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Front cover photography: After a major storm, the carbonate Nullarbor Plain was flooded due to its impermeable layer of clay (photograph: Matej Lipar).
Fotografija na naslovnici: Po močnejši nevihti je bila sicer karbonatna ravnina Nullarbor poplavljena zaradi nepropustne plasti gline (fotografija: Matej Lipar).

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EXTENT AND SPATIAL DISTRIBUTION OF KARST IN SLOVENIA

Petra Gostinčar, Uroš Stepišnik

A doline in the dolomite karst at Dovce, Rakek.

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Petra Gostinčar[1], Uroš Stepišnik[2]

Extent and spatial distribution of karst in Slovenia

ABSTRACT: This study investigates the spatial distribution of karst in Slovenia using advanced GIS technologies and accurate lithology, hydrology, and digital relief data. Previous approaches led to an incomplete understanding of karst distribution, as they focused on carbonate lithologies and surface features. Our integrated two-step identification method, involving GIS layer overlays and manual review of lithology data, resulted in a comprehensive digital spatial database. We found that karst covers 49.7% of Slovenia's total area, with a diverse range of associated lithologies. This research has important implications for managing and protecting karst aquifers, forest planning, agricultural subsidies, and glacial geomorphology studies, and enables further processing and enhancement by the karst research community.

KEY WORDS: geomorphology, karst, GIS technology, lithology, classification of karst

Obseg in prostorska porazdelitev krasa v Sloveniji

POVZETEK: Ta raziskava preučuje prostorsko razporeditev krasa v Sloveniji z uporabo naprednih tehnologij GIS ter natančnih litoloških, hidroloških in digitalnih podatkov o reliefu. Dosedanji pristopi so vodili k nepopolnemu razumevanju razširjenosti krasa, saj so se osredotočali na karbonatno litologijo in značilnosti površja. Naša integrirana dvostopenjska metoda identifikacije, ki vključuje prekrivanje slojev GIS in ročni pregled litoloških podatkov, je privedla do celovite digitalne prostorske baze podatkov. Ugotovili smo, da kras pokriva 49,7 % celotnega ozemlja Slovenije, z raznoliko paleto pripadajočih litologij. Ta raziskava ima pomembne implikacije za upravljanje in varovanje kraških vodonosnikov, načrtovanje gozdov, kmetijske subvencije in ledeniške geomorfološke študije ter omogoča nadaljnjo obdelavo in nadgradnjo s strani krasoslovcev.

KLJUČNE BESEDE: geomorfologija, kras, GIS tehnologija, litologija, klasifikacija krasa

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1 Introduction

Karst is a unique geomorphic system characterized by subsurface water flows and is classified in the literature as a subcategory of fluvial geomorphic system (Sweeting 1973; Bögli 1980; White 1988; Ford and Williams 2007). This system is primarily governed by chemical denudation, a surface process that involves chemical weathering of bedrock, particularly through congruent dissolution. Dissolution plays a fundamental role in karst formation, and three basic conditions must be met for its development: soluble rock, water, and the establishment of subsurface drainage (Ford and Williams 2007). Dissolution not only occurs at the surface, but also extends deep into the subsurface, resulting in the formation of dissolution-created channels with high effective permeability (White 2002). These channels are formed from intergranular pores and fractures and allow water to percolate predominantly through the subsurface. In karst systems, aggradation zones are minimal in extent and limited to specific areas such as vadose zone caves and river channels. The dominance of chemical denudation and the absence of aggradation contribute to the characteristic stony surface and diverse landforms unique to this combination of geomorphologic processes (Ford and Williams 2007; Stepišnik 2020; De Waele and Gutiérrez 2022).

Karst, a subtype of fluvial geomorphologic systems characterized by a predominance of subsurface water drainage (Bögli 1980; White 1988), is often defined by the presence of specific landforms rather than by its hydrologic characteristics. Karst areas are usually identified by the presence of dolines or similar karst depressions and cave entrances (Sweeting 1973; Ford and Williams 2007; Sauro 2012) and are often delineated by the absence of a surface drainage network (White 2002). However, this method of classification is problematic because surface form depends on a variety of geomorphologic processes beyond chemical denudation. Consequently, some karst areas have landforms that are not characteristic of karst, such as fluviokarst (Komac 2004; Stepišnik 2021), contact karst (Mihevc 1994; Gams 1995; 2001), and glaciokarst (Smart 1986; Žebre and Stepišnik 2015a; 2015b). Furthermore, the absence of a surface river network does not generally apply to all karst areas; fluviokarst and shallow karst are characterized by the presence of permanent or intermittent surface waters and lakes (Gunn 2004; Stepišnik 2017). Despite these differences, all karst geomorphic systems share common characteristics: soluble bedrock, the presence of water that is not impeded by aridity or cryosphere, and at least some development of subsurface drainage in the karst type of aquifer (Ford and Williams 2007).

The Slovenian karst region occupies an important place in the history of karstology, as this science originated here and has been intensively researched ever since. This research focused on determining the spatial extent of carbonate rocks and karst in Slovenia through various methods. These methods can be categorized based on their approach: identification of karst surface features, distribution of cave entrances, absence of surface drainage networks, and extent of carbonate rocks. Researchers have identified a number of karst surface features, such as dolines (Melik 1935; 1963; Šerko 1947), snow kettles (Melik 1935; 1963; Šerko 1947), and other large karst depressions (Gams 1965; Habič 1982; Novak 1993; Komac and Urbanc 2013a; 2013b; 2016; 2017). They have also studied the spatial distribution of cave entrances (Habič 1982; Novak 1993; Komac and Urbanc 2013a; 2013b; 2016; 2017) to determine the extent of karst in Slovenia. In addition to these features, researchers have considered the absence of a surface drainage network (Šerko 1947; Gams 1965; Habič 1982; Novak 1993; Komac and Urbanc 2013a; 2013b; 2016; 2017) and the extent of carbonate rocks (Melik 1935; 1963; Gams 1974; 2003; Habič 1982; Novak 1993; Komac and Urbanc 2013a; 2013b; 2016; 2017) in defining karst areas. Earlier methods focused mainly on deep karst, which is characterized by surface dissection with karst depressions and the absence of a surface drainage network. However, these methods often excluded other karst geomorphic environments where surface transformations occur by other geomorphic processes. These environments include shallow karst, fluviokarst, glaciokarst, and contact karst (Stepišnik 2020).

Karst distribution inventories are essential for a comprehensive understanding, effective management and sustainable development of karst landscapes. Their importance cuts across all disciplines, influencing hydrogeological research, geomorphological studies, biodiversity conservation efforts, engineering projects and environmental impact assessments. Ongoing efforts to document and update karst inventories on either regional (e.g. Gao, Alexander and Tipping 2005; Petrič et al. 2020a; 2020b), national (e.g. Temovski 2012; Asanidze et al. 2019; Sun et al. 2020), or even global level (e.g. Ford and Williams 2007; Chen et al. 2017; Goldscheider et al. 2020) are essential for informed decision-making, promoting responsible land use practises and ensuring the long-term conservation of these unique and valuable landscapes. Studies on karst distribution usually follow a geology-based approach, where areas with potential for karst development are delineated by compiling areas of soluble rocks from geological maps. In this paper, we have adopted a similar geology-based approach.

The aim of the study is to determine the spatial extent and distribution of karst in Slovenia. For this purpose, the lithostratigraphic map of Slovenia at a scale of 1:250,000 is used as a basis, and other relevant data sources are used as supplementary material (e.g. morphology of the doline surface, location of cave entrances, absence of a surface drainage network, morphology of the karst surface, etc.).

2 Previous research on the extent of karst in Slovenia

So far, various studies have been published on the distribution of karst in Slovenia. The authors use different classifications to categorise the carbonate rocks. In most cases, limestone and dolomite are represented by separate categories, while the descriptions of the impure carbonate rocks vary. Some authors refer to these rocks as »impure carbonate rocks«, while others describe them as »clastic carbonate rocks«. Furthermore, in most cases Holocene carbonate gravel has not been added to the summary values for carbonate rocks.

In addition, most authors dealing with the analysis of the distribution of the karst surface were limited to the classification of the surface by lithological type (e.g. limestone, dolomite). Therefore, the extent of carbonate rocks in Slovenia was often mistakenly considered to be synonymous with the distribution of the karst surface distribution in Slovenia. In this paper, we focus our review of previous research on the sources that define karst as a relief type and not only the extent of carbonate rocks.

The first references in the literature defining the extent of karst in Slovenia were provided by Melik (1935). In his research, he describes different karst areas within the ethnic Slovenian boundaries. In his publication, he does not specify the exact extent of the Slovenian karst, but they can be reconstructed on the basis of the attached map. He made a map of the karst areas on the basis of the spatial distribution of dolines and snow kettles, which he most probably identified from topographic maps available at the time. The descriptions of karst areas and the extent of karst in Slovenia were also provided in his following publications (e.g. Melik 1963). According to Melik (1935; 1963), karst covers 28% of the present-day area of Slovenia. In his classification of karst, he used the division of karst according to Cvijić (1893; 1924) into holokarst or perfect karst and merokarst or incomplete karst.

