ACTA GEOGRAPHICA SLOVENICA

GEOGRAFSKI ZBORNIK

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SLOVENSKE AKADEMIJE ZNANOSTI IN UMETNOSTI
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ACTA GEOGRAPHICA SLOVENICA

60-2
2020

ISSN: 1581-6613
UDC: 91

Issued by/izdajatelj: Geografski inštitut Antona Melika ZRC SAZU
Published by/založnik: Založba ZRC
Co-published by/sozaložnik: Slovenska akademija znanosti in umetnosti

Address/naslov: Geografski inštitut Antona Melika ZRC SAZU, Gosposka ulica 13, p. p. 306, SI – 1000 Ljubljana, Slovenija

The papers are available on-line/prispevki so dostopni na medmrežju: http://ags.zrc-sazu.si (ISSN: 1581–8314)

Ordering/naročanje: Založba ZRC, Novi trg 2, p. p. 306, SI – 1001 Ljubljana, Slovenija; zalozba@zrc-sazu.si

Annual subscription/letna naročnina: 20 € for individuals/za posameznike, 28 € for institutions/za ustanove.
Single issue/cena posamezne številke: 12,50 € for individuals/za posameznike, 16 € for institutions/za ustanove.

Cartography/kartografija: Geografski inštitut Antona Melika ZRC SAZU
Translations/prevodi: DEKS, d. o. o.
DTP/prelom: SYNCOMP, d. o. o.
Printed by/tiskarna: Present, d. o. o.
Print run/naklada: 400 copies/izvodov

The journal is subsidized by the Slovenian Research Agency and is issued in the framework of the Geography of Slovenia core research programme (P6-0101)/Revija izhaja s podporo Javne agencije za raziskovalno dejavnost Republike Slovenije in nastaja v okviru raziskovalnega programa Geografija Slovenije (P6-0101).

The journal is indexed also in/Revija je vključena tudi v: SCIE – Science Citation Index Expanded, Scopus, JCR – Journal Citation Report/Science Edition, ERIH PLUS, GEOBASE Journals, Current geographical publications, EBSCOhost, Geoscience e-Journals, Georef, FRANCIS, SJR (SCImago Journal & Country Rank), OCLC WorldCat, Google scholar, and CrossRef.

Design by/Oblikovanje: Matjaž Vipotnik.

Front cover photography: Larch in the Triglav National Park (photograph: Jure Tičar).
Fotografija na naslovnici: Macesni v Triglavskem narodnem parku (fotografija: Jure Tičar).

ACTA GEOGRAPHICA SLOVENICA

ISSN: 1581-6613
UDC: 91
Number: 60-2
Year: 2020

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Special issue – The disappearing cryosphere in the southeastern Alps

Acta geographica Slovenica, 60-2, 2020, 7–20

FARM HOLDINGS AND THE OWNER'S RESIDENCE LOCATION IN THE ASPECT OF DIRECT PAYMENTS FROM THE EU: A CASE STUDY IN NINE REGIONS IN POLAND

Katarzyna Kocur-Bera

Agricultural areas for cultivation in Poland.

DOI: https://doi.org/10.3986/AGS.6836
UDC: 332.334.4:63(438)
338.246.027(438)
COBISS: 1.01

Katarzyna Kocur-Bera[1]

Farm holdings and the owner's residence location in the aspect of direct payments from the EU: A case study in nine regions in Poland

ABSTRACT: Instruments promoting rural development have been implemented by many countries. Area-based payments for farmers allocated under the Common Agricultural Policy constitute one of such instruments in the European Union. The support system for rural areas, including the size of the declared reference parcels, is monitored as part of the cross-compliance mechanism. Parcels with unfavorable land-use patterns are more difficult to farm. According to estimates, more than 30% of agricultural farms in Poland fall into this category. This study proposes a universal algorithm for controlling the information submitted by farmers in payment applications. More than 76,000 applications were analyzed, and farms with the defective spatial structure of land were randomly selected. The results show that most errors occur in the case of land parcels situated the farthest from a farm holding (declared in the application), but the analysis revealed no strong correlation in this respect.

