round or elliptical in plan, with depths ranging from 2 to 20 m and diameters between 10 and 120 m. These features can appear either individually or in dense clusters, with more than 50 per km^2. Cvijić (1893) distinguished three main types of ordinary dolines based on the ratio of depth to diameter and slope inclination. These types are: bowl-shaped or basin-shaped dolines, which have a small depth relative to their diameter, with the diameter being approximately ten times the depth. The slopes of these dolines are generally gentle, ranging from 10° to 12°. Funnel-shaped dolines, on the other hand, have a diameter about two to three times greater than the depth, with steeper slope inclinations, mostly between 30° and 45°. Well-shaped dolines are characterised by depths that are roughly equal to or even greater than their diameter, with slope inclinations exceeding 45°, resulting in very steep sides.

Cvijić (1893) also identified a special type known as elongated dolines, which he described as valley-like depressions typically found at higher altitudes, though he did not provide specific morphometric criteria for these elongated forms.

Gams et al. (1962) developed a second morphographic typology of dolines, largely based on the work of Cvijić (1893) as seen in Table 1. They characterised well-shaped dolines as having steep, sometimes vertical walls, and a flat floor. Kettle-shaped dolines were also noted for their steep slopes, but with a concave floor. While they acknowledged the existence of bowl-shaped and funnel-shaped dolines due to their distinctive cross-sectional profiles, they did not provide detailed descriptions of these types.

The morphometric analysis of dolines by Gams (1974) did not provide specific morphometric values for each type of doline but instead offered their general dimensions. He found that the depth-to-diameter ratio at the upper edge of dolines typically ranges from 1:6 to 1:10. He also identified regional variations, observing that some areas are characterised by small dolines only a few meters wide, while others contain larger dolines with diameters ranging from 50 to over 100 m.

Péntek et al. (2007) provided a morphodynamic typology of solution dolines based on their morphometric properties. They used depth, horizontal extension and slope shape as the three main morphometric parameters. The solution dolines were classified as dolines widening at rim and base, dolines widening at base, dolines widening at rim and dolines, that are deepening, but not widening.

Jeanpert et al. (2016) developed a morphometric typology based on their analysis of a pseudokarstic environment on ultramafic rocks in New Caledonia. They identified several types of dolines: collapse dolines, which are characterised by an average slope exceeding 30°; bowl-shaped dolines, where the average slope ranges between 15° and 30°; and flat-bottomed dolines, defined by an average slope of less than 15°. The flat-bottomed dolines are further classified into large and small, depending on whether their diameter is greater or less than 10 m.

Sauro (2019) categorised dolines into three distinct types based on their shape: the most common are bowl-shaped dolines, followed by funnel-shaped dolines, which are also fairly common, and the least common are well-shaped dolines. He uniquely linked the shape of dolines to their formation processes, identifying funnel-shaped and bowl-shaped dolines as typical forms of suffosion processes in covered karst areas. He suggested that funnel-shaped dolines may result from either suffosion or collapse processes, making their precise morphogenetic origin challenging to determine. He refers to these as drawdown corrosion dolines.

Cvijić (1893) also classified dolines based on **morphostructural characteristics**, distinguishing them by the presence of sediment or water at the bottom, including »empty dolines« and those that are occasionally or permanently flooded. Čar (2001) expanded this by categorising dolines according to the structural conditions in which they form, identifying six basic types, which are stratification dolines, fissure dolines, bedded-fissured dolines, broken dolines, near-fault dolines, and fault dolines along with contact and reproduced dolines.

Cvijić (1893) first classified dolines based on **morphogenetic mechanisms**, linking different types to processes like corrosion, collapse, and tectonic influences. Cramer (1941) introduced a systematic typology, categorising dolines into collapse dolines, subsidence, solution, suffosion, and alluvial types. Gams expanded these classifications, adding terms like rocky dolines and fossil dolines, and highlighting compound

Table 1: Most notable morphological doline classifications with the original terms used.

Author, year	Doline shape			
Language	Bowl-shaped	Funnel-shaped	Well-shaped	Additional type
Cvijić, 1893 German	*Schüsselförmige Dolinen*	*Trichterförmige Dolinen*	*Brunnenförmige Dolinen*	*Dolinen mit großen Durchmessern (Dolines with large diameters)*
Cvijić, 1895 Serbian	*Karličaste vrtače*	*Levkaste vrtače*	*Oknaste vrtače*	*Nepravilne vrtače (Irregular dolines)*
Gams et al., 1962 Slovenian	*Skledaste vrtače*	*Lijakaste vrtače*	*Vodnjakaste vrtače*	*Kotlaste vrtače (Cauldron-shaped)*
Sauro, 2019 English	Bowl-shaped	Funnel-shaped	Well-shaped	/

and double dolines (Gams et al. 1962; Gams et al. 1973; Gams 1974). Maksimovič (1963) classified dolines by the dominant formation processes as solution dolines, suffosion dolines, subsidence dolines and erosion dolines, including polygenetic types, that are a combination of these processes, while Gams (2003) described the morphological evolution from funnel-shaped to bowl-shaped forms. Sauro (2003) further refined classifications, adding categories like accelerated solution dolines and intersection dolines. Waltham and Fookes (2003) provided a widely accepted typology in engineering geology, focusing on collapse dolines and suffosion dolines. De Waele and Gutiérrez (2022) simplified the typology to solution dolines and subsidence dolines, while Stepišnik (2020; 2024) categorised different dolines based on their formation processes and emphasised the difficulty in distinguishing late-stage collapse dolines from solution dolines. He categorized dolines as collapse dolines, suffosion dolines and solution dolines.

A review of morphometric and morphographic typologies shows that dolines are typically categorized based on parameters such as the extent of the flat floor, the ratio between depth and diameter, and slope inclination. These approaches often classify dolines based on their qualitative descriptions rather than based on morphometric properties, frequently without establishing specific morphometric criteria for different groups. Our analysis builds upon these existing typologies by integrating morphometric parameters to classify dolines more objectively. By applying quantitative criteria, we aim to bridge the gap between existing descriptive typologies and measurable geomorphological characteristics, providing a more consistent and reproducible classification framework.

3 Data and methods

3.1 Data

For the delineation of dolines, we used data from Stefanovski et al. (2024) and feature layers from recent studies on the Slovenian karst (Gostinčar and Stepišnik 2023; Stepišnik and Ferk 2023; Čonč et al. 2024; Mazej 2024; Stepišnik 2024). For this study, we delineated dolines in Slovenia using a DTM with 1 × 1 m spatial resolution. The visual results are only shown for southern Slovenia, as karst prevails in those regions.