More detailed estimates of the extent of karst in Slovenia were published by Šerko (1947). Based on an analysis of maps at a scale of 1:100,000, he estimated the density of the surface drainage network and the presence of karst landforms such as dolines, snow kettles, uvalas, and poljes. He divided the karst in Slovenia into the Dinaric karst, the Alpine karst and the karst in small isolated areas in the Savinja Alps and in northern and southern Slovenia, based on the location of geomorphological environments to which he attributed common morphogenesis and morphodynamics. He did not quantify the extent of karst in Slovenia, but only depicted it on maps. According to his cartographic data, the extent of karst in Slovenia is 30%.

Gams (1965) defines the extent of karst using an approach similar to that of Šerko (1947) taking into account surface forms, especially karst relief depressions and the density of the surface drainage network. He also points out the shortcomings of his estimates, since it is difficult to assess the extent of karst in dolomitic karst areas and on slopes within the alpine highlands because of the lack of typical karst landforms or karst-specific drainage network patterns. He estimates that the proportion of karst in Slovenia is somewhere between 1/3 and 1/2. Gams (1965) also offers a regional classification of karst in his publication, largely adopted from Šerko (1947), dividing it into the karst of the Julian Alps and Kamnik-Savinja Alps, the karst of the Karawanks, the isolated karst of the pre-Alps and Pannonian area, and the karst of the Dinaric Mountains.

Habič (1969) points out that there are no precise data on the extent of karst in Slovenia, and at the same time refers to the fact that karst covers 1/3 of the territory, which corresponds to Gams (1965). In his publication he gives a hydrographic regionalization in which the karst is divided into Alpine karst, Dinaric karst and Isolated karst on the basis of geological, hydrological and geomorphological features, which was largely adopted from Šerko (1947).

Gams (1972) states that the proportion of karst in Slovenia is about 1/3. He did not specify a method for determining the proportion of karst, but probably referred to earlier publications (Gams 1965; Habič 1969). In this publication he presents a new regionalization of karst, based mainly on Šerko's (1947) division of karst. Gams (1972) concludes that karst in Slovenia is primarily located on carbonate rocks.

Gams (1974), in a comprehensive overview of karst, describes in detail the various karst areas in Slovenia and other parts of the Dinaric Mountains. He states that the proportion of carbonate rocks in Slovenia is 43%. The proportion of karst associated mainly with carbonate rocks is somewhat lower.

Habič (1982), in his interpretation of the extent of karst in Slovenia, considered not only hydrological, morphographic, and geological characteristics, but also the distribution of speleological objects. He estimated that the extent of karst in Slovenia is about 44%. Moreover, he characterised karst on the basis of hydrological and lithological characteristics and not only on the basis of spatial distribution, as in previous literature (Gams 1965; 1972; 1974; Šerko 1947). It is divided into deep karst, partial karst, a combination of deep and partial karst, and karst with developed intergranular conductivity. About 31% of the area of Slovenia is attributed to deep karst on limestones, while the area of the other karst types is about 13%.

The estimated proportion of karst identified by Šušteršič (1991) in the overview map of karst in Slovenia is about 50%. He classified karst on the basis of location and hydrological function in an approach similar to Cvijić (1924), Šerko (1947) and Habič (1982). He divides it into alpine karst, low and high Dinaric karst, and isolated and incomplete pre-alpine karst. In his typification he does not define the poljes as karst areas.

Novak (1993) states that karst covers an area of 9,000 km^2, which is 44.4% of the area of Slovenia. Like his predecessors (Gams 1965; 1972; Habič 1969; 1982; Šerko 1947; Šušteršič 1991), he characterises karst according to its location and states that karst in Slovenia was formed in limestones and dolomites dating from the Triassic to the Oligocene and in Pleistocene conglomerates.

In the Geographical Atlas of Slovenia (Fridl et al. 1998) two general maps of the karst in Slovenia are published at a scale of 1:750,000. On a general map of the karst area, Mihevc (1998) divided the karst into Alpine, Pre-Alpine, High-Dinaric and Low-Dinaric karst and marked many karst landforms, e.g. karst plateaus, plains, poljes, large collapse dolines, caves, blind valleys and others. The estimated karst area in Slovenia is 50.2% on his map (Mihevc 1998). In the same publication, Kranjc (1998) shows two types of karst on a map of karst waters, namely on limestone and dolomite. On both types of karst he marks karst poljes or »flood-prone areas on karst« as he writes on the map. The estimated karst area in Slovenia is 45% on his map.

Gabrovec and Hrvatin (1998; 2016) published a map of genetic relief types, on which they also determined the areas of limestone and dolomite karst relief. According to their 1:750.000 (1998) and 1:1,000,000 (2016) scale map, limestone karst covers 25% of the area in Slovenia and dolomite karst covers 14% of the area. Altogether, the karst covers 39% of Slovenia. The sources do not indicate what data they used to determine the extent of karst relief. The authors describe that in some areas there is an interweaving of different geomorphic systems. Therefore, poljes are not counted as karst genetic relief types, but as an accumulative fluvial-denudational relief. High-mountain regions where the glacial genetic relief type occurs are designated as glacial, regardless of the bedrock.

The most frequently cited figure for the proportion of karst was given by Gams (2003) in a comprehensive regional overview of karst areas in Slovenia. Despite a detailed overview of all karst areas, he quotes an old data for the proportion of karst, where it is estimated at 43%–35% on limestone, and 8% on dolomite (Gams 1974).

Some recent interpretations of the extent of karst were made by Komac and Urbanc (2013b). They summarise the proportion of karst according to Gams (1974). In their GIS-based karst classification, they used the method of Habič (1982), dividing karst areas into two categories based on the spatial distribution of carbonate rocks, the presence of dolines and cave entrances, and the absence of a surface drainage network. Intensively karstified areas cover an estimated 24% of Slovenia, and less intensively karstified areas 21%.

Subsequent studies by Komac and Urbanc (2013b) indicate that the proportion of karst in Slovenia is 45.6%. They determined the proportion based the spatial distribution of carbonate rocks on geological map of Slovenia in scale 1:250,000 (Buser 2010a). Based on the concurrent presence of caves, dolines and surface water streams, they determined that intensively karstified areas make up 31.8% of the Slovenian territory. All other areas on carbonate rocks, accounting for 13.7% of Slovenia, were classified as potentially karstified. They found that limestone is the predominant rock type subject to karstification, but that dolomite is also common in intensively karstified areas. In areas where dolomite is the predominant rock, the degree of karstification is lower as dolomite is less prone to karstification. In their classification of karst, they have excluded areas covered by poljes and areas where karst is overlain by younger sediments. The authors have also published comparable data in some other publications (Komac and Urbanc 2016; 2017).

As part of the World Karst Aquifer Mapping project, the World Karst Aquifer Map (WOKAM; Chen et al. 2017) was created using the Global Lithological Map (GLiM) (Hartmann and Moosdorf 2012) and other relevant data sources (e.g. karst water sources, cave locations, etc.). For WOKAM, the following main mapping units were assessed: carbonate rocks (sedimentary or metamorphic), evaporites, other sedimentary formations, and other metamorphic rocks and igneous rocks. In Slovenia, karst outcrops account for 49.5% of the surface.

3 Materials and methods

The spatial analysis we used to determine the distribution of karst in Slovenia was carried out using two approaches. A vector map of rock types for the entire country was used as a basis. The first approach represented an attempt to fully quantify and objectively determine the karst areas by spatially overlaying the following data: the presence of dolines, cave entrances and the surface river network. The second approach was a manual inspection of the rock type polygon dataset and a manual determination of the presence of karst and the type of karst. For the manual analysis, we relied on the results of the analysis of the first approach for decision-making and reviewed the spatial data considered both spatially (i.e. on the map; Figure 1) and in the associated attribute table. ESRI ArcGISPro 3.0.0 software was used to perform the spatial analyses.