KEY WORDS: rural area, land spatial structure, area-based payments, cross-compliance monitoring, Common Agricultural Policy, Poland

Kmetijska gospodarstva in lokacije bivališč njihovih lastnikov z vidika neposrednih plačil iz EU: študija primera za del Poljske

POVZETEK: Številne države imajo instrumente za podporo razvoju podeželja. Ena takih oblik podpore v državah Evropske unije so subvencije za kmetijske površine kmetijskih pridelovalcev, ki se izvajajo v okviru Skupne kmetijske politike. Podporni sistem za podeželje, vključno s površinami, ki jih kmetijski pridelovalec prijavi za subvencije, je predmet nadzora. Kadar imajo parcele pomanjkljivo prostorsko strukturo, je kmetijska dejavnost na njih otežena. Takih posestev kmetijskih pridelovalcev je na Poljskem več kot 30 %. Članek predstavlja univerzalen algoritem za izvajanje kontrole podatkov v prijavah kmetijskih pridelovalcev. Analizirali smo več kot 76.000 prijav kmetijskih pridelovalcev, med katerimi smo naključno izbrali skupino kmetijskih pridelovalcev z razpršeno prostorsko strukturo. Rezultati kažejo, da se večina napak pojavlja pri zemljiščih, ki so najbolj oddaljeni od kmetijskega gospodarstva (navedeni v vlogi), vendar analiza ni pokazala močne korelacije v zvezi s tem.

KLJUČNE BESEDE: podeželje, prostorska struktura zemljišč, subvencije za kmetijske površine, skupna kmetijska politika, spremljanje skladnosti, Poljska

This article was submitted for publication on July 2nd, 2018.
Uredništvo je prejelo prispevek 2. julija 2018.

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1 Introduction

The main goals of the European Union's Common Agricultural Policy (CAP) are to provide financial support to farmers, increase the competitiveness of agricultural markets in the Member States, increase productivity by promoting technical progress in agriculture, stabilize the agricultural market and guarantee fair incomes and a fair standard of living for the farming community. The last goal is addressed by the area-based payment scheme (Latruffe and Davidova 2007; Zadravec and Zalik 2009; Zygmunt et al. 2015; Janković et al. 2018). Polish farmers became entitled to financial support under the CAP after Poland joined the EU in 2004. Area-based payments are one of the key support instruments for the Polish agricultural sector. The Land Parcel Identification System (LPIS) was originally devised for registering agricultural reference parcels eligible for annual payments under the CAP (Grandgirard and Zielinski 2008; Kocur-Bera and Piórkowska 2018). The LPIS is a computerized system that identifies agricultural (reference) parcels based on aerial and spatial ortho-imagery (Milenov and Kay 2006; EC 2009). It is the key control mechanism to verify the eligibility of reference parcels for direct payments (Sagris and Devos 2008; Zimmermann

