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Research article

Use of the TPI and TWI Methods for Identifying Karst Dolines in Purwosari District, Gunungkidul Regency, Indonesia

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Abstract

Gunung Sewu Karst, located in the Gunungkidul Regency within the Special Region of Yogyakarta, features a distinctive karst topography consisting of dolines, hills and caves. Despite its aesthetic appearance, the area often experiences water scarcity due to the lack of surface water. Dolines, basin-like depressions formed during the karstification process, play a crucial role in biodiversity conservation, ecology, hydrology and land-use management planning. This study aims to map and identify the spatial distribution and morphometric characteristics of dolines in the Purwosari subdistrict, which have important implications for water resource management and drought mitigation in karst regions. The findings are intended to guide spatial planning and environmental mitigation strategies. Data for the study were derived from a digital elevation model (DEM), more scalable and accessible elevation data, to generate the Topographic Position Index (TPI) and Topographic Wetness Index for analysing doline spatial patterns, their terrain shapes, their types (dry or watery), and morphometry. The results show that dolines are associated with negative TPI values (58%) and low TWI values (53.48%), with most landforms classified below the plain level (27.91%). A significant proportion of dolines (79.06%) contain water, with the classification accuracy between TPI and TWI being 65.11%. Morphologically, most dolines are U-shaped, with oval-shaped dolines being the most common (41.86% of observations). The findings reveal that dolines in the Purwosari Subdistrict have significant underground water storage potential, making them crucial for mitigating regional drought risks.

Keywords: doline; distribution; Gunungkidul; Topographic Position Index (TPI); Topographic Wetness Index (TWI); morphometry.

1. Introduction

Karst is an earth form with hydrological conditions that occur due to rock dissolution and which develop good secondary porosity (Ford & Paul, 2007; Aprilia, 2019). Karst areas are characterised by closed basins (dolina), scarce surface rivers, and many caves and underground rivers (Haryono & Tjahjo, 2004). Karst phenomena, both on the surface and underground, are formed by the dissolution process; that is, the chemical corrosion of rocks by water in soluble limestone, gypsum and other stone. Dolina is formed due to weathering that occurs in limestone areas. They are an exokarst morphological feature, most commonly found on the surface, as the beginning of karstification. The subsequent development of mature karst, or sometimes categorised as polygonal karst, is marked by the merging of the dolina, thus forming an uvala (Haryono & Adji, 2004; Damayanti & Diah, 2018; Diah *et al.*, 2021).

Dolines, or sinkholes, in karst landscapes play a crucial role in the hydrology, ecology and land-use management planning of these areas. In hydrology, they control the spatial distribution of water and airflows by directing water into the depressions, affecting water movement patterns, soil moisture, soil depth, air temperature and humidity (Antonic *et al.*, 2001). These hydrological benefits include increased soil moisture to support vegetation requiring high moisture levels; localised water accumulation and storage to maintain water supplies; and improved drainage to reduce flood risks. In ecology, dolines can contribute to ecological restoration through canopy growth and organic carbon absorption (Valjavec *et al.*, 2022), serving as essential refuges for specific plant species (Bátori *et al.*, 2014) and as microhabitats for wildlife due to the abundant vegetation growth (Čonč *et al.*, 2022). The study Dolines and Cats: Remote Detection of Karst Depressions and Their Application to Study Wild Felid Ecology by Čonč *et al.* (2022) reveals that both lynx and wildcats are attracted to these karst features, with lynx utilising them for hunting. In land use management planning, karst sinkholes are particularly vulnerable to anthropogenic disturbances, such as agricultural expansion, urban development, and mining activities, which often negatively impact their ecological and conservation value. These disturbances can disrupt the unique microhabitats within dolines, resulting in reduced plant diversity and altered species composition (Bátori *et al.*, 2020; Čonč *et al.*, 2022). Additionally, they contribute to diminishing storage capacity, rapid water loss, and deterioration of water quality in hydrology (Haryono, Adji, & Widyastuti, 2017). Therefore, implementing careful management and conservation strategies is essential to mitigate human impacts on these sensitive ecosystems (Bátori *et al.*, 2014).

Identifying the spatial distribution of karst dolines is paramount for effective land-use management and environmental conservation. A clear understanding of the geomorphological features and spatial patterns of such depressions forms the foundation for developing strategies to preserve ecological functions and mitigate human impact. Various research methods for mapping dolines have been developed, ranging from traditional field surveys to advanced remote sensing techniques. However, conventional methods—such as field mapping and relief digitisation—often face limitations, including inaccuracies, time constraints, high costs and data subjectivity (Grlj, 2020). In contrast, advanced remote sensing techniques, from aerial images to Light Detection and Ranging (LiDAR)-derived high-resolution digital elevation models (DEMs) and UAVs (unmanned aerial vehicles), provide high-resolution data that enhance the accuracy and efficiency of doline mapping. UAVs enable detailed spatial identification of dolines (González-Díez *et al.*, 2021; Ferreira *et al.*, 2023). However, they are less effective for large-scale mapping, while DEMs offer broader coverage but lack the fine detail provided by UAVs. UAVs and DEMs also have limitations in vegetated areas because mixed ground and vegetation elevations can reduce terrain precision. LiDAR, however, is particularly effective in large landscapes such as karst regions, as it can penetrate vegetation to capture underlying features, making it highly suitable for doline identification (Čonč *et al.*, 2022).

Nevertheless, the high cost of LiDAR may impede its extensive utilisation. Therefore, this research proposes a scalable and accessible solution for the early identification of dolines by leveraging the extensive availability of DEM resources. The morphometric approach employed in this study integrates the Topographic Position Index (TPI) to ascertain relative position and the Topographic Wetness Index (TWI) to evaluate moisture accumulation, leveraging digital elevation model (DEM) data. Additionally, identifying dolines based on their relative position and wetness level can help assess their potential to contribute to groundwater recharge and mitigate drought risk.