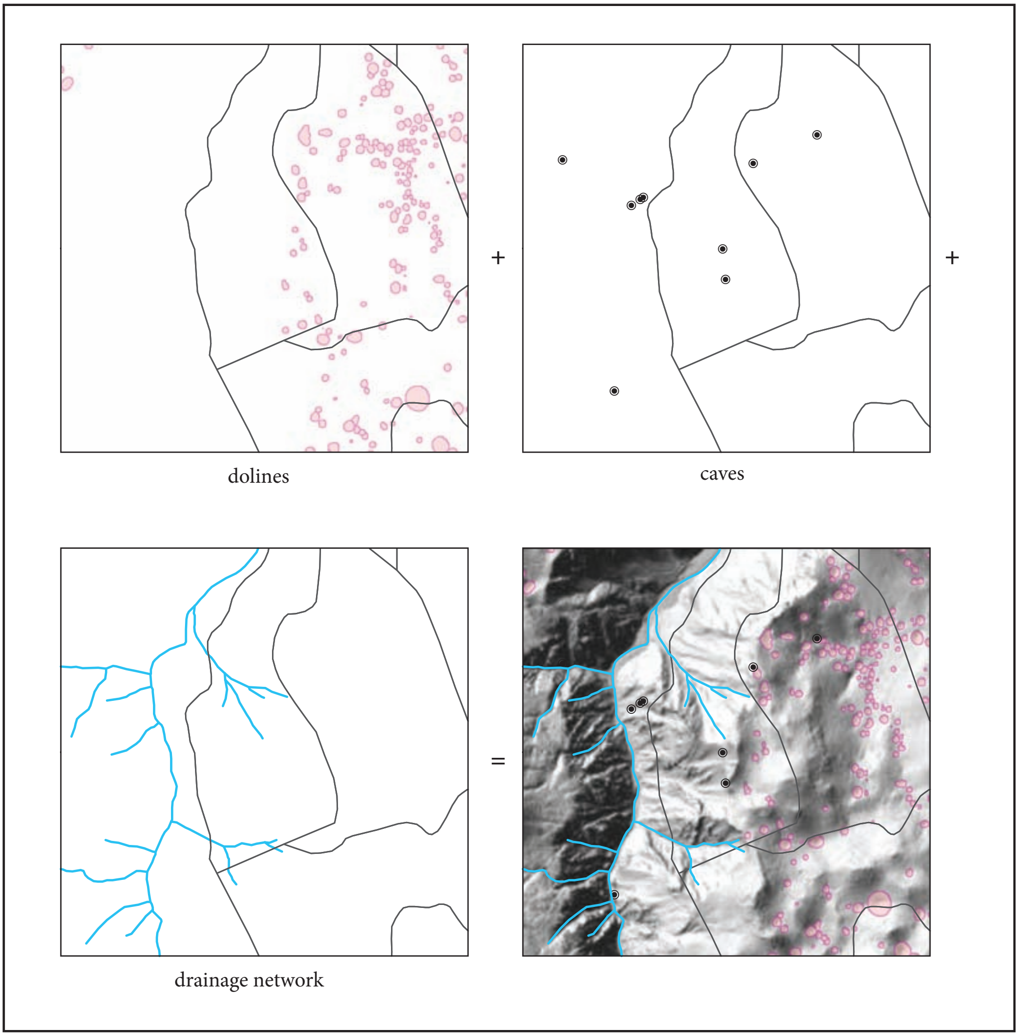


Figure 1: Schematic representation of the steps in the spatial analysis of the lithological units.

3.1 Data sources

As a spatial data source for the surface lithology a vector map of rock types in Slovenia was used (Zemljevid tipov kamnin 2012). This data source was based on the lithostratigraphic map of Slovenia (Litostratigrafska karta Slovenije 2011), which was primarily based on 1:25,000 vectorized geological maps of Slovenia. The data on surface lithology was prepared at a scale of 1:100,000 and is currently the only available and updated lithologic map at this scale that does not contain missing or inconsistent data on the contacts of the individual sheets of the Basic geological map of Slovenia. It is considered more detailed than the 1:250,000 scale geologic map of Slovenia by Buser (2010b), because it is not as generalised and provides data directly from the base geologic maps of Slovenia. The lithological map of Slovenia consists of 12,635 polygon features divided into 25 lithostratigraphic units (Perko, Hrvatin and Ciglič 2015; Hrvatin 2016). All polygons within the layer have a reference to the Basic geological map of Slovenia data: the age and the description of the lithological unit. The database was provided by the authors in a vector format (.shp) and could be analysed in a GIS environment. The data were topologically ordered: all overlapping polygons and all holes in the data set were removed. Such data can then be used for spatial analyses. Using this data source, the occurrence of carbonate rocks in Slovenia was calculated (Gostinčar 2016) and used as a data source for this study. Each polygon contained an attribute defining whether it was classified as carbonate rock (limestone, mixed limestone-dolomite bedrock, dolomite, clastic carbonate rock) or non-carbonate rock.

Dolines are small to medium sized closed depressions and are the most numerous karst feature in Slovenia. The outlines of dolines in Slovenia from Mihevc and Mihevc (2021) were used. A georeferenced catalogue of the dolines is freely available at https://dolines.org/ (polygon, .shp). Dolines were determined using a trained algorithm on the Lidar DEM of Slovenia. The catalogue contains 471,192 dolines in all Slovenian karst areas (Mihevc and Mihevc 2021).

The digital vector layer (point, .shp) of the Cave Register of the Cave Association of Slovenia and the Karst Research Institute ZRC SAZU, as of March 2022, was used to locate the caves. In addition to the coordinates of the cave entrances, the cave register also contains other attributes (e.g. length and depth of the cave, year of discovery, etc.). Cave locations vary in terms of accuracy. The locations of some caves were determined using hand-held GPS, medium-scale maps (e.g. 1:25,000, 1:50,000), while some more recent data are based on lidar data. The data layer we used contained 14,695 caves.

The vector line layer (.shp) of surface waters in Slovenia from the Water Atlas was used as a data source for the surface water network (Slovenian Environment Agency 2022). It is considered the most detailed data source for the surface drainage network in Slovenia; it is based on watercourses marked on topographic maps in 1:5,000 scale, which had been digitised and georeferenced using the national Lidar DEM.

As a source for DEM, we used high-resolution lidar data DEM obtained from the Slovenian national aerial laser scanning conducted in the period between 2011 and 2015 (Triglav Čekada and Bric 2015; Atlas okolja 2022 – http://gis.arso.gov.si/atlasokolja/), which has been widely used for morphographic analyses of the karst surface in recent research, especially in geomorphometric studies of dolines (e.g. Čeru, Šegina and Gosar 2017; Grlj 2021; Mihevc and Mihevc 2021; Ciglič, Čonč and Breg Valjavec 2022). A DEM with a cell resolution of one meter was used. To visualise the high-resolution digital elevation model, the following visualisations from DEM were used to represent the relief: hillshade and sky view factor (Kokalj and Hesse 2017).

3.2 Spatial analysis

To determine whether karst occurs in a particular lithological unit, we added information about the spatial presence of dolines, caves, or a surface drainage network to each polygon of the lithologic map. We used the *Select by Location* function for each of the datasets to determine the polygons of the lithologic layer on which any of the three aforementioned objects are located. Three attributes were assigned to the attribute table of lithologic units: *cave*, *doline*, and *water*, having the following values: »1«: yes (cave / doline / water is present) or »0«: no (cave / doline / water is not present).

The presence of the surface water network could not be fully used as an indicator of the presence or absence of karst. On the karst surface, the surface drainage network is often absent, but in many places, water flows on top of karst – e.g. on fluviokarst, shallow karst, contact karst, etc. Therefore, we were able to calculate the higher probability of occurrence of karst on a single lithologic unit using only the sum of the attribute values for caves and dolines. For all polygons where the value of the attributes *cave* and *doline* is equal to 1, we found that the occurrence of karst is more likely there. In this way, a total of 373 polygons with an area of 1,544 km^2 (7.6% of the total area) were identified as possible karst areas.

Either because of the specificity of individual data layers or because of errors in the data in a large part of the study area, the spatial accuracy of the data used for spatial analysis is insufficient. For example, due to the difference in scale between the lithologic map, which is based on the 1:100,000 scale geologic map, and the other data layers, which are based on more detailed analyses (e.g. lidar), the lithologic map is shown with an offset relative to other layers in at numerous locations (Figure 2 and 5). There were also significant differences between previously identified areas of carbonate rocks in Slovenia (Gostinčar 2016) and polygons representing potentially karstified areas (as indicated in the previous paragraph). Thus, dolines and cave entrances also occur in areas previously determined to be non-carbonate rocks (Gostinčar 2016), e.g. in areas with Quaternary alluvial deposits (e.g. poljes), covered karst, etc. However, we know from previous studies that karst can occur in areas where there is neither specific surface morphology, i.e. dolines, or cave entrances (e.g. Staut 2003; Knez, Mihevc and Slabe 2007; Knez and Slabe 2011).

3.3 Manual inspection

As mentioned above, only 373 polygons (7.6% of the total area of Slovenia) were defined as possible karst areas. These numbers differ strongly in comparison to the karst extent defined in previous studies (as described in chapter 2). Due to the complexity of determining the karst surface, we could therefore not rely only on selected quantitative indicators from selected spatial data, but had to use visual determination of karst occurrence for all polygons of the lithological layer. Therefore, all polygons of the lithological map (12,635 polygons in total) were assessed qualitatively, namely by visual inspection. For the visual inspection of the data, we used the results of the previously calculated spatial data on the potential presence of karst and the data contained in the lithological layer – the age and description of the lithological unit. As a basis for the data of the digital relief model, we used a lidar-derived DEM and shaded relief.