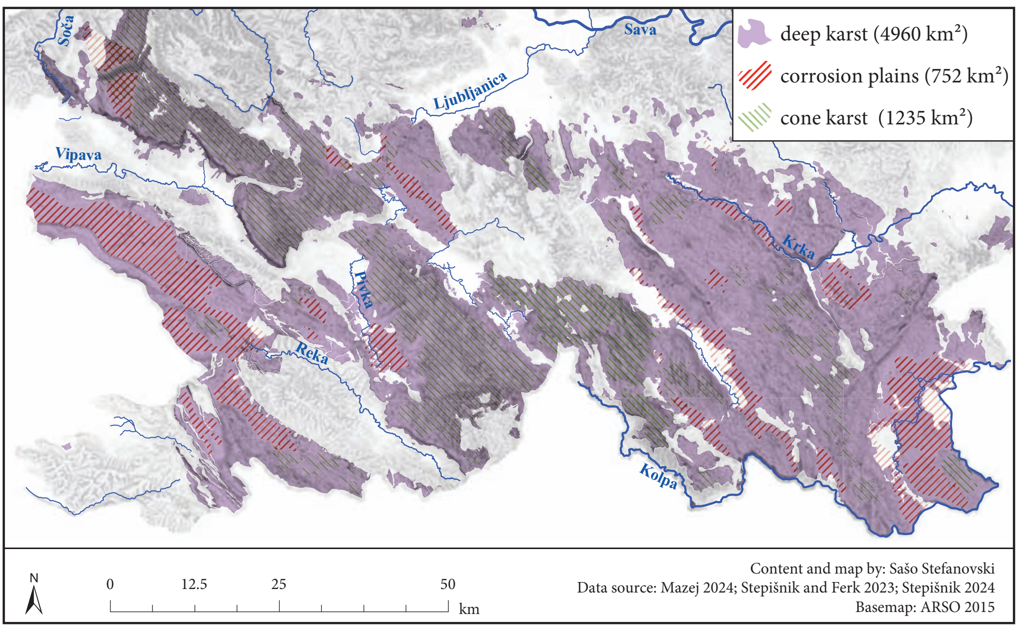


Figure 1: Extent of corrosion plains and cone karst in Slovenia.

Karstic regions in southern Slovenia are less fragmented, which simplified the interpretation of spatial patterns and the relationship between doline types and the characteristics of the karst landscape. Two main types of surface topography in deep karst where dolines are most common were identified: **corrosion plains** and **cone karst** (Figure 1). Corrosion plains are broad, flattened bedrock surfaces that cut horizontally across geological structures and are typically dotted with dolines and occasional conical hills (Stepišnik and Ferk 2023). In contrast, cone karst is a highly dissected terrain dominated by steep, conical hills and uvalas, formed by uneven vertical chemical denudation and the absence of surface water flow (Mazej 2024). The division into these two types of surface topography was chosen to investigate whether the types of dolines are influenced by the type of deep karst. These are currently the only two types of deep karst topography with precisely defined spatial extents, making them the sole input data for the analysis. The spatial extent of corrosion plains was obtained from Stepišnik and Ferk (2023) while cone karst extent was determined by Mazej (2024). For areas that do not fall into either category, there is currently insufficient information available to include them in the study. These areas are mostly karst slopes and areas with limited cone karst features that are not flat, based on the extent of cone karst and corrosion plains in Figure 1.

The general surface topography of karst in Slovenia is characterised by significant barren surfaces, though some areas are entirely covered by fine sediments (Gostinčar and Stepišnik 2023), referred to as uncovered and covered karst, respectively (Ford and Williams 2007). The extent of **uncovered karst** features in deep karst was calculated using the outcrop feature layer presented by Čonč et al. (2024). Outcrops were identified based on Topographic Position Index (TPI) values equal to or greater than 1 standard deviation, combined with slope thresholds that varied according to lithology. Our analysis aimed to explore whether the types of dolines are influenced by the distribution of sediments.

3.2 Doline delineation and classification

For the delineation of dolines, we applied the method presented by Stefanovski et al. (2024). Firstly, we identified dolines based on hydrological filling of sinks (Obu and Podobnikar 2013; Kobal et al. 2015; Ciglič et al. 2022; Čonč et al. 2022). Then their boundary was determined using Sky-View Factor (SVF) (Zakšek et al. 2011; Kokalj and Somrak 2019; Stefanovski et al. 2024). Since the goal was to classify standalone dolines, we excluded compound features and did not delineate dolines near roads, other routes, or buildings (within 5 meters). We removed all collapse dolines, that form with undermining in the subsurface, with the use of the collapse doline registry (Stepišnik 2010; Stepišnik 2024). The perimeters were smoothed by first shrinking each doline by ¼ of its width and then expanding it by the same factor. Features where the length exceeded the width by more than a factor of 2 were removed, as dolines are generally circular or slightly elongated (Gams et al. 1973; Gams 2003). These elongated features can be considered as other landforms, such as unroofed caves or landforms of fluvial origin. This process resulted in 179,288 standalone dolines used for classification.

We then calculated the basic morphometric properties of the dolines. Existing typologies typically differentiate doline types based on slope steepness and the extent of the doline floors, so we focused on these basic parameters for classification (Table 2). To calculate slope, we first applied a low-pass 3×3 mean filter to the DTM to smooth the surface. We used a value of 30° as the threshold for steep slopes. The threshold value for steep slopes was chosen as a previous study discussed this value as a threshold for active slopes, which indicate slopes where mass wasting is present (Stepišnik and Kosec 2011). Gently sloped terrain primarily indicates the doline floors. The 7° threshold was determined through testing on various examples to effectively capture doline floors, as lower values often failed to identify rugged floors. This value proved to be reliable for distinguishing doline floors from surrounding slopes, despite their gradual transitions, as floor morphology plays a crucial part in doline classifications (Cvijić 1893). The calculated value represents the share of a doline's surface area that meets the specified slope threshold used for classification. The perimeter axial ratio was also included, as elongation may indicate specific morphogenetic processes, such as horizontal cave denudation or the influence of fluvial activity (Sauro 2003; Grlj and Grigillo 2014; Stepišnik 2024). Perimeter axial ratio value of 100 represents dolines, where both axes are the same distance. A value of 50 represents dolines with lengths twice their width. Importantly, the classification lacks clearly defined morphometric thresholds, as the classes are continuous and gradually transition into one another.

Table 2: Morphometric parameters used in the process of classification.

Morphometric parameter	Description	Value
Percentage of steep slopes	Percentage of area with steep slopes (30° or more)	0–100
Percentage of gently sloped terrain	Percentage of area of gently sloped terrain (7° or less)	0–100
Perimeter axial ratio	Ratio between width and length	50–100

The classification was performed using ArcGIS Pro 3.0.0 software. Since the classification is raster-based, the morphometric parameters had to be rasterised. First, the polygon feature layer was converted into a point layer, so each doline was represented by a single 10 m^2 cell during rasterization. The point layer was then rasterised three times, once for each parameter. These layers were merged using the composite function and classified using ISO (Iterative Self-Organising) clustering, an unsupervised method ideal for identifying natural groupings without prior knowledge and suitable for parameters lacking a normal distribution (Jensen 2016). We defined a maximum of four classes, based on a literature review of typologies (Cvijić 1893; Cramer 1941; Gams 2003; Sauro 2003; Sauro 2019). While the results were homogeneous, it was not immediately clear which doline type each class, based on the literature, corresponded to. This was determined through class interpretation, where an observer identifies the existing classes and assigns them appropriate labels or descriptions (Oštir 2006).