Dolines are closed basins with a round, oval or irregular shape several meters in size, up to approximately 1 km (Ford & Paul, 2007; Saputra, 2008; Suri & Susilo, 2020). The formation of dolines is influenced by the physical characteristics of their location, such as topographic relief, hydrology and morphometry. Doline karst has attributes in the form of morphological elevations with contour patterns getting lower inward. Lowland terrain forms clusters, while undulating plains are randomly scattered (Damayanti & Diah, 2018; Suri & Susilo, 2020). A thick layer of coral reef limestone forms the topography in karst areas.

Such topography determines the presence or absence of active water movement through weathered materials. Moreover, topography also affects the process of leaching and surface erosion, which determine the removal rate of weathering products (Mulyanto & Surono, 2009). Topography is calculated using the TPI method by observing differences in elevation and slope. GIS applications classify landforms as TPI, which is a calculation to measure the topographic position of slopes, being the height difference between a point and the average height of the surrounding area (Setiawan *et al.*, 2018), with automation of landform classification (Weiss, 2001; Putro & Fitri, 2017; Sutanta & Tiera 2019; Abdullah & Abdulrahman, 2019; Yusra, 2018; Suri & Susilo, 2020). The topographic classification is divided into two forms, namely slopes (ridges and valleys) and landforms (Weiss, 2001).

TPI, on the other hand, is a convolution technique that uses a high-pass filter with a variable kernel (window perimeter) to improve the topographic position or elevation difference between a given point and its surroundings (residuals) (Gallant & Wilson, 2000; Lindsay *et al.*, 2015; Weiss, 2001; González-Díez, *et.al.*, 2021). Convolution is a mathematical technique that describes the overlap between two functions by combining them. Digital signal processing and image processing are two applications employed for convolution. Gazali *et al.*, (2012) claim that one drawback of TPI is its reliance on scale; as a result, the kernel size and resolution of the DEM will determine the residual topography, or the positive or negative location of a point. The absence of guiding criteria is another issue.

Topography is an important factor controlling the spatial distribution of hydrological conditions (Sorensen *et al.*, 2006). Such conditions will affect the response to rainfall. Rain falling in karst areas will mostly percolate into the ground through cavities, so the river system that develops is an underground one (Sulastoro, 2013). The TWI method describes hydrology based on wetness levels (Pourali *et al.*, 2014; Nucifera & Sutanto, 2017). It measures the tendency of water accumulation in an area by considering the topography of the upper and lower slopes. TWI calculation is based on the DEM or DTM data of an area (Budiharso & Andre, 2023). DEM is a remote sensing product that has many functions, so it has been widely used in studies, including TPI mapping (Weiss, 2001; Putro & Fitri, 2017; Sutanta & Tiera, 2019; Abdullah & Abdulrahman, 2019; Yusra, 2019; Suri & Susilo, 2020) and TWI mapping (Budiyanto, 2016; Nucifera & Sutanto, 2017; Budiharso & Andre, 2023). The TWI method quantitatively assesses the effect of local topography on rainwater runoff, which in turn provides a land wetness value that assumes more dolines emerge as ponds (Nucifera & Sutanto, 2017).

The characteristics of doline distribution can also be established based on morphometric aspects. Morphometry is the measurement and mathematical analysis of the configuration of the earth's surface, and the shape and dimensions of the landscape (Herrmann & Bucksch, 2014). The morphometry of dolines serves to determine the stage of their formation, uvala, and continues to the next stage to form a polje (Saputra, 2008: Damayanti & Diah, 2018; Diah *et al.*, 2021).

This research is an initial study to identify the distribution of dolines in Purwosari Subdistrict, Gunungkidul Regency, based on topographic, hydrological and morphometric characteristics. The research area is in the Gunungsewu Karst Area, which is mostly karst hills and valleys in dolines. Purwosari sub-district often experiences drought, but during the rainy season, the dolines frequently turn into lakes. This research aims to inventory the distribution of dolines using the TPI and TWI methods, and based on their size and shape to determine their type. The variables determining doline identification in this study differ those in the work of Damayanti and Diah (2018), who used terrain shape, vegetation density, and surface temperature variables, with spatial analysis. This research also involves differences and similarities in variables and TWI methods and their analysis to the studies of Setiawan *et al.* (2018), Budiyanto (2016), and Putro and Fitria (2017), including elevation, plan curvature, profile curvature, and TWI. This research utilises DEM for the TPI method, contrary to Saputra (2008), who used the Rupa Bumi Indonesia map.

2. Research Methods

2.1 Study Area and Research Concept

This study covers the karst area of Purwosari District, Gunungkidul Regency, with geology, topography and hydrology being the characteristics used to determine the area. Geology is determined from the structure and type of rock; topography from the elevation and slope; and hydrology from the flow pattern. The morphology focused on in this study is exokarst, or doline. Dolines are identified from topographic and hydrological conditions, which are then observed from the distribution pattern derived from the geology, topography and hydrology characteristics. In addition, the study considers the distribution of doline types, namely watery and dry dolines. The morphometric focus in the study is the size and shape of the doline. Size is interpreted as the perimeter, area and volume, while the shape of the doline is interpreted as being round, oval or irregular. Figure 1 shows a flow diagram of the research concept.