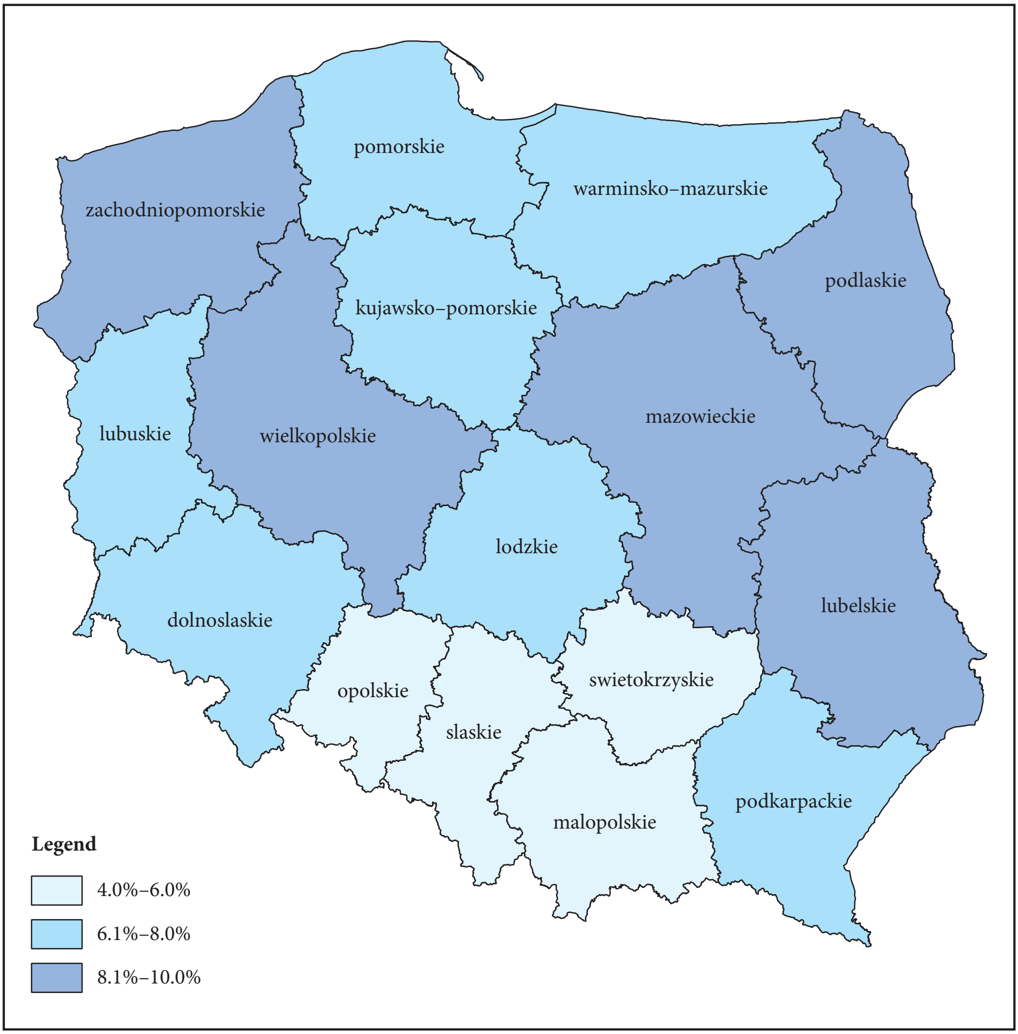


Figure 1: The percentage share of farm holdings in a region, where the farmstead is located farther than 10 km from the closest cadastral parcel (Kozłowski 2015).

et al. 2016). EU Member States have defined reference parcels in different ways as cadastral parcels (CP), agricultural parcels (AP), farmer's blocks (FB) (one or several agricultural parcels cultivated by a single farmer) or physical blocks (PB) (one or several agricultural parcels cultivated by one or several farmers) (Inan and Cete 2007; Sagris and Devos 2008; Inan et al. 2010; Levavasseur et al. 2016; Kocur-Bera 2019). In Poland, a cadastral parcel was accepted as a reference parcel (Kocur-Bera 2019). A reference parcel may contain one or many agricultural parcels declared for aid by one or several farmers, and it is provided with a unique identifier (Inan et al. 2010). An agricultural parcel (AP) determines the subject of the aid application, its geographic location and the extent (area) of the agricultural activity. It represents the land for which payments can be claimed, and it is also a subject of administrative crosschecks and control procedures established in the Integrated Administration and Control System (IACS). Due to the dynamic nature of agricultural activities, an agricultural parcel can be unstable over time and space (Inan et al. 2010; Kocur-Bera and Piórkowska 2018).

The LPIS is the main component of the IACS. Around 5% of all beneficiaries of CAP programs are inspected for cross-compliance each year. Agricultural producers are required to analyze maps and indicate the size of their reference parcels in the payment application, excluding non-eligible areas and objects such as buildings, yards, shrubs, roads, forests, and lakes. Cross-compliance inspections are not easy to perform, particularly in farms with defective structures. Farms with faulty land spatial structures in Europe result mainly from historical social and economic processes (van Dijk 2003; Vitikainen 2004; Latruffe and Piet 2014; Janus et al. 2016; Leń 2018; Prus and Szylar 2018).

Many researchers focus primarily on land fragmentation, defined as defective spatial structure (Bański 1999; Leń and Noga 2010; Sobolewska-Mikulska 2012; Leń 2018; Noga et al. 2018). Fragmentation is considered to be a comprehensive set of farm holding components, such as size of parcel/ownership, dispersion of parcel, shape of parcel, accessibility of parcel, number of parcel, type of ownership, distance from farmstead (van Dijk 2004; Demetriou, Stillwell and See 2012; Latruffe and Piet 2014; Demetriou 2014; Noga and Król 2016; Leń 2018). The distance between cadastral parcels and the farmstead is one of the attributes of a defective spatial structure(Woch 2001; Harasimowicz, Janus and Ostragowska 2009; Janus 2018). According to Kozłowski (2015), in Poland, in the Zachodniopomorskie and Podlaskie voivodeships, over 10% of farm holdings have their farmsteads farther than 10 km from even a single cadastral parcel; in the Wielkopolskie, Mazowieckie and Lubelskie voivodeships – it is 8–10% of farms; in other seven voivodeships (Podkarpackie, Łódzkie, Dolnośląskie, Lubuskie, Kujawsko-pomorskie, Pomorskie, Warmińsko-mazurskie) – it is 6–8%; and 4–6% in the remaining regions (Figure 1).