3.3 Class interpretation

Class interpretation is a crucial step in unsupervised classification, transforming data-driven clusters into actionable insights by assigning meaningful labels. This ensures practical and relevant results. This was done by analysing the correlation between doline classes, extent of cone karst or corrosion plain and the presence of sediment cover. We began by interpreting the classification results, examining parameter distribution by class and analysing class distribution within corrosion plains and cone karst areas. The chi-square

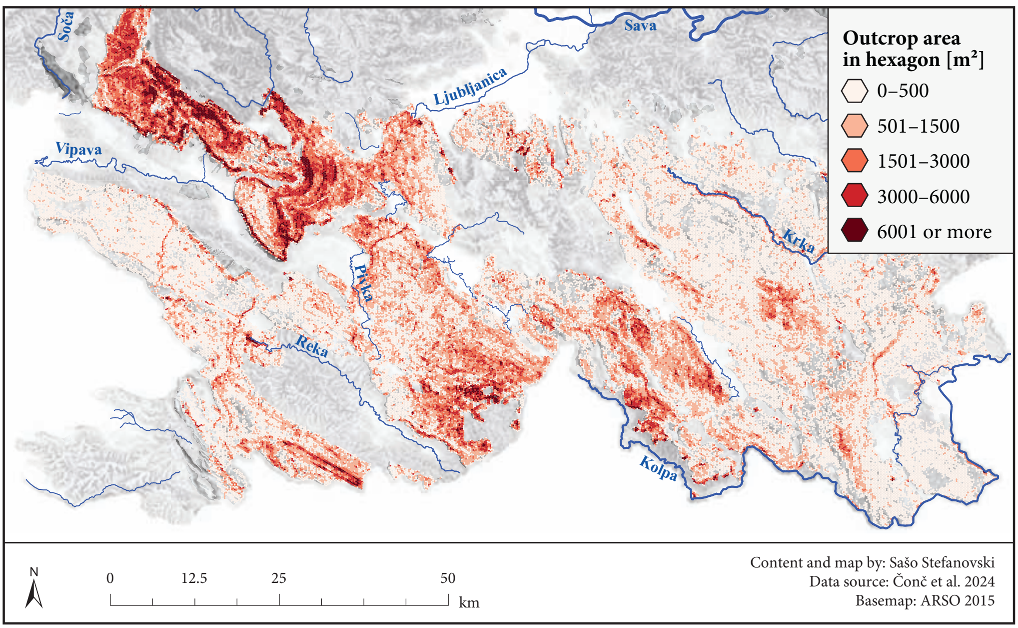


Figure 2: Extent of uncovered karst in 10 ha hexagons.

test was used to assess correlations between these deep karst types and doline classes, identifying significant relationships. The analysis was conducted in two steps: first, by comparing the classification (4 classes) with the presence or absence of corrosion plains, and second, by comparing the same classification with the presence or absence of cone karst areas.

To interpret the results, we also created density maps for each doline class using a 570 m radius in the point density tool, covering about 1 km² per calculation. These layers were standardised to a 0–1 scale using the fuzzy membership tool and displayed with a minimum-maximum stretch. The proportion of uncovered karst features in deep karst was calculated using a feature layer from Čonč et al. (2024) with the study area divided into 10 ha hexagons. The Summarise Within tool calculated the extent of uncovered karst per hexagon (Figure 2). We used IBM SPSS Statistics 26 for correlation analysis and the Mann-Whitney U test for comparing two independent groups. Both tests were chosen for their suitability with non-normally distributed data (Sheskin 2007).

4 Results

4.1 Morphometric properties of classified dolines

Figure 3 shows that the distribution of active slope percentages in dolines is strongly left-skewed, which means that dolines with a smaller share of steep slopes are more common. Specifically, 57,504 dolines feature steep slopes that account for 1% or less of their total area. The distribution of gently sloping terrain is similar, showing that dolines with a smaller percentage of gently sloped terrain are more common. This suggests that, on average, dolines have a small proportion of steep slopes and gently sloping terrain, with slope inclinations between 7° and 30° being most common. These dolines make up approximately 85% of doline cases analysed. The axial ratio distribution is peaking around the interval between 82 and 84, indicating a more normal distribution. This suggests that most dolines have a slightly elongated shape rather than being perfectly circular. Table 3 shows the mean, median and 95th percentile of morphometric parameters used in the classification.

Table 3: Basic descriptive statistics of morphometric parameters used in the process of classification.

Morphometric parameter	Mean	Median	95th Percentile
Percentage of steep slopes	8	3	29
Percentage of gently sloped terrain	15	9	51
Perimeter axial ratio	78	80	92

4.2 Classification results

In this study, dolines were classified into four classes using the ISO clustering method, an unsupervised classification approach where the number of classes was set by the user according to literature suggesting three to four doline types. The classification criteria included the proportion of steep slopes, gently inclined slopes, and axial ratio (Table 4; Figure 4).

Class 0 is characterised by a small proportion of steep slopes and gently sloping terrain, with approximately 85% dolines having slope inclinations between 7° and 30° and being slightly elongated but rounder than the average of all the dolines in the study area, which is 78. Class 1 differs from other classes primarily in having a large area of steep slopes (Figure 4), with most dolines featuring over 10% active slopes and being more elongated than those in Class 0. Class 2 typically lacks extensive areas of steep slopes, is characterised by gently sloping terrain, and includes dolines that are more elongated compared to Class 0 and 1, as indicated by a right-skewed axial ratio histogram. In contrast to Class 2, Class 3 shows a decrease in steep slopes and gently sloping terrain, with a left-skewed slope inclination histogram, and these dolines are distinctly elongated, as reflected by their axial ratio.