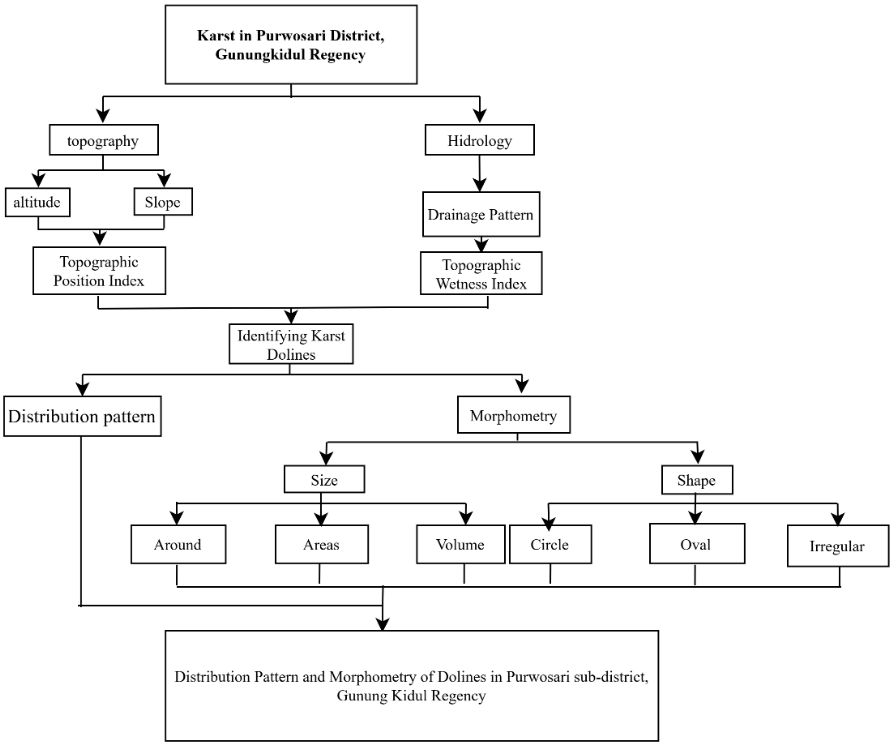


Figure 1. Research Concept Flowchart.

Purwosari sub-district is located in the southern part of Gunungkidul Regency. It has an area of 67.6333 km^2 and comprises five villages: Girijati Village, Giriasih Village, Giritirto Village, Giricahyo Village and Giripurwo Village. The largest village in this sub-district is Giripurwo Village, with an area of 28.2644 km^2, or around 41% of the total area. The administrative boundary of Purwosari Sub-district is bordered to the north by Imogiri Sub-district, to the south by the Indian Ocean, to the west by Pundong and Kretek Sub-districts and to the east by Panggang Sub-district (Figure 2).

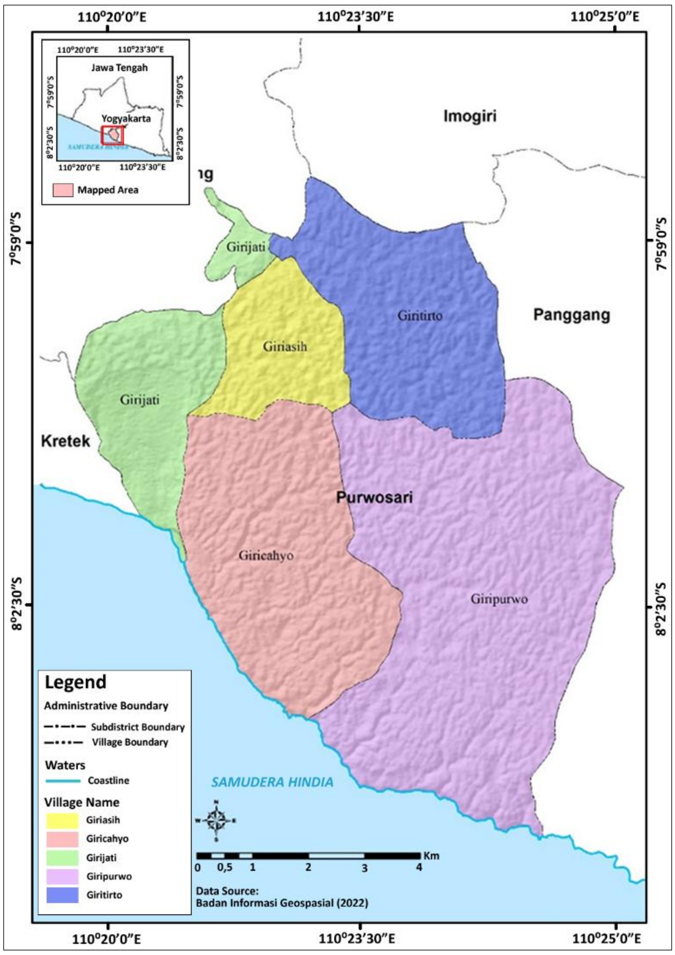


Figure 2. Research Area.

The identification of Dolina was made using digital elevation model data, referred to as DEMNAS (Digital Elevation Model Nasional). The data were retrieved from the Geospatial Information Agency (Badan Geospasial Indonesia) website on May 17, 2022, with a high spatial resolution of 8.1 meters. The dataset is the result of a data integration process from multiple sources, including IFSAR (5-meter resolution), Terra SAR-X (5-meter resolution), and ALOS PALSAR (11.25-meter resolution). The integration process led to the creation of a more contemporary and precise elevation model, which has been standardised in Indonesia. The use of this model facilitates spatial analysis, particularly in the context of complex karst regions.

The distribution and morphology of dolines were classified based on terrain shape and hydrological index, using elevation/height and slope variables and the TPI method. TPI measures the difference in elevation at the centre point (z0) and the average elevation (z), with a certain radius, as formulated in Equation 1, with a scale factor of 100 (Weiss 2001):

$$tpi < scale\ factor > = int\Big(\big(dem - forcalmean(dem, annulus, irad, orad)\big) + .5\Big) \quad (1)$$

where scale factor = area radius in map units; irad = inner radius of the annulus in cells; orad = inner radius of the annulus in cells; and int = Raster mathematic integer. If TPI value > 0 = Ridge Area; TPI = 0 = Flat area; TPI < 0 = Valley Area.

The dolina samples in this study were determined using a purposive sampling method, their location being based on a 250 x 250-meter grid. The application of a grid is very suitable for organising spatial data that varies and is continuous in space, such as altitude slope, into specific units so that the grid size can be determined by the user based on the purpose, scale or format of its use (ESRI, 2001). Based on the area of Purwosari Subdistrict, the number of grids generated was 1177. Furthermore, the cross-sectional formula determined the sample size (Lemeshow & David, 1997), using Equation 2.

$$n = \frac{Z\alpha 2p\ (1-p)N}{d2(N-1)} + Z\alpha 2p(1-p) \tag{2}$$

where: n = minimum sample size; Zα = standard confidence (α = 10%, then Z = 1.64); p = proportion of the sample studied in the population; N = total population; and d = tolerance of error (5%). The cross-sectional formula calculation resulted in a total of dolina samples of at least 55.