Agricultural producers are unable to maintain parcels located too far away in good condition due to labor shortages, poor fertilization, high fuel- and time-related costs (Neupane 2000; van Dijk 2003; Niroula and Thapa 2005). Increased production costs, the effect of excessively long distances between parcels, hinder agricultural development and reduce the competitiveness of farmers (Niroula and Thapa 2005). Even a small loss of agricultural payments poses a massive problem because area-based subsidies constitute the main source of income for Polish farmers. The purpose of the research is to examine the impact of the allocation of agricultural producer's residence in relation to agricultural plots that are part of a farm.

The procedure of selecting farms for cross-compliance inspections was described in the first part of the study. The distance of the parcel from the farmstead (owner's residence) influences the quality of agricultural operations and is responsible for the discrepancies between the declared and the measured size of reference parcels. The resulting errors affect the value of financial support granted under the CAP. The correlations between errors in the declared size of reference parcels and other error-promoting factors were analyzed in the second part of the study.

2 Methods

Farms applying for area-based payments have to submit an application to the local branch of the national payment agency (the Agency for the Reconstruction and Modernization of Agriculture in Poland). As of 2018, applications have been submitted online (through the *eWniosekPlus* platform). Written applications are accepted only under extraordinary circumstances, for example, when the applicant does not have Internet access. The applications are checked for completeness, coherence and data content, and the applicant is placed on a list of inspection candidates. Administrative controls can be carried out in a simplified or a reference mode. In the simplified mode, the declared information is checked for compliance with the Land Administration System (LAS), whereas in the reference mode, the declared information is compared against the data declared by other farmers (to prevent double funding for the same parcel). The number of inspection candidates is determined at the beginning of each year. Various methods are used to select inspection candidates (Table 1), and most of them involve aerial imaging and on-site visits. Tolerance levels are set for dealing with differences between the declared and the measured size of the parcel. Farms, where tolerance levels are exceeded, are fined.

The case study was carried out by selecting a group of farm holdings where at least one parcel is located at least 5 km from the farmstead. It was assumed that the farmstead is a farmer's place of residence and the address declared in the EU payment applications. The farms were selected based on the procedure for monitoring cross-compliance in farms receiving area-based payments and the algorithm presented in Table 1. The allocation of cadastral parcels with respect to the farmstead is of particular interest to the control authority (Polish Agency for Restructuring and Modernization of Agriculture). The calculated differences in the parcel area declared in the payment application and the on-site measured area were added up and the general difference for each cadastral parcel was obtained. Subsequently, the errors were added up for each

Table 1: The procedure for monitoring cross-compliance.

Step 1	*Start* – The beneficiary submits an application (A).		
Step 2	The submitted documents are checked for completeness and coherence (B).		
	and	Simplified mode (B1)	Data are checked against the applications submitted in the previous years and are compared with the LAS database.
		Reference mode (B2)	Data are checked against the information declared by other applicants to prevent double funding for the same parcel.
Step 3	Number of inspection candidates is determined (C).		
Step 4	Inspection candidates are selected (D).		
	or	Risk analysis method (D1)	Risk is analyzed based on several risk factors, including errors in previous years, fines imposed in previous years, farm size and the number of declared reference parcels.
		Random method (D2)	Inspection candidates are selected randomly.
		Manual method (D3)	Applicants are inspected based on a justified suspicion of non-compliance or third-party reports.
Step 4	A list of inspection candidates is developed (E).		
	and	Location-based method (E1)	Farms are grouped based on their location.
		Area-based method (E2)	Farms are grouped based on their size.
Step 5	An inspection schedule is developed for the selected farms (F).		
Step 6	The inspection method is selected (G).		
	or	On-site visits (G1)	Farms are inspected by on-site visits.
		Aerial imaging (G2)	Farms are inspected by orthophoto map analysis and by local visits.
Step 7	The inspector and the inspection date are selected (H).		
Step 8	Relevant documentation is developed (I).		
Step 9	Inspection (J).		
	or	Measurements are performed using a digital tachymeter (J1).	
		Measurements are performed using a GPS tools (J2).	
		Measurements are performed using a tape measure (J3).	
		Combined measurements are performed with the use of tape measure and a digital tachymeter (J4).	
		Measurements are performed by orthophoto map vectorization (J5).	
Step 10	The inspection report is developed (K).		
Step 11	Tolerance levels for the applied measuring device are set (L).		
Step 12	The severity of the cross-compliance breach is determined in the inspected farm (M).		
Step 13	The penalty rate is set (N).		
Step 14	The penalty is communicated to the beneficiary (O).		
Step 15	*End* – The penalty is imposed on the beneficiary (P).		