The following types of karst based on lithological properties were determined:

- **karst in limestone**: where limestone is indicated as the only or predominant lithology in the description of the geological map (e.g. nummulitic limestone, limestone with shells, massive limestone);

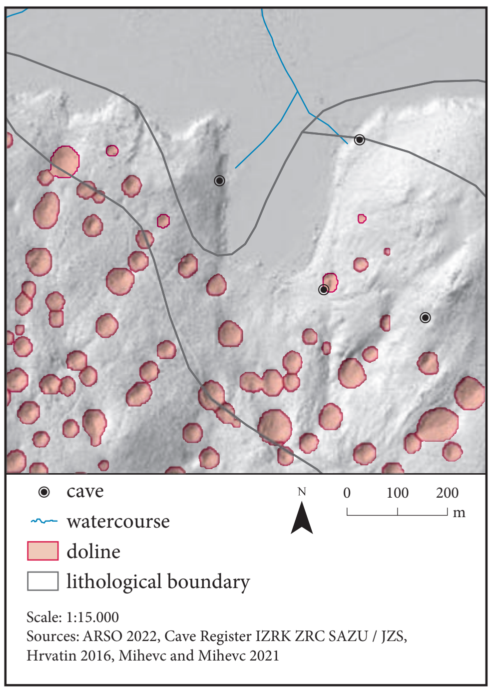


Figure 2: An example of an offset of the lithological map in relation to the other layers on the S margin of Cerknica Polje, resulting in a false spatial overlap of the layers.

- **karst in dolomite**: where dolomite is indicated as the only or predominant lithology in the description of the basic geological map (e.g. dolomite, grey dolomite, sometimes with chert, dolomite with limestone lenses);
- **karst in limestone and dolomite**: the description of the lithostratigraphic units mention both limestone and dolomite without indicating which of the lithologies predominates (e.g. grey limestone and dolomite, white limestone and granular dolomite);
- **karst in clastic carbonate rocks**: lithostratigraphic units of pre-Holocene cemented clastic carbonate rocks (e.g. insets of banded limestone between Lower Carboniferous clastites, Oligocene limestone breccia, limestone breccia);
- **carbonate till-covered karst**: covered karst, where glacial carbonate till is deposited on the surface (e.g. moraine, older consolidated moraine);
- **karst in flysch**: where the predominant lithology is flysch or sedimentary rock characterised by alternating layers of fine grained and coarse grained sedimentary rock (e.g. flysch, breccia deposits, conglomerates and calcareous sandstone in flysch);
- **fine grained sediment-covered karst**: covered karst, where fine grained sediments are deposited over the karst surface (e.g. bauxite clay, alluvium: predominantly clay and sand);
- **carbonate gravel-covered karst**: covered karst, where unconsolidated gravel is deposited (e.g. slope gravel, gravel, partially consolidated slope breccia).

For each polygon, the area was calculated. In conducting the visual inspection, we encountered many cases where there was a dilemma as to whether a particular lithology should be classified as karst or not.

Blind valleys are characteristic contact karst landforms. The inflow part, which usually consists of a fluvial part, usually forms on non-carbonate (non-karstic) lithologies, e.g. shale, sandstone, flysch. At the contact with carbonate rocks, a broader and shallower surface is covered by the non-carbonate alluvium overlying the deeper carbonate rocks. In terms of surface lithology, these areas were mapped as areas of Quaternary alluvium. During visual inspection, such polygons were cut into two parts – the tributary area formed on non-carbonate lithologies was defined as non-karst areas, while the lower parts covering the carbonate rocks were defined as karst (Figure 3).

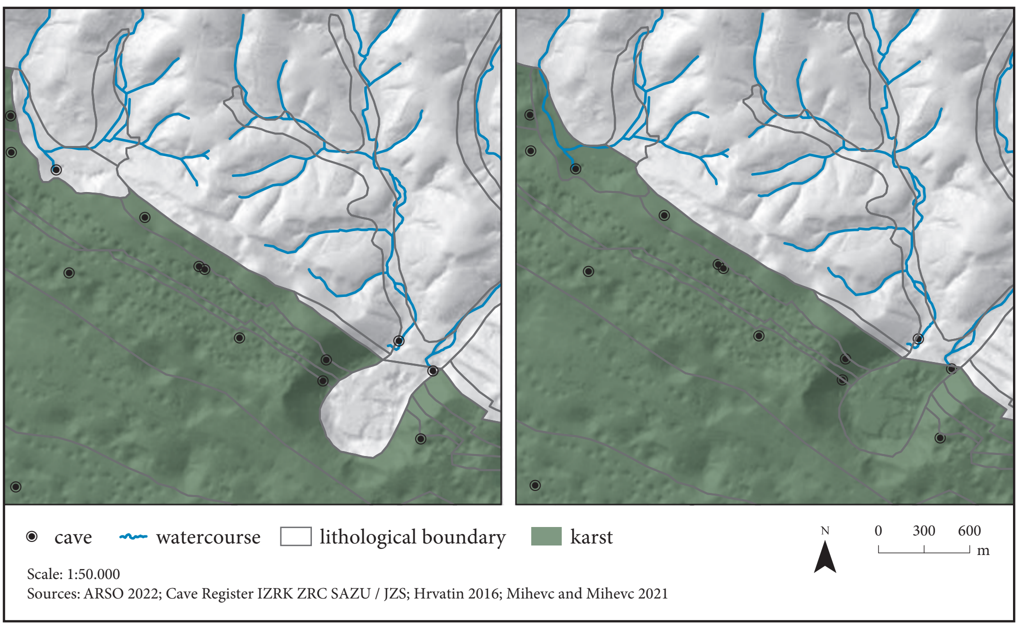


Figure 3: Example of a blind valley where the lithologic polygon has been cut to distinguish between the inflow area (non-karst area) and an outflow area (karst area). Left: polygons before cutting; right: polygons after cutting.

In Slovenia there are numerous areas where covered karst occurs. Some areas of corrosional plateaus in SE Slovenia and most poljes have Quaternary alluvial sediments deposited on the surface and are marked as such in the lithological map. Therefore, in determining the areas of alluvial deposits on the poljes, we used the locations of karst poljes according to Stepišnik (2021). A similar method was used in the area of the Kras Plateau and corrosional karst plateaus in the SE part of Slovenia, where a large part of the surface is covered with Plio-Quaternary sediments, e.g. terra rossa (Figure 4).

Fluviokarst areas are karst areas where the surface is subjected to severe mechanical weathering. Most often, this type of karst is present on dolomite bedrock, which is why dolomite karst is also used as a synonym for fluviokarst in the literature (Gabrovec 1994; 1995; Komac 2003; 2004; 2006; Gostinčar 2016). Fluviokarst environments are also common on impure limestones and in tectonically deformed areas (Roglić 1958; Gostinčar 2016; Stepišnik 2021). Fluviokarst environments are characteristic only of slopes on these rocks, where all precipitation does not drain vertically through the weathered mantle into the karst aquifer, but in some cases also drains superficially. Surface flows reshape the surface through erosion and accumulation processes. For this reason, identifying karst areas in fluvial karst regions is challenging because the surface does not have karst surface morphology but has landforms typical of fluvial areas. The delineation of the extent of this karst type was based on the extent of the lithological units. When karst, especially caves and dolines, were found in the flat areas of a lithological unit, the entire lithological unit was defined as a karst area, even if it contained only fluviokarst landforms.

A similar solution to that used in determining the extent of fluviokarst areas was also used in determining the extent of karst in high mountain environments. Karst slopes in high mountains are modified by the interaction of fluvial, nival, and glacial processes. These slopes generally do not have karst depressions, although they are karst areas with predominant subsurface water drainage. Therefore, when determining the extent of karst in the high mountainous areas, the lithological units were determined as karst if the same units had been identified as karst in other (non-mountainous) areas.

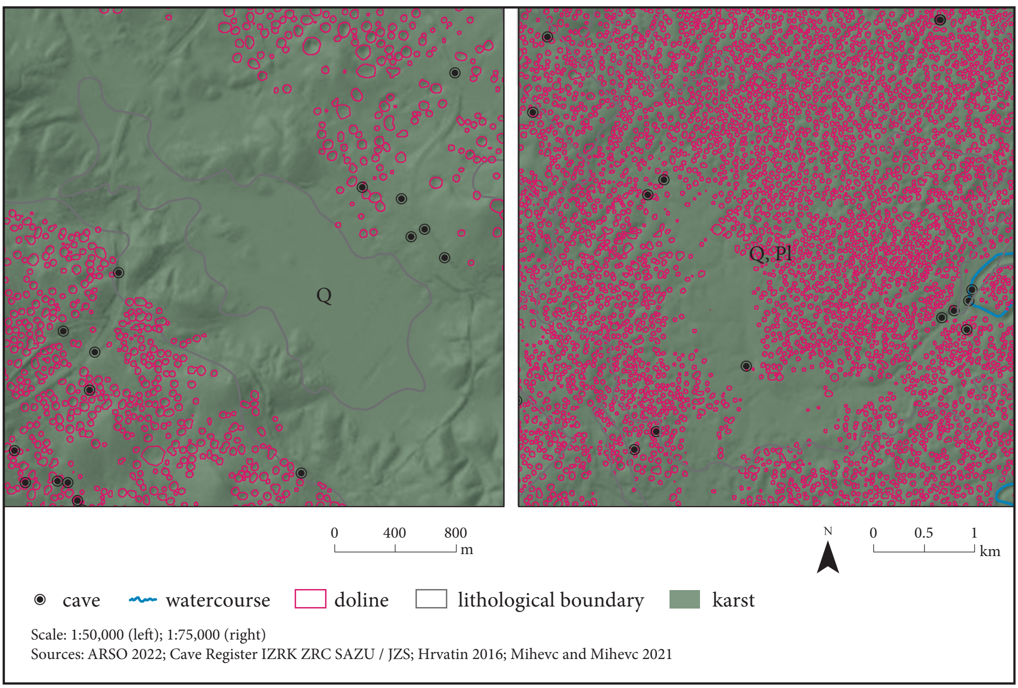


Figure 4: Examples of covered karst. Left: the Rakek–Unec Polje (lithology: Q alluvium – silt, clay, sand), right: doline-dissected karst of White Carniola (*Bela krajina*), covered with brown clay and terra rosa (Q, Pl).