For the spatial distribution of dolines, the pattern of dolina distribution was determined using nearest neighbour analysis. This distribution pattern will produce three designs. The way is generated based on the nearest neighbour index value. The clustered pattern, or clustered nearest neighbour index value, reaches 0; random or random with a value of 1; and uniform or uniform with a nearest neighbour value of 2.15.

Processing terrain shape data using DEMNAS converted into terrain analysis, dolina morphometry, and landform classification. Classification was based on nine classes, by considering the low radius scale TPI type and large radius scale TPI, and by calculating the difference between elevation at the centre point and standard deviation (Table 1). The slope was calculated by taking into account the classification of the centre slope/flat area, which is higher than the surrounding (TPI/DEV≥0), and taking into account the hill that is lower than the surrounding (TPI/DEV<0), as shown in Table 2.

Table 1. Terrain Shape Classification (Weiss, 2001).

Class	Terrain shape classification	Slope Narrow	Radius Size	Broad Radius Size
1	Canyon		$Z_0 < -$ SD	$Z_0 < -$ SD
2	Shallow valley		$Z_0 < -$ SD	-SD ≤ Z_0 < 0
3	Drainage plateau		$Z_0 < -$ SD	0 ≤ Z_0 < 0
4	U-shaped valley		$Z_0 < -$ SD	Z_0 > SD
5	Plain	≤ 5°	SD ≤ Z_0 < SD	Z_0 < − SD
6	Open slope		SD ≤ Z_0 < SD	0 ≤ Z_0 ≤ SD
7	Upper slope	>5°	SD ≤ Z_0 < SD	− SD ≤ Z_0 < 0
8	Hills		SD ≤ Z_0 < SD	Z_0 > SD
9	Hilltop		Z_0 > SD	Z_0 < − SD

Table 2. Classification of TPI values (Weiss, 2001).

Classification	Topographic Position
= <1	Valley Area
= 0	Flat Area
= >1	Ridge Area

In addition to TPI, the wettability index (TWI) was also calculated using DEM data. The TWI method is used to assess the potential for inundation basins in the presence of flow patterns, direction and accumulation. In the TWI data processing using ArcGIS 10.8 software DEM data were input and the projection changed to UTM. A map was then created of the flow direction flow accumulation; slope data created; the slope calculated in degrees; the gradient calculated in angles, with the formula slope degree multiplied by 1.570796/90 in the raster calculator; and then the equation calculated using Equation (3). Based on cited in Miardini and Grace (2019), the main procedure used for TWI calculation is as:

$$W = \ln ⟦\alpha/(\tan\beta)⟧ \tag{3}$$

W= wettability index; α = specific catchment area (Flow Accumulation); β = slope (radian). The TWI index value calculation results can determine areas prone to inundation. Watery dolina is determined if the wetness index classification of TWI value is low, medium, fairly high or high, while dry dolina refer to TWI value classifications of very low (Table 3). The TWI index processing resulted in values ranging from 0-19. Furthermore, based on the TPI and TWI classifications, a matrix of aqueous dolina and dry dolina was produced (Table 4).

Table 3. TWI Value Classification.

TWI Classification	Class
< 6.5	Very Low
6.6 – 8.5	Low
8.6 – 11.1	Medium
11.2-14.5	Fairly High
>14.5	High

Table 4. Dolina types based on TPI and TWI.

TPI Value	TWI Value	Type of Dolina
>1	< 6.5	Dry
0	<6.5	Dry
0	6.6 – 8.5	Watery
<1	8.6 – 11.1	Watery
	11.2-14.5	Watery
	>14.5	Watery

The dolina morphometry referred to in this study is size and shape. The size of the dolina (circumference, area and volume) was generated based on digital calculations using Arcmap and Arcscene software (specify version data software). The shape of the dolina was developed by considering its length and width using a cartesian diagram. A round-shaped dolina has a ratio of approximately 1:1; an oval-shaped one of roughly 2:1; while an irregular shaped dolina has a ratio of 1:1 to 2:1.

3. Results and Discussion

3.1. Dolina Distribution Pattern

The distribution of dolina in Purwosari District of Gunungkidul Regency shows a clustering pattern. The index value of the nearest neighbour analysis of dolina distribution is 0.858488, with a z-score value of -1.77. This value means that less than 10% of the dolina distribution is randomly patterned. Figure 3 shows that dolina distribution patterns tend to cluster, but there are also dolina with random distribution patterns. The grouped dolina distribution has an average distance of 500 meters.