landowner studied. The assumptions made are consistent with the procedure for controlling the landowners. Sanctions and/or penalties are imposed when exceeding specific limits with respect to all cadastral parcels declared for payments from the EU. The distance of every analyzed cadastral parcel was measured from the geometric center of the agricultural parcel and the farmstead (Euclidean distance, in GIS) and it was expressed in kilometers. Initially, approximately 76,000 beneficiaries of CAP support schemes who reside in Poland were evaluated. Ultimately, 216 parcels owned by 18 beneficiaries were selected for analysis. The declared parcels were situated in nine Polish regions: Pomerania (Pomorze), West Pomerania (Zachodniopomorskie), Wielkopolska (Wielkopolskie), Lower Silesia (Dolnośląskie), Swietokrzyskie Voivodeship (Świętokrzyskie), Lodz Voivodeship (Łódkie), Subcarpathia (Podkarpackie), Lubusz Voivodeship (Lubuskie), and Warmia and Mazury (Warmińsko-Mazurskie) (Figure 2).
The difference between the agricultural parcel area (a) declared in the application and the area measured on-site (m) was calculated using the equation:

$$D_{ap} = \frac{(A_d - A_m)}{A_d} \cdot 100\,\%$$

where:
D_{ap} – difference between the declared (A_d) and the measured (A_m) agricultural parcel area (error in declared area);
A_d – agricultural parcel area declared in the application;
A_m – agricultural parcel area measured on-site (with GPS tools, tachymeter).

The correlation analysis revealed significant relationships between the observed differences for every cadastral parcel *(Diff)* and other land-use attributes, such as distribution *(Dist)*, parcel area *(Ar)*, number of parcels in a farm *(Disp)*, number of regions where farm holdings are situated *(RD)* (Table 2). The observed correlations were interpreted on a six-point scale proposed by J. Guilford (Kocur-Bera 2016a).

Table 2: Description of the land-use attributes.

No.	*Attribute*	*Symbol*	*Description*	*Measure*
1	Difference	*Diff*	Difference between the cadastral parcel area declared in the application and the area measured on-site.	%
2	Distance	*Dist*	Distance between the cadastral parcel and the landowner's address declared in an EU application.	km
3	Area (measured)	*Ar*	Area of a cadastral parcel.	ha
4	Dispersion	*Disp*	A number of cadastral parcel belonging to the landowner.	number
5	Regional Dispersion	*RD*	A number of regions where the cadastral parcels belonging to the landowner are situated.	number