The areas of carbonate conglomerates that make up part of the intermountain basins are also karst areas. In these lithological units, the extent of karst has been defined solely on the basis of surface formations, dolines and caves, and the absence of a surface river network. The lithological units that exhibited these features were defined as karst areas.

4 Results and discussion

A spatial database was created in the form of a polygon shape file (.shp) containing data on the occurrence of karst and the lithological type of karst for each of the 1:100,000 scale lithological polygons in Slovenia. With the help of a spatial database, we can calculate and map the distribution of karst in Slovenia very accurately.

So far, data layers on karst distribution in Slovenia were either created at a small scale and used only as overview maps (e.g. 1:750,000 and smaller), or the maps were produced before the creation of basic 1:100,000 scale geological maps for the territory of Slovenia (created in 1968–1998), they were not created using modern GIS technologies that allow the creation of accurate spatial data, or they were created at a smaller scale than the data layer presented in this article. Our data layer on karst distribution also includes areas with karst poljes, which many authors did not include in their studies, although karst poljes are one of the larger and more characteristic forms of the karst surface.

There are 12,734 polygons in the data layer – due to polygon cutting (as described in the methodology chapter), the number of polygons has increased compared to the initial layer of lithological units (Zemljevid tipov kamnin 2012). The polygons are divided into eight different karst types based on the lithology: karst in limestone, karst in limestone and dolomite, karst in dolomite, karst in clastic carbonate rocks, carbonate-gravel-covered karst, fine grained sediment-covered karst, carbonate till-covered karst, and karst in flysch.

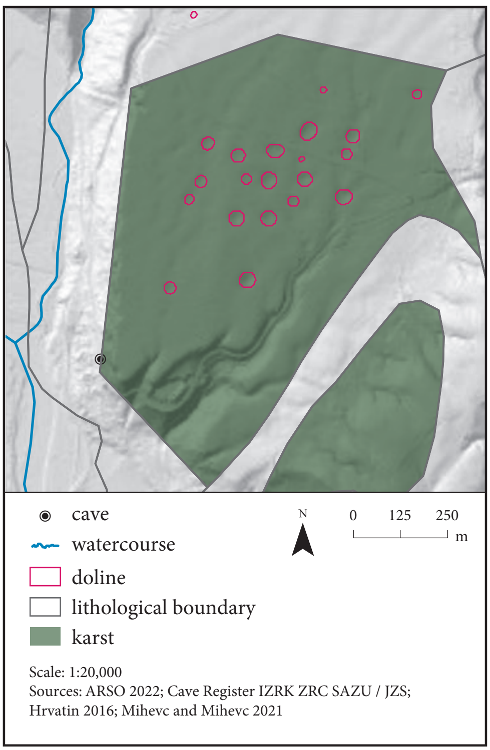


Figure 5: Conglomerate karst with typical circular depressions, indicating the presence of karst.

In identifying karst areas, only surface lithology and morphology were considered. Non-exposed outcrops of karstified rocks, such as karstified strata beneath surface, non-karstified surface strata (flysch megabeds; Placer et al. 2004) or karst in mines (e.g. Šarc et al. 2022), were not considered in our method.

The results of the spatial analysis show that karst occurs on 49.7% of the total area of Slovenia, i.e., about half of the country is karstified (Figure 6). The largest karst area in Slovenia is occupied by karst in limestone (24.6%), followed by karst in dolomite (12.4%) and karst in mixed lithology of limestone and dolomite (1.9%). Karst on relatively pure carbonate rocks occupies a total of 38.9% of the area of Slovenia. Karst in carbonate-clastic rocks has developed on 5.1% of the area. Other karst types in Slovenia, based on the lithology, are carbonate gravel-covered karst (2.5%), fine grained sediment-covered karst (2.0%), carbonate till-covered karst (0.8%) and karst in flysch (0.5%) (Table 1).

Analysis of lithological types shows that 50% of the total karst in Slovenia was formed in limestones, 25% in dolomites, and another 4% in mixed limestone-dolomite lithologies. Karst on carbonate rocks has developed on 78% of the karst areas in Slovenia, and as much as 22% of the total karst has developed in other lithologies (including unconsolidated carbonate sediments, such as gravel or glacial till). These values show the importance of an integrated approach to defining karst in Slovenia, because if we equate the extent of carbonate rocks and karst, we cannot identify more than one fifth of the karst area in Slovenia (Figure 8).

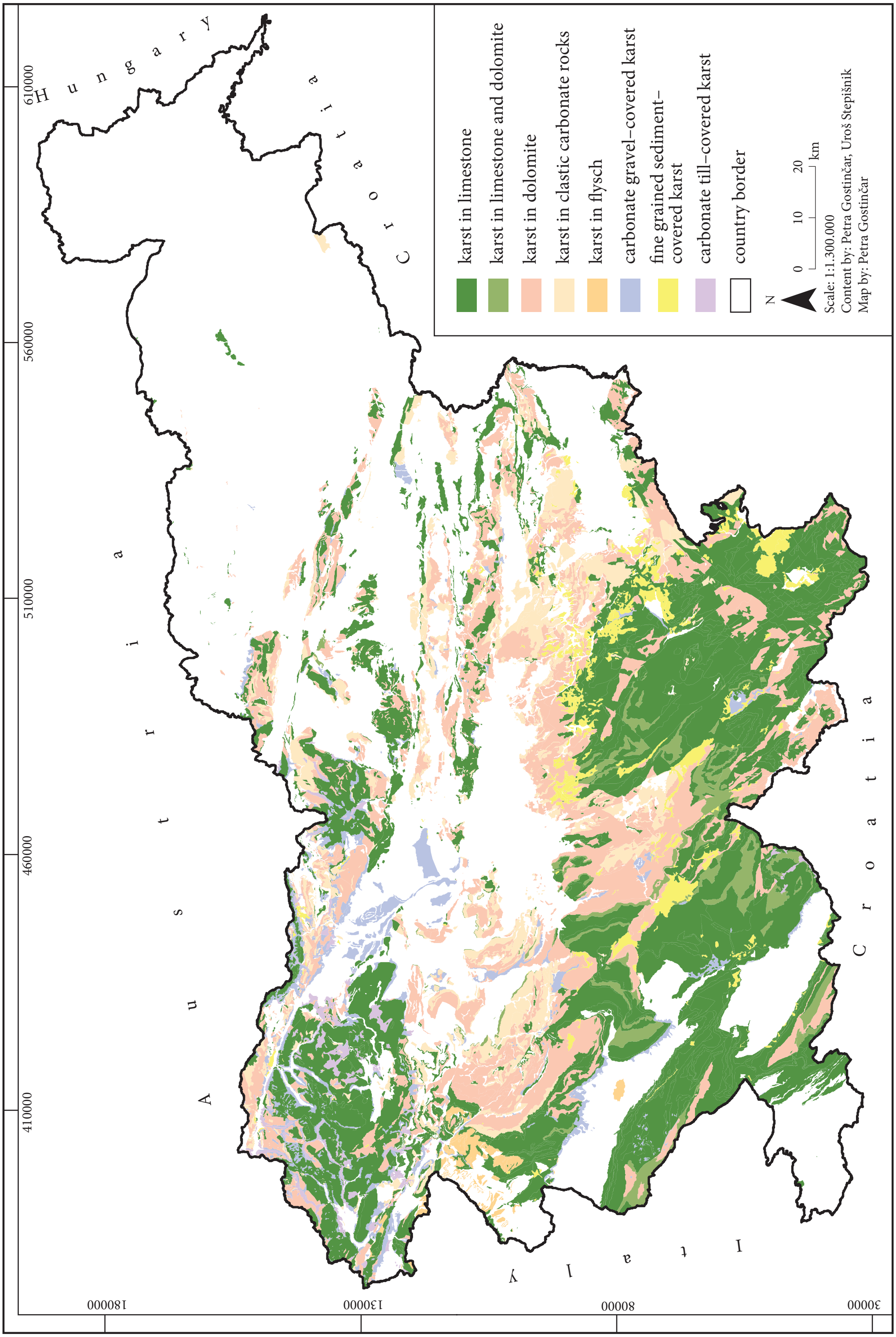
Our approach has allowed us to include a wide range of lithologies where karst occurs, which was not possible with other methods, even though these karst areas and features have been described in the literature. For example, conglomerate karst (Žlebnik 1978; Gabrovšek 2005; Kranjc 2005; Lipar and Ferk 2011; 2022), karst in flysch layers (Mihevc 1992; Staut 2003; Knez and Slabe 2011; Božič 2021), karst in breccias (Knez, Mihevc and Slabe 2007), covered karst (Knez and Slabe 2007; Gams, Otoničar and Slabe 2011).