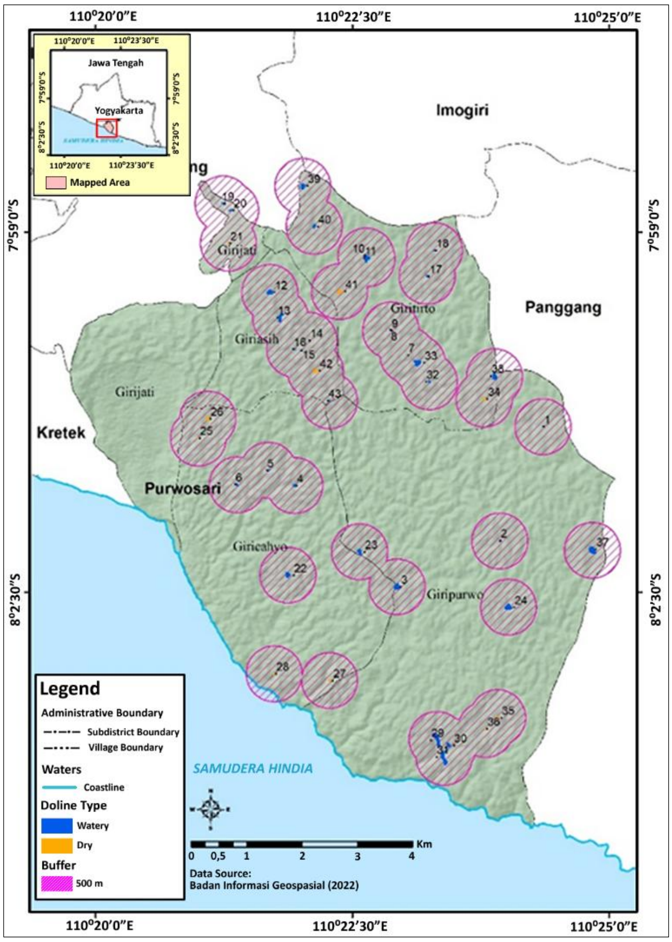


Figure 3. Pattern of Dolina Distribution in Purwosari Sub-district, Gunungkidul Regency.

The dolina distribution pattern tends to cluster in the north (Figure 3). The distribution is influenced by geological characteristics, namely the presence of geological structures of karst areas in the study location, in the form of faults and fractures, which facilitate the formation of dolines. Water entering through the fractures will quickly dissolve the limestone, so the contour pattern becomes increasingly lower to form a dolina basin. The hydrological characteristics of the doline are in the form of multibasinal flow patterns, including river flow that disappears below the earth's surface. No surface flow was found in the northern part of the Purwosari sub-district.

3.2. Distribution of dolina based on TPI Value

In general, the topography of Purwosari Sub-district comprises karst hills. Based on the topographic index data processing, three TPI classes were obtained. Figure 4 shows the distribution of dolina with a negative TPI of a minimum value of -105.5 (white dolina); a TPI of zero (grey dolina) indicates plain areas; and a positive TPI (black dolina) indicates hills with a maximum value of 51.5. Figure 4 and Table 4 show that the research area is generally in a negative topographic condition, in the form of a valley or basin. The indication of dolina in the study area is dominated by the negative TPI classification, with a total number of dolina of 29 pieces (67%).

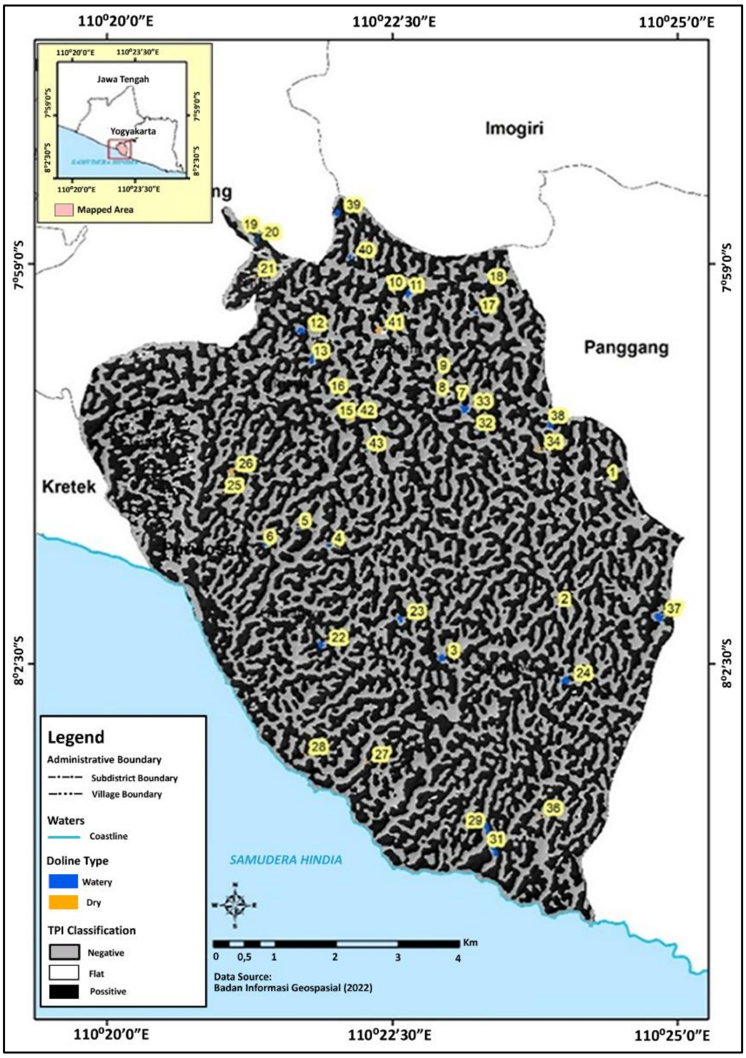


Figure 4. Distribution of dolina by TPI value.

The zero TPI classification with five dolines (11%) and the remaining positive TPI with nine (20%) mean that the dolines are distributed in lower areas, such as valleys and hollows. A negative TPI allows the dolines to form faster in lower regions, facilitating the dissolution process. Dolina is most widely scattered on landforms in the form of plains, with 12 examples (27.91%). Furthermore, there are ten dolina (25.58%) in the river canyon area, with the lowest number of two (4.65%) in the plateau drainage area,. This distribution of dolina is due to the distribution of surface water rarely found in karst areas. Many surface rivers in karst areas are cut off and lost.

The TPI technique has been extensively employed for altimetry (Doneus, 2013; Hiller & Smith, 2008; Kennelly, 2008; Kincey *et al.*, 2014). However, TPI exhibits deficiencies when employed to filter geomorphic features of a specific size (Lindsay *et al.*, 2015; Sofia, 2020). Lindsay *et al.* (2015) integrated TPI filters across different image bands to visualise scale characteristics in heterogeneous reliefs and to address this limitation. Nevertheless, the scale dependence of TPI complicates its practical application (Sofia, 2020). The primary finding of the study conducted indicates that the TPI method is capable of cartometrically mapping and monitoring objects without the necessity for on-site field surveys, making it highly pertinent for regions characterised by limited accessibility or intricate topography.