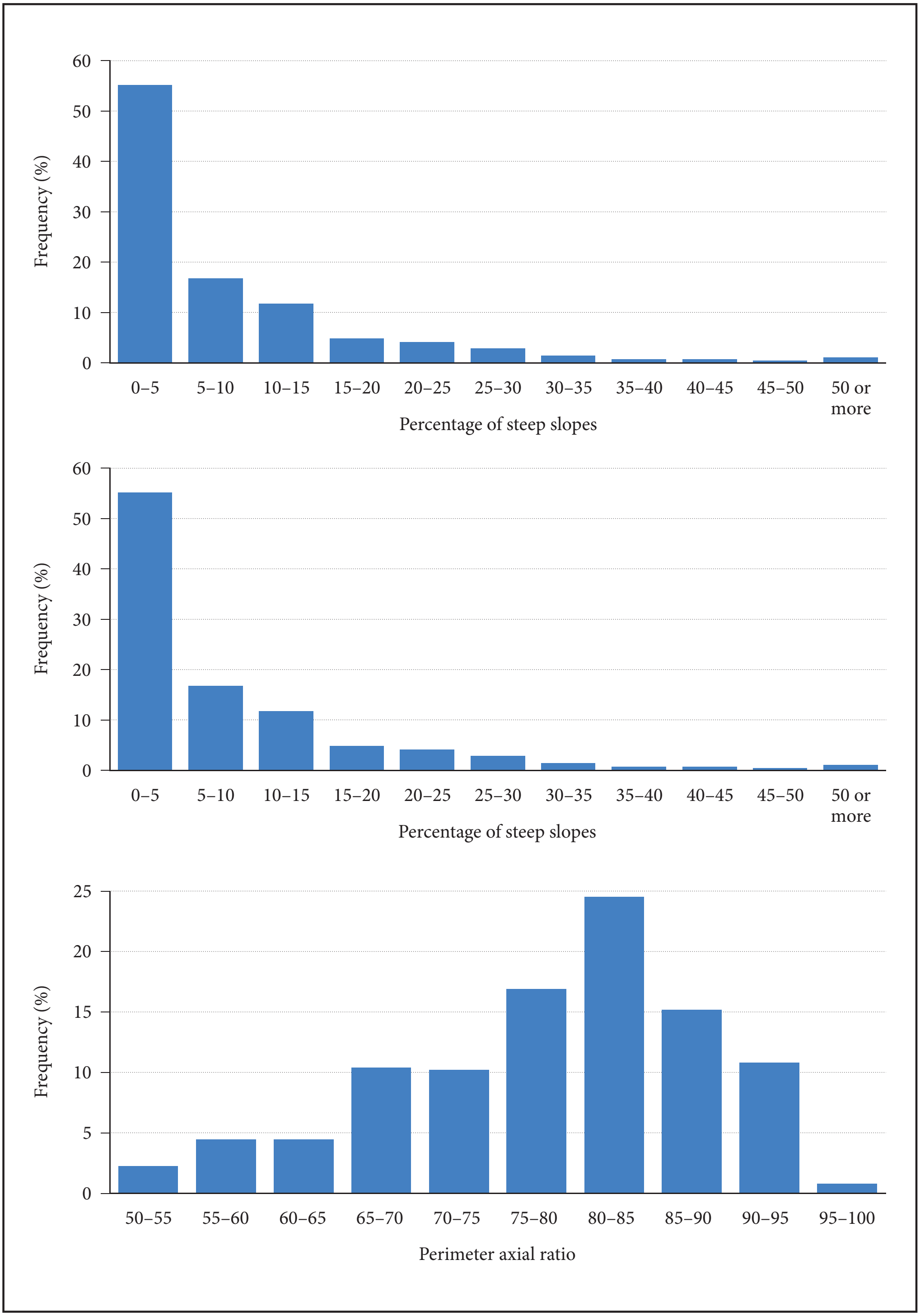


Figure 3: Histograms of morphometric parameters of dolines with descriptive statistics.

Table 4: Basic descriptive statistics of morphometric parameters used in the process of classification based for each class.

Morphometric parameter	Statistic	Class 0	Class 1	Class 2	Class 3	All classes
Percentage of steep slopes	Mean	3	23	1	7	8
	Median	2	19	0	4	3
	95th Percentile	9	50	4	23	29
Percentage of gently sloped terrain	Mean	11	4	52	12	15
	Median	9	4	47	9	9
	95th Percentile	27	12	89	29	51
Perimeter axial ratio	Mean	84	83	75	66	78
	Median	84	83	75	67	8
	95th Percentile	92	93	90	74	92

4.3 Spatial distribution of doline classes

Class 0 dolines are the most numerous in Slovenian deep karst, followed by Class 3 (Figure 5). Class 1 is only slightly less common, being 4% behind Class 3, while Class 2 is the rarest. In corrosion plains, the proportion of Class 0 dolines is even higher than the general distribution, with a notable increase in the percentage of Class 2 dolines, suggesting that Class 2 dolines may be typical of corrosion plains. Class 1 dolines are the least common in these areas. In contrast, cone karst areas show a different pattern, where Class 1 dolines are more prevalent, and Class 2 dolines are the least common. The percentage of Class 3 dolines also is higher in cone karst areas, though Class 0 dolines remain the most common type in these regions.

The chi-square results are indicating a strong correlation between class distribution and whether the area is a corrosion plain or a cone karst area (Table 5). The p-values, all below 0.05, further confirm a significant correlation. This suggests that the distribution of doline classes is not random but is instead related to the specific type of karst, meaning certain classes are more likely to be found in particular karst environments.

The highest density of **Class 0 dolines** is found in corrosion plains of all types, with the Logatec-Begunje dry polje having the highest concentration. Lower densities are observed on high karst plateaus such as Nanos, Snežnik, and Trnovski Gozd, although Class 0 dolines still occur in these areas. Overall, Class 0 dolines are present across nearly all deep karst regions in Slovenia (Figure 6).

Class 1 dolines show a markedly different spatial distribution compared to Class 0. The highest density of Class 1 dolines is found in the cone karst area of Kočevski Rog. Some parts of the corrosion plains also exhibit higher concentrations of Class 1 dolines. Additionally, there are localised areas of high density in the Ljubljanica River catchment, particularly in the hinterland of major ponors and springs.

Class 2 dolines rarely exhibit high densities, and when they do, these are very localised. Notably, higher densities are observed in areas of corrosion plains, with the highest densities found in the Karst corrosion plain, as well as Kočevje corrosion plain and Bela Krajina corrosion plain.

Class 3 dolines are more densely concentrated in areas with greater slopes, such as the sloping terrain between Nanos and Hrušica. Menišija also exhibits a high density of Class 3 dolines. These dolines are more frequently observed in cone karst areas and especially in dolostone karst.

Table 5: Chi-square test results for correlation between doline classes and the two karst types.