Karst in limestone occurs in larger compact areas in the Karst Plateau, Podgorje Karst Plateau and Podgrad Lowland, where it is formed in combination with dolomite karst. Limestone karst is also found in the compacted areas of the Javorniki Hills, the Upper Pivka River, and Snežnik Plateau, where it partly alternates with dolomite. The high Dinaric karst plateaus of the Trnovo Forest Plateau (*Trnovski gozd*), Mount Nanos, the Hrušica Plateau, and the Menišija Plateau, as well as the southwestern part of the Gotenica Mountains (*Goteniška gora*), the Big Mountains (*Velika gora*), the Little Mountains (*Mala gora*), the Little Kočevje Mountains (*Kočevska Mala gora*), the Kočevje Rog Plateau (*Kočevski Rog*), the Mount Poljane (*Poljanska gora*), and Dry Carniola (*Suha krajina*). Limestone karst is present in White Carniola (*Bela krajina*), where it mainly alternates with fine grained sediment-covered karst. In the high mountain regions of the Julian Alps and the Kamnik–Savinja Alps, limestone karst mainly alternates with dolomite karst and carbonate till-covered karst. **Karst in dolomite** is the predominant karst type in the Idrija–Cerkno Hills

Table 1: Spatial distribution of karst in Slovenia based on lithology.

Karst type based on lithology	Number of polygons	Area (km^2)	% of surface	
karst in limestone	2023	4993.0	24.6	karst 49.7%
karst in limestone and dolomite	143	385.5	1.9	
karst in dolomite	1464	2504.6	12.4	
karst in clastic carbonate rocks	1336	1033.4	5.1	
carbonate gravel-covered karst	670	501.9	2.5	
fine grained sediment-covered karst	381	414.0	2.0	
carbonate till-covered karst	169	153.6	0.8	
karst in flysch	136	97.2	0.5	
non-karst area	6412	10,189.8	50.3	
SUM	12,734	20,273.0	100	

Figure 6: Spatial distribution of karst in Slovenia in various lithological units. ➤ p. 123
Figure 7: Spatial distribution of karst in Slovenia. ➤ p. 124


karst in limestone
karst in limestone and dolomite
karst in dolomite
karst in clastic carbonate rocks
karst in flysch
carbonate gravel–covered karst
fine grained sediment–covered karst
carbonate till–covered karst
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Scale: 1:1.300.000
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Map by: Petra Gostinčar
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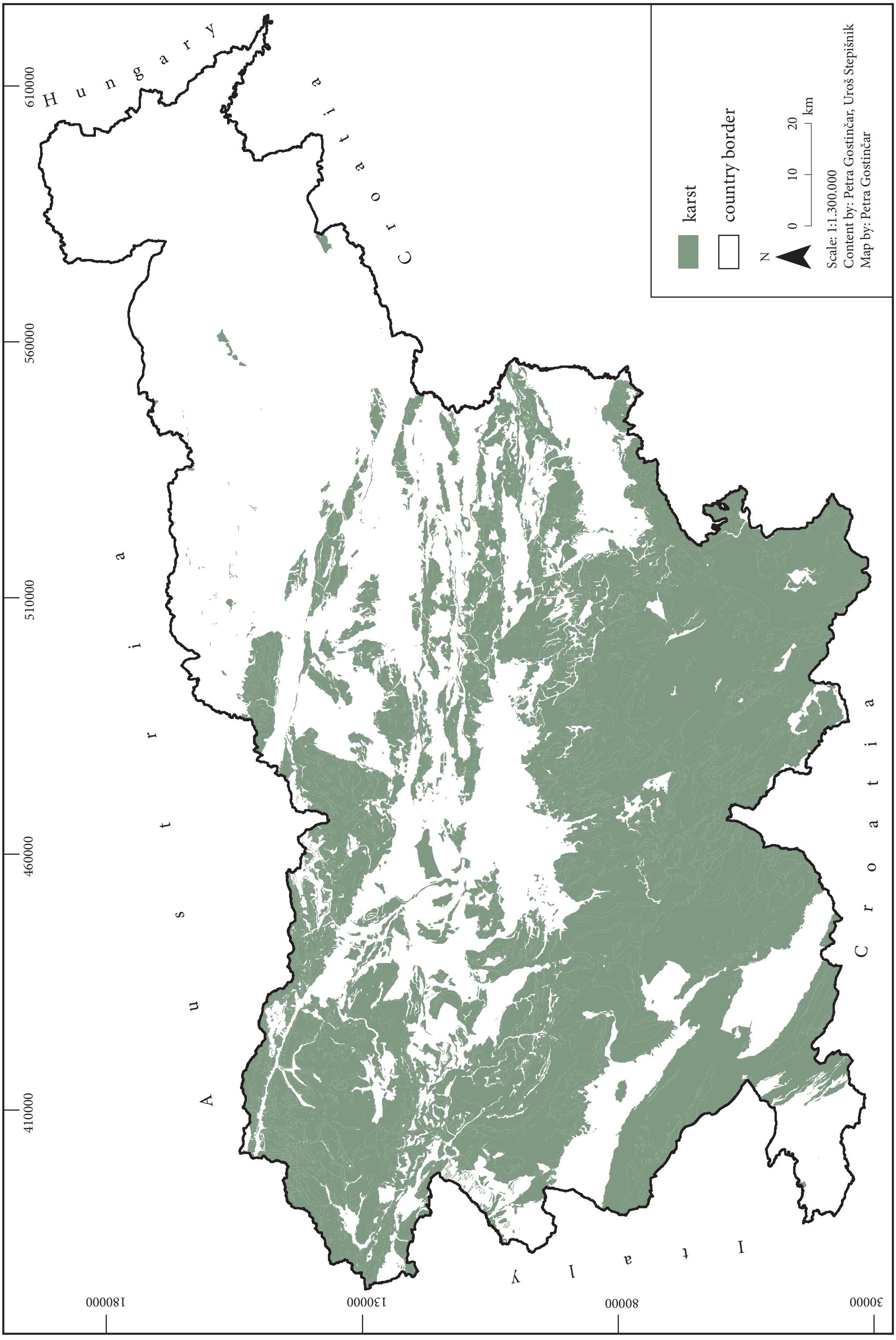
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and on the northern edge of the Trnovo Forest Plateau. It also makes up a large part of the Inner Carniola karst (*Notranjsko podolje*): the Menišija Plateau and Bloke Plateau and, south of Loški Potok, the area surrounding Osilnica and Kostel. Dolomite karst forms the southeastern parts of the Little Kočevje Mountains and the Kočevje Rog Plateau. In the southern part of the Sava Hills, dolomite karst mainly alternates with karst in clastic carbonate rocks, whereas in the central part it mainly alternates with karst in limestones. Areas where **karst in clastic carbonate rocks** is formed are usually highly fragmented. This type of karst is found in the Idrija–Cerkno Hills and the Polhov Gradec Hills, in the Krim Hills, on the Bloke Plateau, and in the Velike Lašče region. Karst on clastic carbonate rocks is the predominant type of karst in the Sava Hills and in the Gorjanci Hills, where it mainly alternates with karst in dolomites. This karst type exists in the Kozje Hills (*Kozjansko*) and in the northeastern part of the Kamnik–Savinja Alps and Kozjak, where it alternates with limestone and dolomite karst. **Carbonate gravel-covered karst** occurs in river basins with higher potential energy, namely in the Julian Alps and the Kamnik–Savinja Alps. Larger compact areas of this karst type are formed in the broad floodplain of the Sava River; namely, the Kranj–Sora Polje, the Dobrave, and the Udin Boršt. **The fine grained sediment-covered karst** type is found at the bottom of the poljes of the Inner Carniola (*Notranjska*) and Lower Carniola (*Dolenjska*) karst – poljes in the catchment area of the Ljubljanica and Krka rivers, where the karst is mainly covered by alluvium. The fine grained sediment-covered karst type occurs in the karst of Lower Carniola and White Carniola, where a variety of clays, mainly from the Plio-Quaternary, are deposited over the karst surface (e.g. bauxite clay). The largest areas of **carbonate till-covered** karst are the Julian Alps and the Kamnik–Savinja Alps, where glacial tills are mainly deposited on high karst plateaus (the Pokljuka Plateau and Jelovica Plateau), where they mostly alternate with karst in limestone. Carbonate till-covered karst is also located at the bottoms of valleys that were influenced by glaciation in past climatic periods. Furthermore, this type of karst is found in the Snežnik Plateau. **Karst in flysch** occurs in western Slovenia – namely Kambreško and in the Vipava Valley (known as Planina breccia). Our method did not detect karst in the flysch megabeds of Slovenian Istria.