Table 5. Distribution of dolina by terrain and type.

Terrain Shape	Type of Dolina		Total	Percentage (%)
	Watery	Dry		
Canyon	11		11	25.58
Shallow valley	4		4	9.3
Drainage plateau	2		2	4.65
U-shaped valley	5		5	11.63
Plain	12		12	27.91
Open slope		5	5	11.63
Upper slope		2	2	4.65
Hills		2	2	4,65
Hilltop				0
Total			43	100

3.3. Dolina distribution based on TWI values

Figure 5 and Table 5 show the distribution of dolina based on the TWI value. Dolina in the study area predominantly have low TWI values (orange), totalling 23 (53.48%). Furthermore, the number of dolina with a very low TWI value (red) was nine (20.9%). No dolina with high TWI values were found in the study area, given the dry hydrological conditions of karst on the surface due to the large number of rivers below the surface. The higher TWI value indicates that the site has high wetness, usually located in channels or rivers with a particular slope, flow direction and flow pattern.

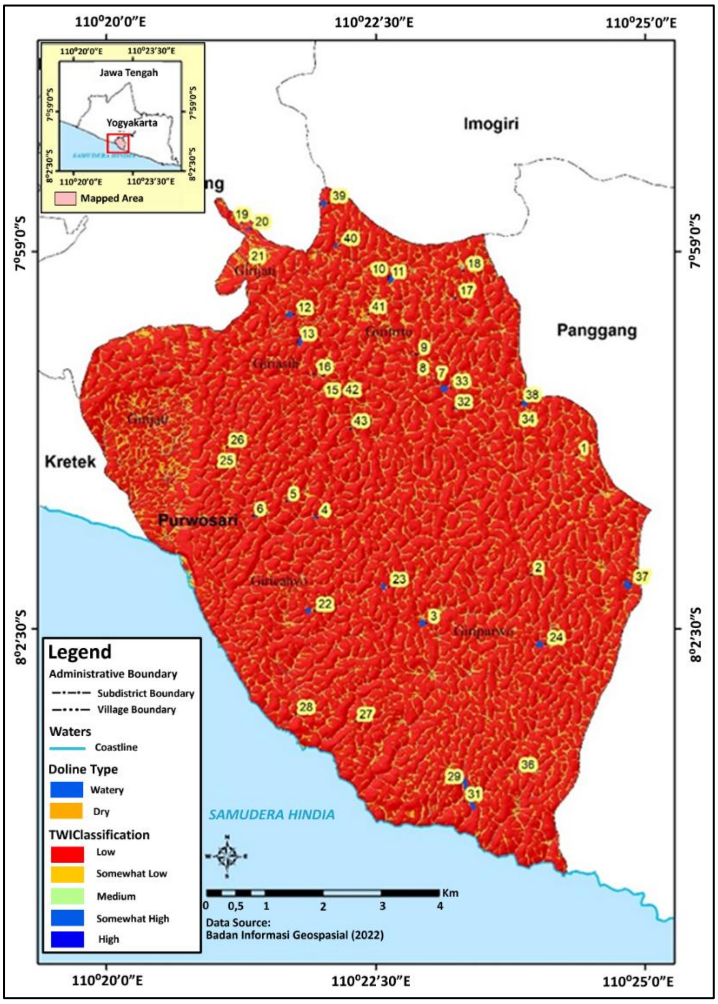


Figure 5. Distribution of dolina by TWI value.

Table 6. Distribution of TWI-classified dolines by terrain shape.

Terrain Shape	TWI					Total	Percentage
	Very Low	**Low**	**Moderate**	**Fairly High**	**High**		**(%)**
Canyon		5	6			11	25.58
Shallow valley		4				4	9.3
Drainage plateau		1		1		2	4.65
U-shaped valley		4	1			5	11.63
Plain		9	1	2		12	27.91
Open slope	5					5	11.63
Upper slope	2					2	4.65
Hills	2					2	4.65
Hilltop							0
Total	9	23	8	3		43	100

3.4. Dolina Distribution by Type

The results of dolina identification based on TPI and TWI values that match the sample points show a total of 37 examples (86%). Due to land cover factors, the remaining six dolina samples do not match the location (Figure 6). The combined classification of TPI and TWI values resulted in the distribution of dolina dominated by watery ones, with 34 instances (79.06%), with nine examples (20.93%) of dry dolina. The field survey results show that the classification accuracy of TPI and TWI values was 65.11%. The percentage value is sufficiently accurate to determine the watery and dry dolina types. Based on the shape of the terrain, the type of watery dolina is dominated by the classification of plains, where the total distribution of dolina is 12 (27.91%). In addition, the open slope classification dominates the dry dolina type, with a full allotment of five dolina (11.63%).