Karst type	Chi-square value	P-value	Null hypothesis
Corrosion plain	7873.3	0.00	Rejected
Cone karst	3375.5	0.00	Rejected

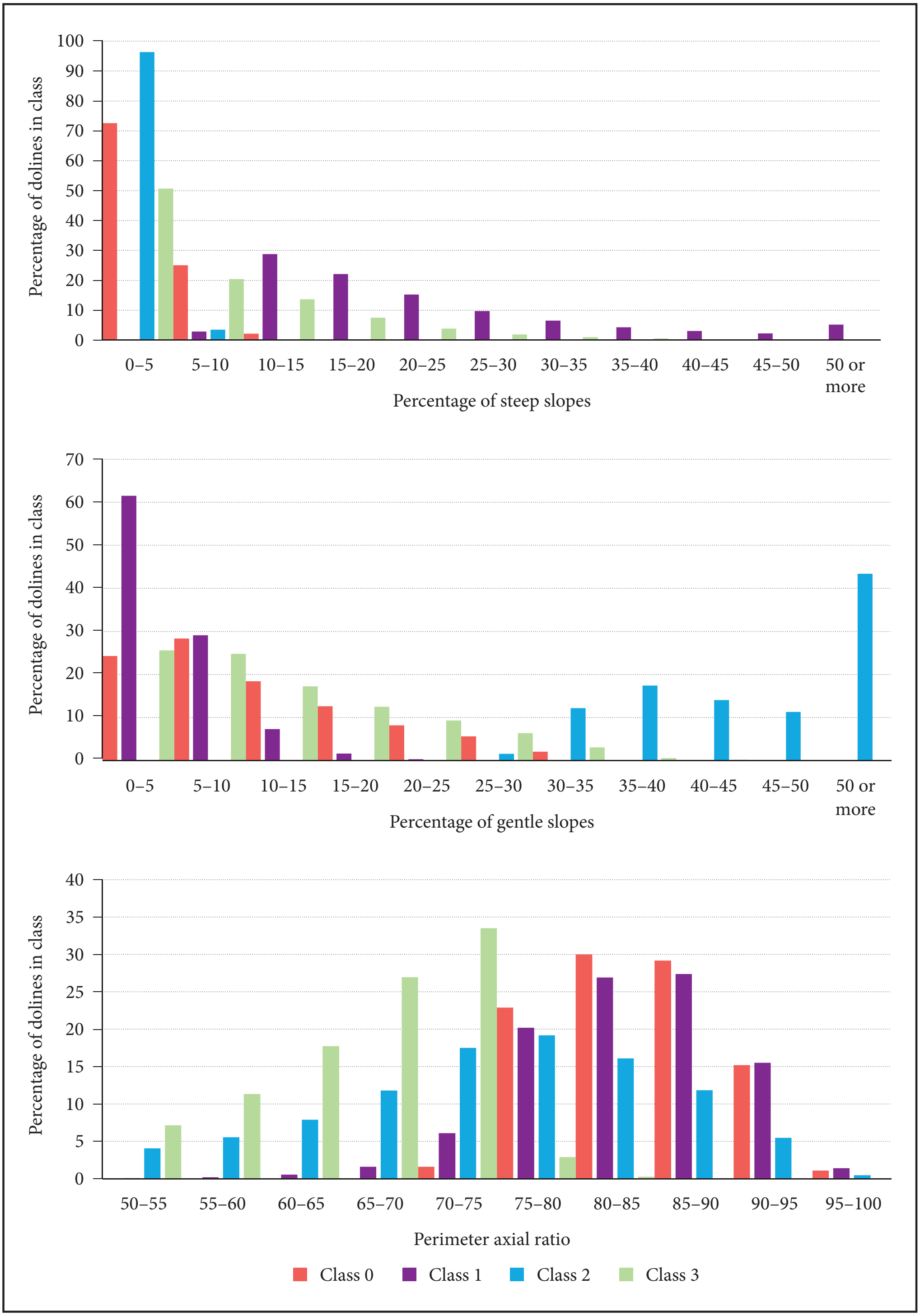


Figure 4: Histograms of dolines ISO classification parameters.