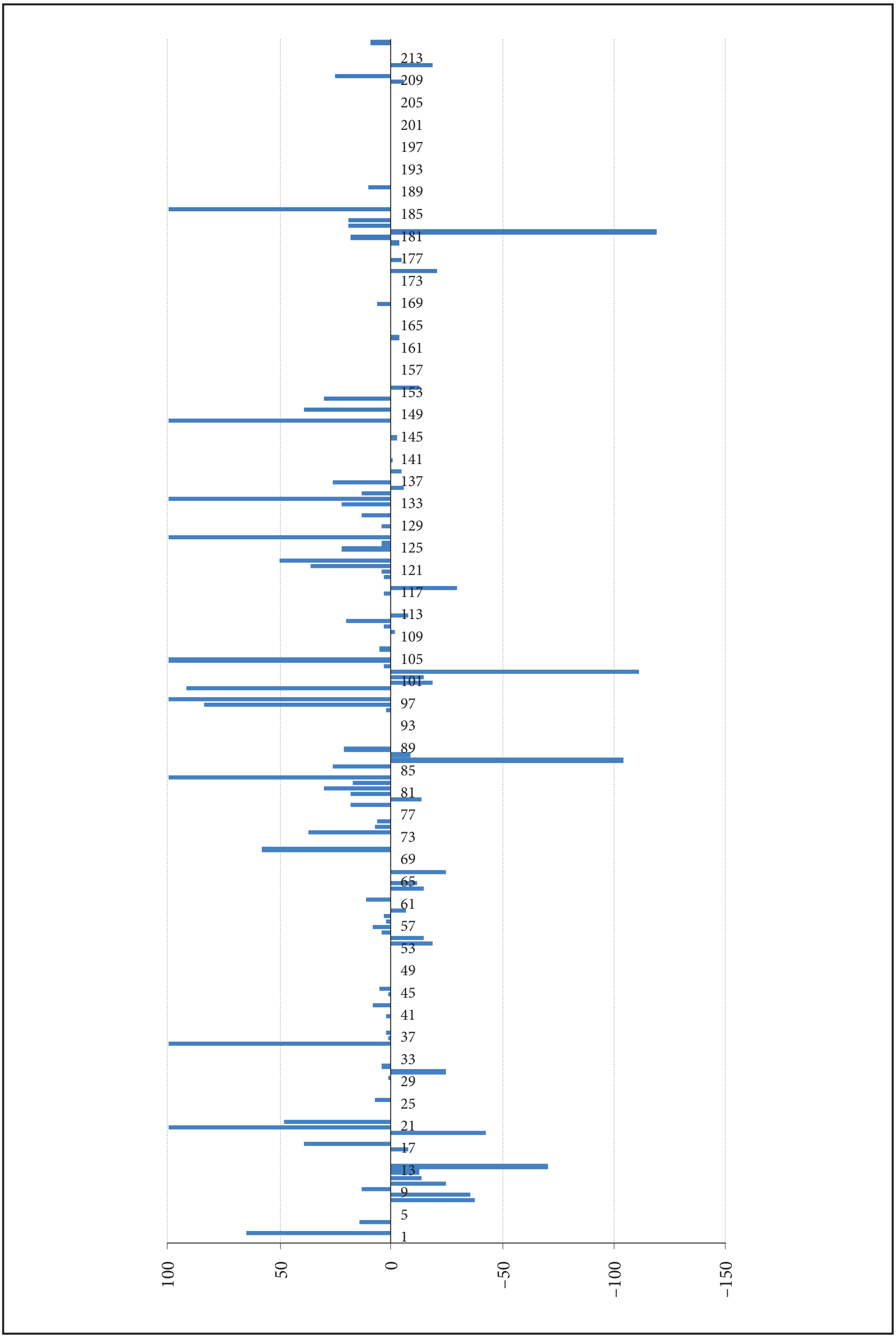
3 Results

Farms were selected for analysis using the algorithm for selecting inspection candidates (Table 1). The analysis relied on the above algorithm to focus solely on farms with an allocation of the owner's residence. Differences for each agricultural parcel were measured and the total sum of errors was calculated in relation to each cadastral parcel. Differences in 216 plots in 18 farms were examined. In 58 cases the difference was different from zero. The results are presented in figure 3.

In 83% of the parcels where inconsistencies were determined, the declared area was greater than the area used for agricultural production. In 39% of the analyzed farms, the average difference between the declared area and the measured area did not exceed 3%; in 44% of the analyzed farms, the difference was determined at 4–20%; and in 17% of the analyzed farms, the difference exceeded 20%. The average differences between the area declared in the application and the area measured on-site for evaluated farms are presented in Table 3.

Figure 2: The Polish regions included in the analysis (marked with blue color). ➤
Figure 3: The differences between the declared area and the area measured on-site, for 216 cadastral parcels [%]. ➤ p. 14


Russia
Azerbaijan
Armenia
Georgia
Turkey
Ukraine
Moldova
Belarus
Estonia
Latvia
Lithuania
Finland
Sweden
Norway
Romania
Bulgaria
Greece
Albania
Serbia
Montenegro
Slovakia
Hungary
Croatia
Slovenia
Austria
Czech Republic
Germany
Denmark
Netherlands
Belgium
Luxembourg
Switzerland
Italy
Malta
Monaco
France
Andorra
Spain
Portugal
Gibraltar (UK)
United Kingdom
Jersey (UK)
Ireland
Faeroe Islands (Denmark)
Iceland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49
45
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29
25
21
17
13
9
5
1
100
50
0
–50
–100
–150

Table 3: The average differences between the parcel area declared in the application and the area measured on-site in the evaluated farms.