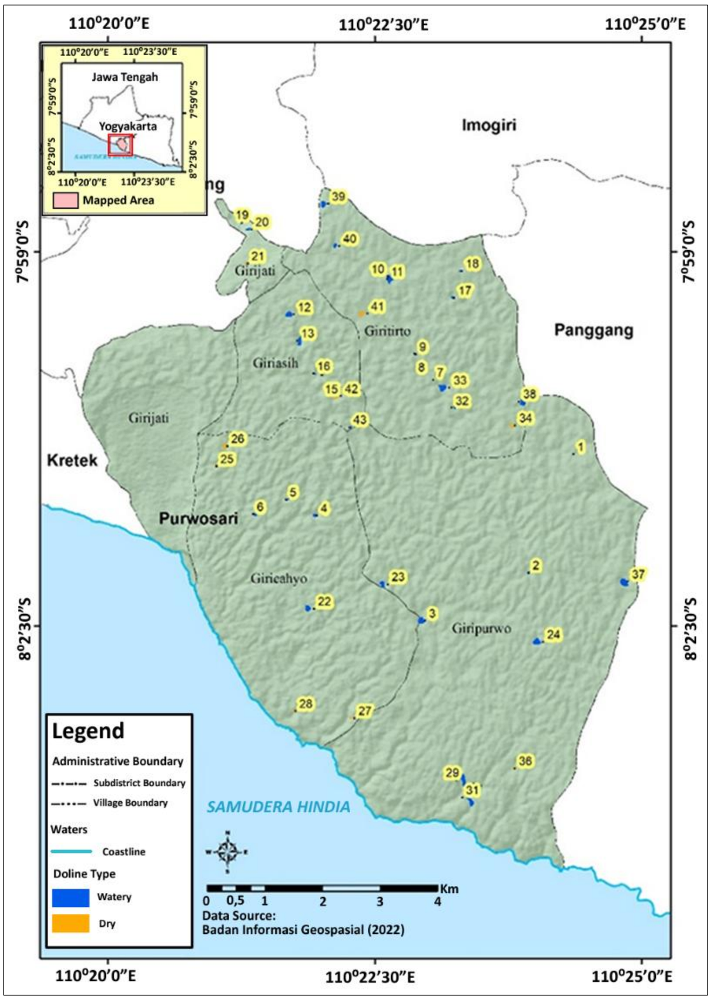


Figure 6. Distribution of dolina by type.

Almost all of the dolines identified as water dolines using TPI and TWI were found in fields such as ponds or lakes. The surrounding community uses these lakes as a source of irrigation for dry land agriculture and for bathing livestock such as cattle and buffalo; for example, in Telaga Ploso and Telaga Palgading (Figure 7a). Lake Palgading is located in Giripurwo village and has a negative TPI value, but a relatively high TWI value. According to research by Budiharso and Andre (2023), who used the TWI value to indicate areas prone to flooding, a high value indicates that the area has high soil moisture and the potential for greater surface water flow when it rains. Lake Palgading is located in an upland river basin. The surrounding community uses the lake for mixed farming because it is far from settlements. The lake is 195 meters above sea level, with a perimeter of 248.58 m and a surface area of 8141.36 m^2.

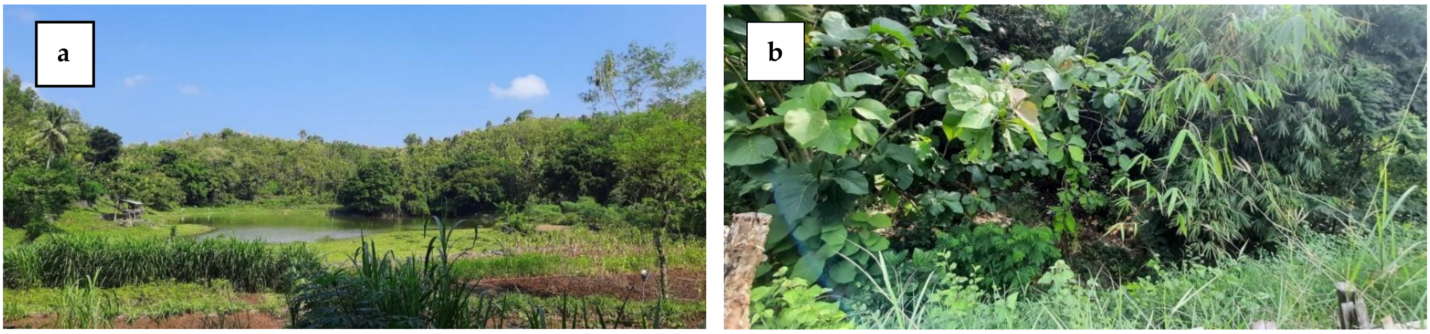


Figure 7. Examples of (a) an aqueous dolina –Palgading Lake and (b) a dry dolina Basin N25 field conditions.

Water dolines, also called lakes, indicate the integrity of the doline's base, which can retain water and facilitate the dissolution of limestone through hydration. Conversely, dolines classified as dry ones are commonly referred to as closed basins or, in fields, as ponds that have begun to recede. The formation of closed basins is attributed to vertical circulation, which establishes a conduit for water to penetrate through rock fissures, resulting in subsidence and the development of subterranean rivers. The receding of a lake is influenced by the dry season or the erosion of the watertight layer of the doline. This progression leads to water entry into cracks, drying out the lake bed. The transformation of a dry doline into an exokarst, manifesting as a polje, is exemplified by Telaga Dukuh, where the vast majority of the surface is dedicated to agricultural use. One notable example of a dry doline is the N25 grid basin in Giritirto Village, Purwosari District, as observed during the field survey. The N25 basin is classified as having a positive TPI and a very low TWI value, with an open slope terrain classification. The collapse of the basin has led to the proliferation of weeds and bamboo trees in the surrounding area. The basin's altitude is 232 meters above sea level, with a perimeter of 41.42 meters and an area of 104.24 square meters, as shown in Figure 7b. The doline in Purwosari District has been identified as having significant groundwater storage potential; therefore, mitigating drought risk in the area is imperative.

The Gunung Sewu karst area also has a high diversity of flora and fauna, with different species of plants and animals dependent on the karst environment. The ecosystem around the doline supports various types of vegetation that play a role in maintaining soil stability and slowing down the erosion process. Endemic species, such as rare plants and typical karst fauna, are essential for maintaining the ecological balance. Therefore, the conservation of the karst land in this area is vital for preserving the continuity of flora, fauna and natural processes, including the sustainability of the distribution of the doline itself.