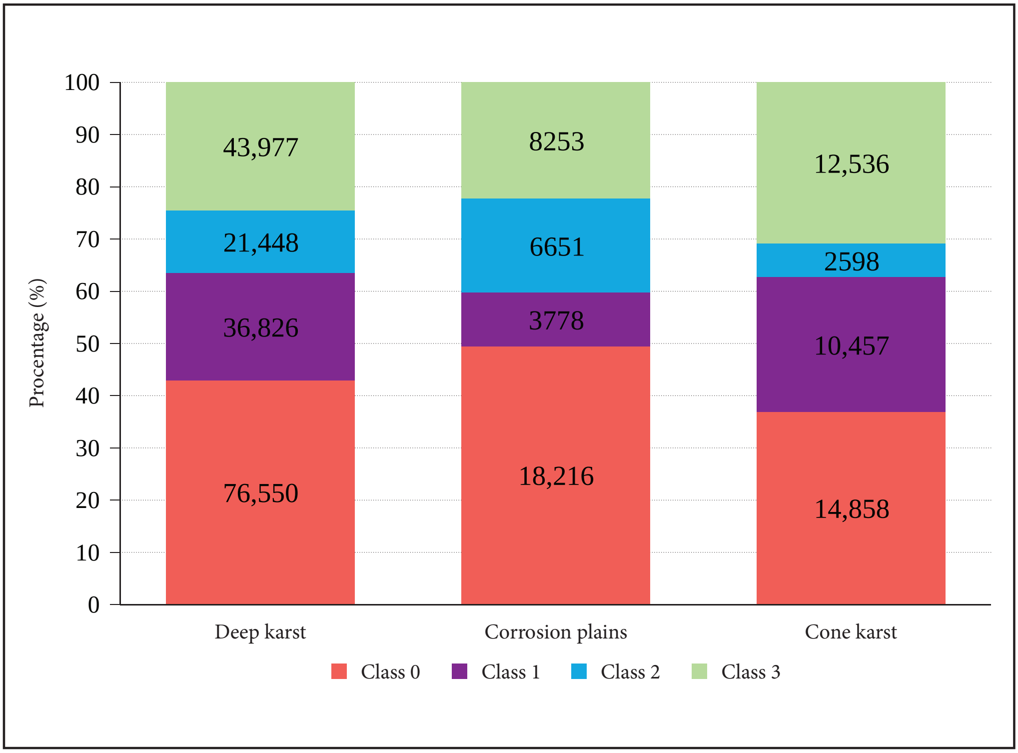


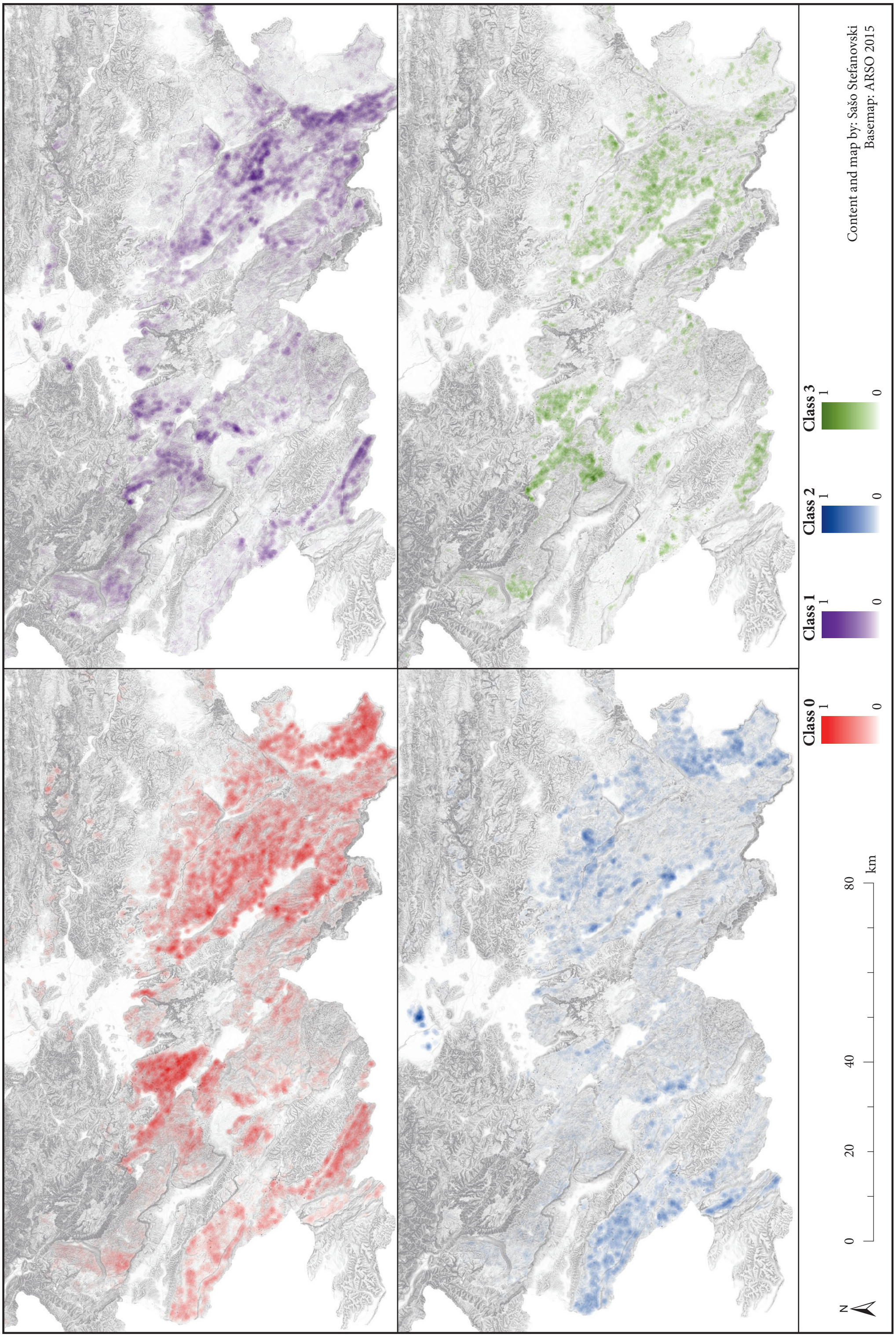
Figure 5: Distribution of doline classes across different karst types.

4.4 Doline classes and sediment cover

Some doline classes are more prevalent in karst environments extensively covered by sediment (Figure 7). Notably, Class 2 stands out, with approximately three quarters of its dolines in covered karst with 5 m^2 or less outcrops in their surroundings, and it also has the lowest mean and median values. In contrast, Class 1 shows the opposite trend, having the fewest dolines that are completely covered by sediments compared to other classes. Class 1 dolines are the most frequent class in areas with 25 m^2 or more outcrops in their surroundings, and they exhibit the highest mean and median values, indicating a preference for rocky terrain. Nearly half of the Class 0 dolines have little to no outcrops nearby, with the remainder mostly showing low values. Class 3 is similar to Class 1 regarding covered karst area, with the second-highest mean and median values and a high percentage of dolines with more than 25 m^2 of outcrops in their surroundings.

Table 6 displays the results of the Mann-Whitney U test. The differences in the share of uncovered karst between the classes are statistically significant, since the p-value does not exceed 0.05. Thus, we can reject all null hypotheses. This suggests that some doline types are linked to areas with continuous sediment cover, while others occur in regions with sparse or minimal sediment.

Figure 6: Doline density by class. ➤ p. 20


Class 0
1
0
Class 1
1
0
Class 2
1
0
Class 3
1
0
0
20
40
80
km
N
Content and map by: Sašo Stefanovski
Basemap: ARSO 2015

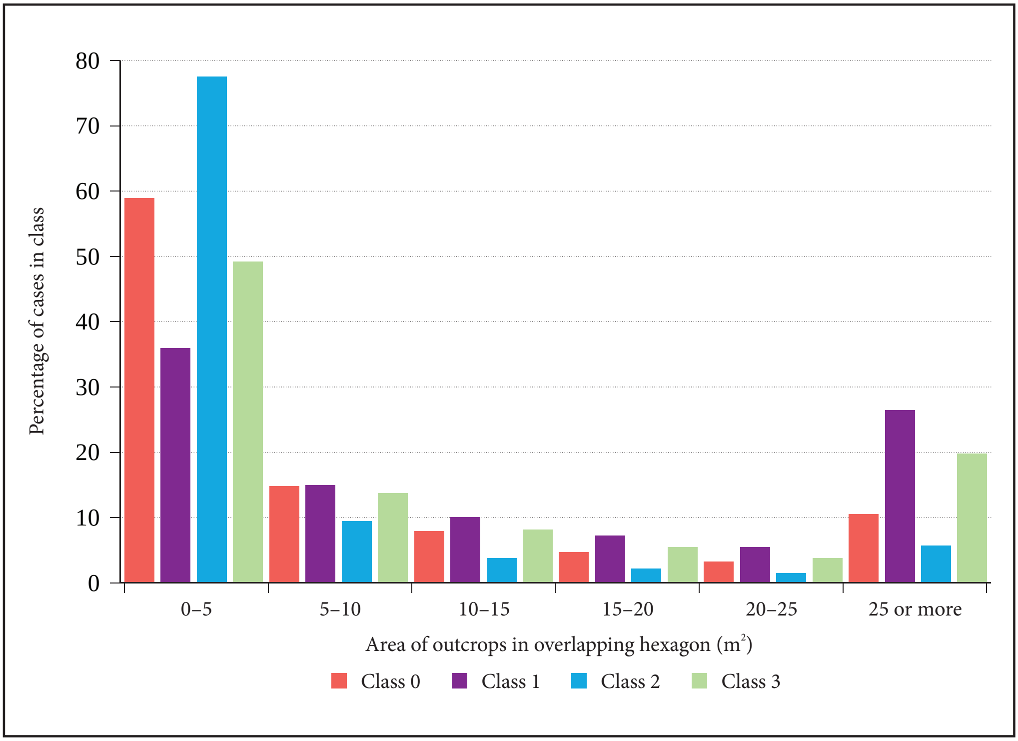


Figure 7: Area of outcrops in doline surroundings.