Number of landowners	*The average differences in the area of all plots for one landowner (in one farm)[%]*	*Number of cadastral parcels on the farm*	*The average distance between the cadastral parcel and the landowner's address declared in application [km]*	*Number of regions where the cadastral parcel belonging to the landowner are situated*
1	–1.06	10	9.00	2
2	25.97	12	100.00	1
3	1.30	6	10.80	2
4	1.48	4	100.00	1
5	56.31	4	3.75	2
6	1.11	12	48.75	2
7	1.97	11	9.54	2
8	–8.20	9	33.33	2
9	22.00	6	100.00	1
10	9.66	15	100.00	1
11	16.25	18	77.22	3
12	6.27	16	89.37	3
13	7.44	48	85.62	4
14	–4.22	8	6.87	2
15	9.90	9	2.22	2
16	1.17	9	4.44	2
17	0.00	7	1.43	2
18	6.58	12	2.08	2

As the distance between the evaluated parcels and the farmstead was measured it was found that 39% of the analyzed agricultural parcels were situated at a distance of up to 20 km from the farmstead (*Zone* 1), 13% of the parcels were situated at a distance of 21–50 km (*Zone* 2), and 48% of the parcels were at a distance of more than 50 km (*Zone* 3). The percentage differences in the area declared and measured on-site concerned 58 reference parcels, with an average difference of 30.75%. The smallest number of differences was observed in *Zone 2* (21–50 km), it concerned 15 reference parcels and the average difference was 20.37%. The distribution of individual differences in zones is shown in Figure 4.

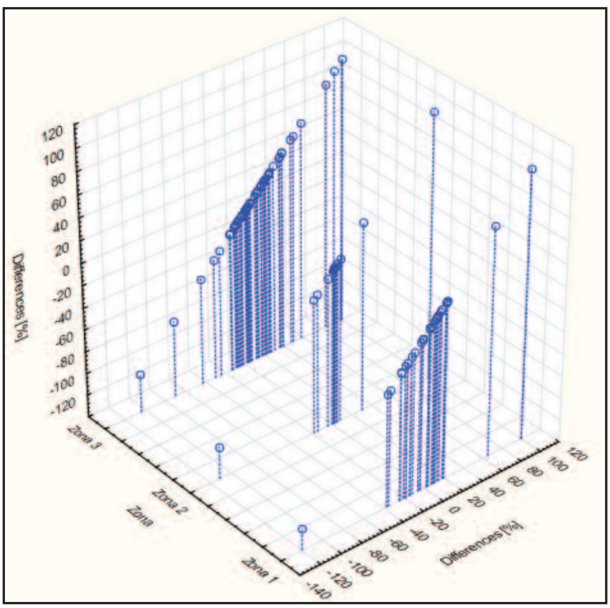

Figure 4: Diagram of the distribution of the percentage differences occurring in individual distance zones.

Table 4: Correlation coefficients (*Diff* – difference between the cadastral parcel area declared in the application and the area measured on-site differences; *Dist* – Distance between the cadastral parcel and the landowner's address declared in an EU application; *Ar* – Area of a cadastral parcel.; *Disp* – A number of cadastral parcel belonging to the landowner; *RD* – A number of regions where the cadastral parcels belonging to the landowner are situated.

Variable	*Diff*	*Dist*	*Ar*	*Disp*	*RD*
Diff	1.0000	0.1514	0.0030	0.0923	0.0868
Dist		1.0000	0.0868	0.4622	0.2311
Ar			1.0000	–0.0195	0.0210
Disp				1.0000	0.8621
RD					1.0000

The calculated Pearson's coefficients (Table 4) were analyzed to reveal that the difference *(Diff)* between the declared parcel area and the measured on-site was determined by the distance *(Dist)* between the reference parcel and the landowner's address declared in an EU application. The correlation was weak (according to Guilford's scale weak correlation is $0.1 < r \leq 0.3$) and is 0.15 but statistically significant at level of significance $p < 0.05$. The distance between the cadastral parcel and owner's residence *(Dist)* has a moderate correlation (0.46; according to Guilford's scale moderate correlation is $0.3 < r \leq 0.5$) with the number of cadastral parcels of the farm holding (*Disp*) and have a weak correlation with the number of regions where the cadastral parcels belonging to the landowner are situated (*RD*) – 0.23. The number of cadastral parcels on the farm holding *(Disp)* is strongly correlated (according to Glifford's scale very strong correlation is $0.7 < r \leq 0.9$) with the number of regions *(RD)* in which these cadastral parcels are located (0.86).