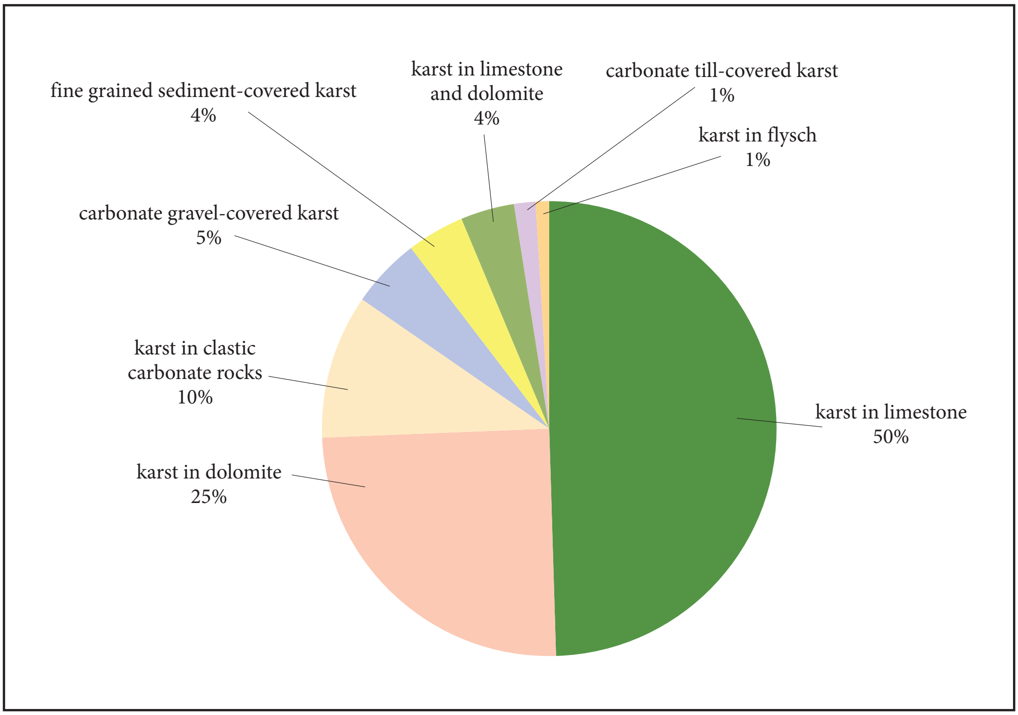

Figure 8: Distribution of different karst lithologies in Slovenia.

5 Conclusions

In the long history of Slovenian karst research, there have been numerous attempts to determine the spatial distribution of karst using various methods. Early approaches relied on characteristic landforms such as karst depressions, poljes, and caves, since few geological data were available. More recent studies have focused on areas of carbonate rocks, where the presence of surface morphology, cave entrances, and the absence of a surface river network are consistent. However, these approaches were only partially successful because they failed to identify all karst areas in Slovenia, considering only »pure« carbonate lithologies and often omitting large areas, usually within karst poljes.

Using advanced GIS technologies and more accurate data layers on lithology, hydrology, and digital relief models, we conducted a two-step identification of karst areas in Slovenia. The first step consisted of overlays of GIS, followed by a manual review of the data layer for lithology. In this way, we were able to determine the spatial distribution of karst in Slovenia and create a comprehensive digital spatial database that contributes to the broader understanding of the Slovenian environment.

Karst covers a significant part of Slovenian territory, and many water sources are located in karst aquifers. The spatial data on karst distribution, when combined with other spatial data such as subsurface water flow, can play an important role in the integrated management of surface and subsurface karst areas. Identification of karst areas has several implications, such as designating karst aquifers for effective management and protection, planning forest management, determining eligibility for agricultural subsidies, and supporting glacial geomorphology research.

The digital format of the data layer produced allows for immediate further processing and enhancement by the karst research community, as well as the creation of digital or web materials and content layers in GIS applications. This study not only provides valuable insight into the extent and diversity of karst in Slovenia, but also provides a solid foundation for future research and management efforts related to this unique and important landscape.

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6 References

Asanidze, L., Lezhava, Z., Tsikarishvili, K., Gaprindashvili, G., Chikhradze, N., Polk, J. 2019: Karst map of Georgia (Caucasus region) scale: 1:1,500,000. Carbonates and Evaporites 34-4. DOI: https://doi.org/10.1007/s13146-019-00525-z

Bögli, A. 1980: Karst hydrology and physical speleology. Berlin, Heidelberg, New York.

Božič, M. 2021: Sedimentologija in geomorfologija eocenske Planinske breče v Vipavski dolini. Bachelor's thesis. University of Ljubljana. Ljubljana.

Buser, S. 2010a: Geološka karta Slovenije 1:250.000. Geološki zavod Slovenije. Ljubljana.

Buser, S. 2010b: Geološka karta Slovenije 1:250.000 (povzeto po OGK 1:100.000 in posodobljeno). Geološki zavod Slovenije. Ljubljana.

Chen, Z., Auler, A. S., Bakalowicz, M., Drew, D., Griger, F., Hartmann, J., Jiang, G., et al. 2017: The World Karst Aquifer Mapping project: Concept, mapping procedure and map of Europe. Hydrogeology Journal 25-3. DOI: https://doi.org/10.1007/s10040-016-1519-3

Ciglič, R., Čonč, Š., Breg Valjavec, M. 2022: The impact of digital elevation model preprocessing and detection methods on karst depression mapping in densely forested Dinaric mountains. Remote Sensing 14-10. DOI: https://doi.org/10.3390/rs14102416

Cvijić, J. 1893: Das Karstphänomen: Versuch einer Morphologischen Monographie. Wien.

Cvijić, J. 1924: Types morphologiques de terrains calcaires. Glasnik Geografskog društva 10-1.

Čeru, T., Šegina, E., Gosar, A. 2017: Geomorphological dating of Pleistocene conglomerates in central Slovenia based on spatial analyses of dolines using LiDAR and ground penetrating radar. Remote Sensing 9-12. DOI: https://doi.org/10.3390/rs9121213