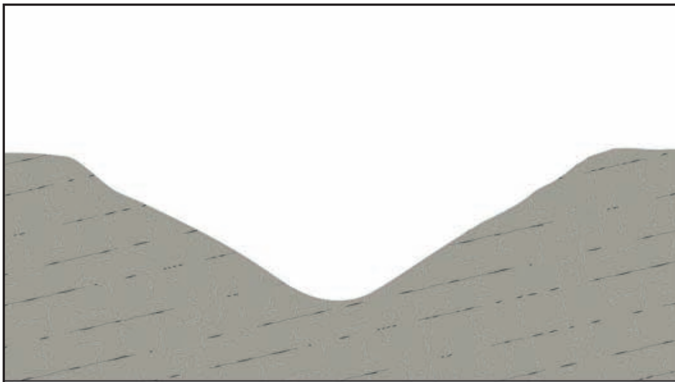
Table 6: Results of Mann-Whitney U test.

Classes	U-statistic	P-value	Null hypothesis
(0, 3)	$1.47x10^9$	0.00	Rejected
(0, 2)	$1.04x10^9$	0.00	Rejected
(0, 1)	$0.99x10^9$	0.00	Rejected
(3, 2)	$0.64x10^9$	0.00	Rejected
(3, 1)	$0.68x10^9$	0.00	Rejected
(2, 1)	$0.19x10^9$	0.00	Rejected

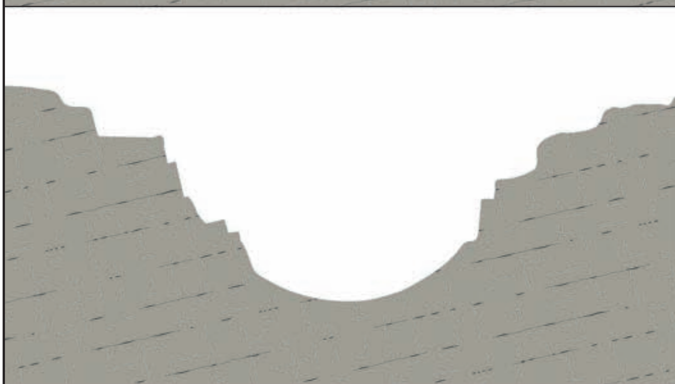
5 Discussion

Using parameters such as steep slopes, gently sloping terrain, and perimeter axial ratio, we conducted an unsupervised ISO classification with four doline classes, based on literature. The results were then linked to morphographic typologies. We applied established doline terms from the literature, clearly defining them both morphographically and morphometrically. This is visible in Figure 8.

Figure 8: Morphological types of dolines and their main features. ➤ p. 22

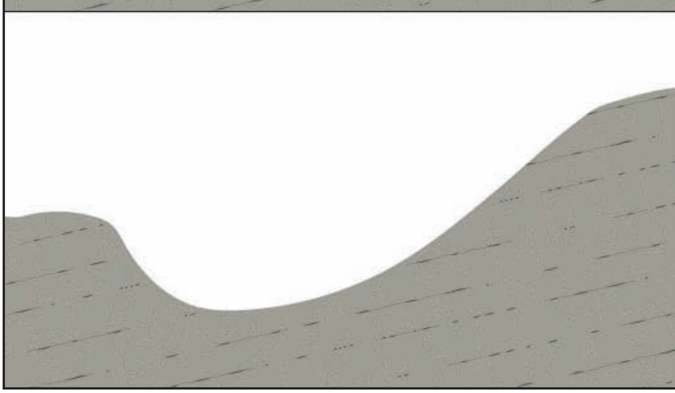


Funnel–shaped doline
- usual presence of active slopes
- narrow concave floors
- slightly elongated
- typical for cone karst and corrosion plains
- typical for covered and semi–covered karst



Well–shaped doline
- large proportion of active slopes
- narrow to semi–narrow concave floors
- typical for cone karst
- typical for semi–covered karst

Bowl–shaped doline
- near absence of active slopes
- extensive flat floors
- moderately elongated
- typical for corrosion plains
- typical for covered karst



Elongated doline
- near absence of active slopes
- narrow to semi–narrow concave floors
- length greatly exceeds width
- typical for dolostone cone karst
- typical for covered karst

Class 0 dolines are characterised by the presence of steep slopes, though these constitute only a small portion of the doline. The slope inclination between 7° and 30° prevails in this class, with a low proportion of gently sloping terrain. Majority of Class 0 dolines have an axial ratio between 80 and 90. Morphologically, they get narrower with depth and have narrow floors, with a slightly elongated ground plan. Cvijić (1893) first described these as funnel-shaped dolines, wide at the top and narrow at the bottom. Gams et al. (1973) also used the term funnel-shaped based on their cross-sectional profile. As this term is still widely used (Gams 2000; Gams 2003; Sauro 2019) we propose maintaining the usage of »**funnel-shaped dolines**« (sl. *lijakaste vrtače*) for this type.

Class 1 dolines are characterised by a large proportion of steep slopes, with most having an area of 10% or more. Gently sloping terrain is rare, with 68% of these dolines having 5% or less of such terrain. The axial ratio is slightly lower than in Class 0 dolines, but they remain only slightly elongated. These dolines have steep slopes, often with walls, and narrow floors are more common than larger ones. Cvijić (1893) first described dolines with steep, vertical, or inclined slopes, which he termed well-shaped. Gams' descriptions (Gams et al. 1962; Gams et al. 1973; Gams 2000; Gams 2003) align Class 1 dolines with well-shaped and kettle-shaped dolines, though the term kettle-shaped is problematic, as it is typically used for glaciokarst features (Kunaver 1983; Žebre and Stepišnik 2015; Ferk et al. 2017). Therefore, we recommend using the term »**well-shaped dolines**« (sl. *vodnjakaste vrtače*) for those with a high proportion of steep slopes, regardless of floor morphology.

Class 2 dolines are characterised by the near absence of steep slopes, with almost all having less than 5% of their area comprising steep slopes. Conversely, these dolines have the largest percentage of gently sloped terrain, with nearly all having at least 30% gently sloped terrain. The axial ratio varies, but most dolines fall between 70 and 80, indicating slight elongation. These dolines rarely experience mass wasting processes and typically feature extensive, flat floors, often due to anthropogenic alterations. Given their gentle slopes and broad floors, these dolines are generally shallow. Cvijić (1893) first described such dolines as bowl-shaped, noting their small depth relative to their diameter and lack of steep slopes. The term »**bowl-shaped doline**« (sl. *skledaste vrtače*) remains widely used (Gams 2003; Sauro 2019; De Waele and Gutiérrez 2022), making it an appropriate term for this class.