3.5. Dolina morphometry

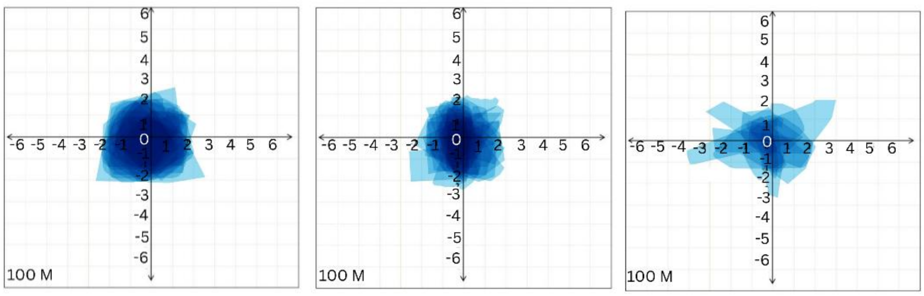
Dolinas in the Purwosari sub-district have different shapes and sizes in terms of perimeter, area and volume. The dolina in Purwosari subdistrict has a U-shaped valley with an average perimeter of 310 m. With the largest average size (5525.97 m^2) and the most significant volume (47779.12 m^3), it is located in a U-shaped valley terrain form (Table 6). There are few dolina in shallow valley terrain, but since the landscape remains a basin, such a shape can also accelerate dissolution and increase the size of the valley. In general, the size of the dolina is associated with the terrain form: the lower and deeper the basin, the larger the dolina size. The size of the dolina also depends on its type. A watery dolina will affect its volume due to rainfall, which will accelerate the dissolution process and thus increase the volume of the dolina. Dry dolinas have a size that tends to be small because they correspond to the classification of sloping terrain. The incoming water will go to the lower area and disappear below the surface.

Morphometry is the measurement and mathematical analysis of the configuration of the earth's surface and the shape and dimensions of the landscape (Herrmann & Bucksch (2014). The shape of the dolina is produced by observing its length and width using a cartesian diagram. A round dolina has a ratio of approximately 1:1; an oval dolina one of roughly 2:1; while an irregularly shaped dolina has a ratio of 1:1 to 2:1. The circumference of the dolina in meters is calculated using the measure in the ArcMap application. The dolina area is based on geometry calculated in ArcMap in units of m^2, while the volume is computed using Arcscene software, and its surface volume tool in units of m^3.

According to the results of previous research (Damayanti & Diah, 2018), there are three types of dolina shapes in Purwosari Subdistrict: round, oval and irregular. 16 (37.21%) dolina in Purwosari Subdistrict are round; 18 (41.86%) oval; and nine (20.93%) irregular. Dolina in the Purwosari Subdistrict are predominantly scattered in the plain area, with 12 such examples (27.91%). They are also scattered in the canyon terrain, with 11 (25.58%) cases of thgese. Oval dolina dominate the study area. They have an excellent ratio of length to width. In its development, this type of dolina will change into an irregular shape due to active karstification or dissolution. A round dolina has the potential for subsidence to form a cave hole if it continues to be karstified. Irregular dolines will develop into uvula-shaped exokarsts or join several dolines. Due to the dissolution process, the shape of the dolina is likely to change more rapidly when its conditions are watery. Meanwhile, doline shapes with dry doline characteristics will tend to remain fixed. An illustration of the dolina form is shown in Figure 8.

Table 7. Average dolina size by terrain shape.

Terrain Shape	Average Perimeter (m)	Area (m^2)	Volume (m^3)	Type of dolina	Total	Percentage (%)
Canyon	282,3	5314,3	21297,6	Watery	11,0	25,6
Shallow valley	189,2	2234,1	19437,2	Watery	4,0	9,3
Drainage pla-teau	183,2	4445,7	31400,4	Watery	2,0	4,7
U-shaped valley	310,1	5526,0	47779,1	Watery	5,0	11,6
Plain	181,9	2398,6	9325,0	Watery	12,0	27,9
Open slope	204,1	3850,7	72367,5	Dry	5,0	11,6
Upper slope	101,3	642,7	942,0	Dry	2,0	4,7
Hills	50,7	321,4	471,0	Dry	2,0	4,7
Hilltop	-	-	-		0,0	0,0



(a) Round dolina **(b)** Oval dolina **(c)** Irregular dolina

Figure 8. Dolina shape.

This research has made an important contribution to developing the fields of geography, geomorphology and hydrology, especially in the context of karst research in Indonesia. The methodological approach used in the study can be adopted in further studies on karst areas in Indonesia and others worldwide. By combining perimeter, area and dolina volume analysis, we can develop a more comprehensive understanding of the heterogeneous nature of the study area. These three measures complement each other and provide a richer perspective on the area's topographic variations and geomorphic processes.

The study is, however, subject to certain limitations, including the morphometric measurement. The morphometric analysis of dolines in the study was limited to the parameters above (perimeter, area, volume and shape), while other factors, such as weathering rates or more complex long-term geomorphological activities, were not thoroughly examined. Further research is necessary to quantify the changes in doline morphology over time. A more sophisticated hydrological model needs to be developed that relies on TWI and considers seasonal rainfall, surface water flow patterns, and interactions with underground river systems. The resulting doline typology should be discussed in terms of its proximity to hydrogeological features and its impact on underground vulnerability, as is the case in Ferreira *et al*. (2023).

4. Conclusion

The pattern of dolina distribution in the study area forms is clustered. Geological structures in the form of faults and fractures influence this characteristic. The topographic position of the dolina is dominated by low topography or basins, as the lowest area will facilitate the dissolution process to form a basin. The wetness index of dolina is dominated by a low classification. Karst hydrological conditions generally have a multi-basinal drainage pattern, or drainage that disappears into the subsurface. There are two types of dolina with TPI and TWI value categories in the study area: pond-shaped aqueous dolina, and basin-shaped dry ones. The findings reveal that dolines in the Purwosari Subdistrict have significant underground water storage potential, making them crucial for mitigating regional drought risks.

The size of the dolina in the study area is influenced by the U-shaped shape of the valley terrain, with forms forms divided into round, oval and irregular types. The oval dolina is the dominating type in the study area. This dolina shape will later develop into an irregular one due to karstification or dissolution. As dolines can evolve, dynamic mapping that monitors their shape changes as karstification occurs will provide deeper insights into the evolution of karst landscapes.

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Conflict of interest

All authors declare that they have no conflicts of interest.

Data availability

Data is available upon Request.

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