De Waele, J., Gutiérrez, F. 2022: Karst hydrogeology, geomorphology and caves. Hoboken. DOI: https://doi.org/10.1002/9781119605379
Ford, D., Williams, P. D. 2007: Karst hydrogeology and geomorphology. Chichester.
Fridl, J., Kladnik, D., Orožen Adamič, M., Perko, D., Pogačnik, A., Belec, B., Drozg, V. (eds.) 1998: Geografski atlas Slovenije. Ljubljana.
Gabrovec, M. 1994: Relief in raba tal na dolomitnih območjih Slovenije. Ph.D. thesis. University of Ljubljana. Ljubljana.
Gabrovec, M. 1995: Dolomite areas in Slovenia with particular consideration of relief and land use. Geografski zbornik 35-1.
Gabrovec, M., Hrvatin, M. 1998: Površje. Geografski atlas Slovenije. Ljubljana
Gabrovec, M., Hrvatin, M. 2016: Reliefni tipi. Geološki atlas Slovenije. Ljubljana.
Gabrovšek, F. 2005: Caves in conglomerate: Case of Udin Boršt, Slovenia. Acta Carsologica 34-2. DOI: https://doi.org/10.3986/ac.v34i2.274
Gams, I. 1965: Speleological characteristics of the Slovene karst. Naše jame 7-1.
Gams, I. 1972: Geografsko raziskovanje krasa v Sloveniji. Geografski vestnik 44-1.
Gams, I. 1974: Kras: zgodovinski, naravoslovni in geografski oris. Ljubljana.
Gams, I. 1995: Types of the contact karst. Studia carsologica 6-1.
Gams, I. 2001: Notion and forms of contact karst. Acta Carsologica 30-2.
Gams, I. 2003: Kras v Sloveniji v prostoru in času. Ljubljana.
Gams, I., Otoničar, B., Slabe, T. 2011: Development of slope and related subsoil karst: A case study from Bela Krajina, SE Slovenia. Acta Carsologica 40-2. DOI: https://doi.org/10.3986/ac.v40i2.17
Gao, Y., Alexander, E. C., Tipping, R. G. 2005: Karst database development in Minnesota: Design and data assembly. Environmental Geology 47-8. DOI: https://doi.org/10.1007/s00254-005-1240-3
Goldscheider, N., Chen, Z., Auler, A. S., Bakalowicz, M., Broda, S., Drew, D., Hartmann, J., et al. 2020: Global distribution of carbonate rocks and karst water resources. Hydrogeology Journal 28-5. DOI: https://doi.org/10.1007/s10040-020-02139-5
Gostinčar, P. 2016: Geomorphological characteristics of karst on contact between limestone and dolomite in Slovenia. Ph.D. thesis, University of Nova Gorica. Nova Gorica.
Grlj, A. 2021: Omejevanje kraških kotanj z analizo polrezov. Dela 53. DOI: https://doi.org/10.4312/dela.53.5-22
Gunn, J. 2004: Fluviokarst. Encyclopedia of caves and karst science. New York.
Habič, P. 1969: Hidrografska rajonizacija krasa v Sloveniji. Krš Jugoslavije 6-1.
Habič, P. 1982: Pregledna speleološka karta Slovenije. Acta Carsologica 10-1.
Hartmann, J., Moosdorf, N. 2012: The new global lithological map database GLiM: A representation of rock properties at the Earth surface. Geochemistry, Geophysics, Geosystems 13-12. DOI: https://doi.org/10.1029/2012GC004370
Hrvatin, M. 2016: Morfometrične značilnosti površja na različnih kamninah v Sloveniji. Ph.D. thesis, Univerza na Primorskem. Koper.
Knez, M., Mihevc, A., Slabe, T. 2007: Kras v breči Rebrnic v Vipavski dolini. Kraški pojavi, razkriti med gradnjo slovenskih avtocest. Ljubljana.
Knez, M., Slabe, T. (eds.) 2007: Kraški pojavi, razkriti med gradnjo slovenskih avtocest. Ljubljana. DOI: https://doi.org/10.3986/9789612540302
Knez, M., Slabe, T. 2011: Young karst processes in breccia and flysch (Mount Nanos, Slovenia). Congreso de Terrenos Kársticos de Guatemala. Cobán.
Kokalj, Ž., Hesse, R. 2017: Airborne laser scanning raster data visualization: A guide to good practice. Ljubljana. DOI: https://doi.org/10.3986/9789612549848
Komac, B. 2003: Dolomite relief in the Žibrše Hills. Acta geographica Slovenica 43-2. DOI: https://doi.org/10.3986/ags43201
Komac, B. 2004: Dolomitni kras ali fluviokras? Geografski vestnik 76-1.
Komac, B. 2006: Dolec kot značilna oblika dolomitnega površja. Ljubljana.
Komac, M., Urbanc, J. 2013a: Map of the spatial distribution and karstification intensity of surficial karst areas in Slovenia 1:250,000. Geološki zavod Slovenije. Ljubljana.
Komac, M., Urbanc, J. 2013b: Model stopnje zakraselosti za območje Slovenije. Ujma 27-1.
Komac, M., Urbanc, J. 2016: Površinska razširjenost in stopnja zakraselosti. Geološki atlas Slovenije. Ljubljana.

Komac, M., Urbanc, J. 2017: Karta površinske razširjenosti in stopnje zakraselosti kraških območij v Sloveniji 1:250.000. Tolmač. Ljubljana.
Kranjc, A. 1998: Kraške vode. Geografski atlas Slovenije. Ljubljana.
Kranjc, A. 2005: Konglomeratni kras v Sloveniji: zgodovina raziskovanja in poznavanja jam v Udin borštu na Gorenjskem. Acta Carsologica 34-2. DOI: https://doi.org/10.3986/ac.v34i2.275
Lipar, M., Ferk, M. 2011: Eogenetic caves in conglomerate: an example from Udin Boršt, Slovenia. International Journal of Speleology 40-1. DOI: https://doi.org/10.5038/1827-806X.40.1.7
Lipar, M., Ferk, M. 2022: Fluviokarst on Quaternary eogenetic conglomerates; an example from Slovenia. Proceedings of the 18th International Congress of Speleology. Bourget-du-Lac.
Litostratigrafska karta Slovenije. Geološki zavod Slovenije, naročnik ARSO, revizija 2011. Ljubljana.
Melik, A. 1935: Slovenija: geografski opis. Ljubljana.
Melik, A. 1963: Slovenija: geografski opis. Ljubljana.
Mihevc, A. 1992: Gypsum in Tajna jama and in the cave Kubik. Acta Carsologica 21-1.
Mihevc, A. 1994: Morfološke značilnosti Matarskega podolja. Annales: anali za istrske in mediteranske študije. Series historia naturalis 4-4.
Mihevc, A. 1998: Kraško površje. Geografski atlas Slovenije. Ljubljana.
Mihevc, A., Mihevc, R. 2021: Morphological characteristics and distribution of dolines in Slovenia, a study of a lidar-based doline map of Slovenia. Acta Carsologica 50-1. DOI: https://doi.org/10.3986/ac.v50i1.9462
Novak, D. 1993: Hydrogeological research of the Slovenian karst. Naše jame 35-1.
Perko, D., Hrvatin, M., Ciglič, R. 2015: A methodology for natural landscape typification of Slovenia. Acta geographica Slovenica 55-2. DOI: https://doi.org/10.3986/AGS.1938
Petrič, M., Ravbar, N., Gostinčar, P., Krsnik, P., Gacin, M. 2020a: Establishment of a freely accessible GIS database containing the results of groundwater tracing and possibilities of its use. Geologija 63-2. DOI: https://doi.org/10.5474/geologija.2020.017
Petrič, M., Ravbar, N., Gostinčar, P., Krsnik, P., Gacin, M. 2020b: GIS database of groundwater flow characteristics in carbonate aquifers: Tracer test inventory from Slovenian karst. Applied Geography 118. DOI: https://doi.org/10.1016/j.apgeog.2020.102191
Placer, L., Košir, A., Popit, T., Šmuc, A., Juvan, G. 2004: The Buzet Thrust Fault in Istria and overturned carbonate megabeds in the Eocene flysch of the Dragonja Valley (Slovenia). Geologija 47-2. DOI: https://doi.org/10.5474/geologija.2004.015
Roglić, J. 1958: Odnos riječne erozije i krškog procesa. V. kongres geografa FNR Jugoslavije. Cetinje.
Sauro, U. 2012: Closed depressions in karst areas. Encyclopedia of Caves. Amsterdam. DOI: https://doi.org/10.1016/B978-0-12-383832-2.00133-X
Smart, P. L. 1986: Origin and development of glacio-karst closed depressions in the Picos de Europa, Spain. Zeitschrift für Geomorphologie 30-4. DOI: https://doi.org/10.1127/zfg/30/1987/423
Staut, M. 2003: Poskus razlage razvoja jame Kubik kot primera jame v flišu. Bilten: glasilo Jamarskega kluba Železničar 23-1.
Stepišnik, U. 2017: Dinarski kras: plitvi kras Zgornje Pivke. Ljubljana.
Stepišnik, U. 2020: Fizična geografija krasa. Ljubljana.
Stepišnik, U. 2021: Kraška polja v Sloveniji. Dela 53. DOI: https://doi.org/10.4312/dela.53.23-43
Sun, W, Song, J., Yang, W., Zheng, Y., Li, C., Kuang, D. 2020: Distribution of carbonate rocks and variation analysis of karst water resources in China. Carbonates and Evaporites 35-4. DOI: https://doi.org/10.1007/s13146-020-00657-7
Sweeting, M. M. 1973: Karst Landforms. New York.
Šarc, F., Otoničar, B., Gabrovšek, F., Martín-Pérez, A., Covington, M., Rohovec, J., Lupša, A. 2022: Cave in the Mežica mine. Speleology: 29th International Karstological School Classical Karst, Abstracts & Guide Book. Postojna.
Šerko, A. 1947: Kraški pojavi v Jugoslaviji. Geografski vestnik 19-1.
Šušteršič, F. 1991: Kras. Enciklopedija Slovenije. Ljubljana.
Temovski, M. 2012: Map of karst rock outcrops in Macedonia. Karst forms and processes: Guide book & abstracts, 20th International Karstological School Classical Karst. Postojna. DOI: https://doi.org/10.13140/2.1.2170.3040
Triglav Čekada, M., Bric, V. 2015: Končan je projekt laserskega skeniranja Slovenije. Geodetski vestnik 59-3.
White, W. B. 1988: Geomorphology and hydrology of karst terrains. Oxford.

White, W. B. 2002: Karst hydrology: recent developments and open questions. Engineering Geology 65-2,3. DOI: https://doi.org/10.1016/S0013-7952(01)00116-8
Zemljevid tipov kamnin. Geografski inštitut Antona Melika ZRC SAZU, različica 2012. Ljubljana.
Žebre, M., Stepišnik, U. 2015a: Glaciokarst landforms and processes of the Southern Dinaric Alps. Earth Surface Processes and Landforms 40-11. DOI: https://doi.org/10.1002/esp.3731
Žebre, M., Stepšinik, U. 2015b: Glaciokarst geomorphology of the Northern Dinaric Alps: Snežnik (Slovenia) and Gorski Kotar (Croatia). Journal of Maps 12-5. DOI: 10.1080/17445647.2015.1095133
Žlebnik, L. 1978: Kras na konglomeratnih terasah ob Zgornji Savi in njenih pritokih. Geologija 21-1.