Class 3 dolines exhibit a wide range of morphometric characteristics, with their number decreasing as the proportion of steep slopes and gently sloping terrain increases. The most distinguishing feature of these dolines is their axial ratio, which typically ranges from 50 to 75, indicating significant elongation. This elongation is the primary characteristic that sets these dolines apart from other types. Cvijić (1893) was the first to identify such elongated dolines, referring to them as valley-shaped dolines, though he did not provide detailed morphological descriptions. While elongation in dolines is sometimes associated with compound features (Gams et al. 1962; Gams et al. 1973; Gams 2003), this study focuses exclusively on standalone dolines. Previous research on karst anisotropy, also identified elongated dolines as significant geomorphological features in karst landscapes (Verbovšek 2024). The term »valley-shaped doline« can be misleading due to its derivation from the Slavic word for valley (dolina), which could cause confusion. As elongation is the main parameter defining the shapes of these dolines, we propose the term »**elongated dolines**« (sl. *podolgovate vrtače*), as it accurately reflects their defining morphometric characteristic. By »elongated«, we refer to dolines, that are distinctly elongated, somewhat linear depressions with a profile resembling a shallow channel or trough, rather than a circular or bowl-like pit.

We then analysed their spatial distribution in Slovenia and investigated the correlation between doline types and morphogenetic karst types (Stepišnik and Ferk 2023; Stefanovski et al. 2024; Stepišnik 2024). The distribution of doline types and karst types shows a strong correlation, with certain doline types being more characteristic of specific deep karst environments.

Bowl-shaped dolines (Class 2) are mainly found on corrosion plains, with the highest densities on covered karst areas (Figure 9). Well-shaped dolines (Class 1) are most common in cone karst areas with greater elevation changes, though they also appear less frequently on corrosion plains and are more common in semi-covered karst areas. Funnel-shaped dolines (Class 0), the most prevalent type in Slovenian deep karst, occur in both cone karst regions and corrosion plains, with higher densities in covered and semi-covered karst. Elongated dolines (Class 3) are found in cone karst areas, corrosion plains, and covered and semi-covered karst regions. They fall into two distinct groups. The first group is located in the hinterland, where high-discharge watercourses contribute to allogenic recharge in karst systems, and their shape can be linked to the gradual collapse of horizontal cave passages (Bahun 1969; Mihevc and Zupan Hajna 2007; Hajna et al. 2024). The second group is found on slopes, particularly on covered karst slopes in dolostone cone karst areas, where elongated dolines are especially characteristic.

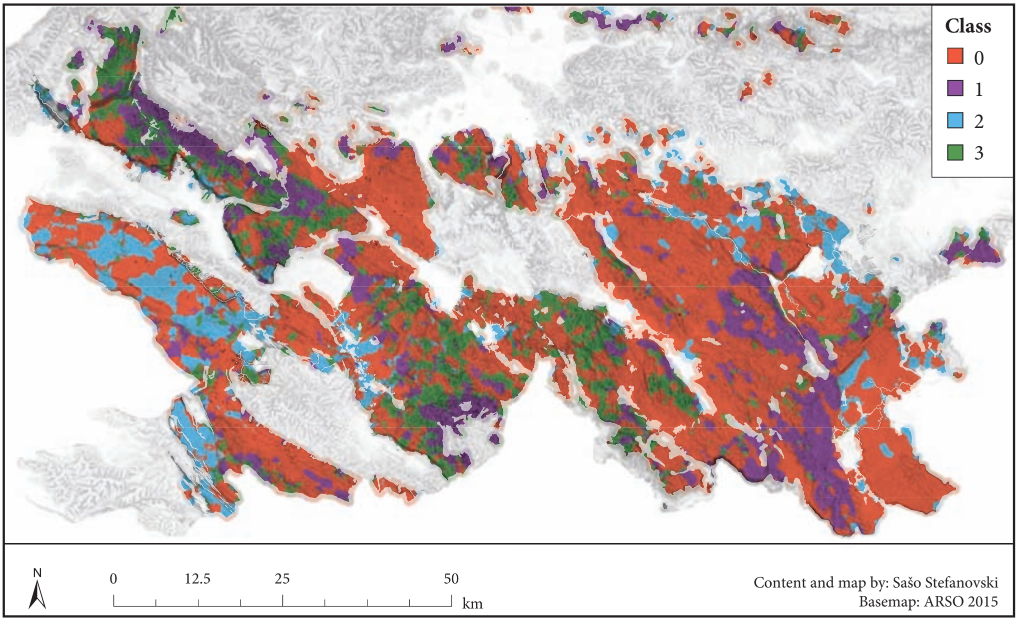


Figure 9: A map of deep karst in southern Slovenia based on the predominant type of dolines.

Although this article does not focus on the morphogenetic interpretation of doline formation, the discussion reveals that doline distribution is closely linked to the prevailing karst type. Deep karst types, shaped by varying denudational processes and sediment presence, suggest that doline types are also accredited to distinct morphogenetic and morphodynamic processes. Sauro (2019) noted that funnel-shaped and bowl-shaped dolines are typical of suffosion dolines, and our study confirms that bowl-shaped dolines are common in covered karst, where suffosion dolines predominate. Well-shaped dolines correspond to earlier stages of collapse dolines, gradually becoming more funnel-shaped as the slope angle decreases (Šušteršič 1973; Šušteršič 1994; Šušteršič 2000; Waltham et al. 2005; Sauro 2012; Lipar et al. 2019; Sauro 2019). Their spatial distribution indicates this, with higher densities found in areas with collapsed dolines due to denser cave systems (Stepišnik 2010). Funnel-shaped dolines may represent a morphogenetic convergence of both collapse and suffosion types, making their exact origin difficult to determine in later stages. Elongated dolines, appear in areas where high-discharge watercourses contribute to allogenic recharge in karst systems, linked to the gradual collapse of horizontal cave passages, and on slopes, particularly covered karst slopes in dolostone cone karst areas, where they are especially characteristic.

6 Conclusion

In this study, we classified dolines in Slovenian deep karst based on their morphometric characteristics and studied their spatial distribution in southern Slovenia. We focussed on classifying dolines based on the extent of steep slopes, floor extent and perimeter elongation, as previous morphographic descriptions of dolines was mainly centred on describing these characteristics. Development in GIS now enables precise morphometric analyses. We defined four different morphometric types of dolines that are consistent with existing typologies. These include funnel-shaped dolines, which narrow with increasing depth; well-shaped dolines, characterised by steep slopes that often form walls; bowl-shaped dolines, characterised by a low slope inclination and a flat, extensive floor; and elongated dolines, which are notable for their significant elongation of the ground plan. The results show that the shape of dolines is closely related to different karst types, suggesting that their formation is driven by processes characteristic of specific karst types.

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RESEARCH DATA: For information on the availability of research data related to the study, please visit the article webpage: https://doi.org/10.3986/AGS.13940.

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