4 Discussion

The study analyzed the impact of localization of landowner's residence (address declared in the application for EU payments) and other factors influencing the error rate reported in EU payment declarations. The existing spatial structure of agricultural land is the result of changes in historical, social, and economic transformations in several generations (Janus 2018). Political transformations in post-socialist countries (including Poland), liquidation of state agricultural companies and privatization of national resources (Bański 2011) rendered it possible to purchase agricultural real estate. Because of no restrictions on buying, people with financial means became landowners. New owners of purchased land situated primarily in locations where the agency (APA) responsible for managing and selling state-owned land (the Agricultural Property Agency of the Treasury in the 1990s; now the Agricultural Property Agency – APA) owned the most of it. This particularly involved the following voivodeships: Warmińsko-Mazurskie, Pomorskie, Kujawsko-pomorskie, Wielkopolskie, Zachodnio-pomorskie, Dolnośląskie and Lubuskie (Sikorska 2008). Agricultural property purchased was not always located near the farmstead. It was in 2016 when Poland introduced regulations on buying agricultural property (Regulation 2016) which considerably limited the possibility of purchasing such real estate by individuals not engaged in agriculture. In the other Member States like France, Germany, Belgium, Hungary and Latvia, the regulations had been implemented earlier (Nurm 2015; Kocur-Bera 2016b).

This study was oriented towards finding a difference between the area declared for agricultural payments and the area measured on-site using specialist methods and equipment (GPS, total station). The final differences were added up first for the cadastral parcel and ultimately for the farm. 216 cadastral parcels owned by 18 farmers were studied. Differences were discovered in 47% of the cadastral parcels. In 83% of the cadastral parcels, the area declared in payment applications was greater than the area measured on-site. All the cases studied were divided into zones, including the landowner's address declared in the payment applications. The highest number of cadastral parcels with differences in the area were in *Zone 3*. However, the relations observed do not indicate that a greater distance automatically means more errors; differences were found in the cadastral parcels in *Zone 1* as well. The least significant differences were spotted in *Zone 2*. The results were additionally proven by an analysis of Pearson's coefficients. The matrix calculated (Table 4) points to a very weak correlation between the differences and the distance from the cadastral parcel to the landowner's address. The differences discovered were also analyzed considering such features as the area of a parcel declared *(Ar)*, the number of cadastral parcels within the farm *(Disp)*, the number of regions where cadastral parcels of a single owner are located *(RD)*. The strongest correlation was determined between the the number of cadastral parcels of a single owner *(Disp)* and the number of regions *(RD)* where they are situated.

Parcels located far from the farmstead are most often cultivated by employees. The farther the parcels are from the rest of the farm, the higher the costs of production which may even lead to ceasing cultivation (Villanueva and Colombo 2017; Noga et al. 2018). Landowners who engage salaried employees to cultivate parcels situated the farthest do not supervise such employees' work properly, hence possible differences between the area declared and the area measured on-site.

Another reason behind the differences might be the quality of cartographic materials used by landowners to complete payment applications if individual parcels are too far from each other. Data from the Land Administration System (LAS) are not always accurate. Some LAS entries have been developed based on low-quality source materials. The Polish land administration system dates back to the 13^{th}-century land management practices and has undergone numerous changes throughout the turbulent history of Central Europe, including wars, conquests, and communism (Siejka et al. 2015). The first digital cadastral maps were developed at the beginning of the 1990s, and contain errors (van Oosterom et al. 2006, Siejka, Ślusarski and Zygmunt 2014; Siejka, Ślusarski and Mika 2015; Noszczyk and Hernik 2017; Mika 2018; Kocur-Bera and Stachelek 2019).

The differences observed may also result from the fact that farmers do not measure areas cultivated on-site. Many farmers declare areas for payments based on, for instance, cartographic materials obtained from the Agency for the Reconstruction and Modernization of Agriculture. Their data are frequently distorted and contain rasterization errors (Tomlinson et al. 2018).

Yet another cause of the differences can be the changes in the guidelines regarding land eligible for payments following the accession of Poland to the EU. For example, in the early years of Poland's membership in the EU, certain elements of the agricultural landscape were not eligible for direct payments, but now they can be (though with some restrictions) (ARMiR 2017).

Farmers who fail to accurately declare the area of reference parcels are fined. If discrepancies are found during an inspection, direct payments to be granted in the calendar year can be reduced or canceled, the farmer can be subjected to long-term sanctions, additional inspections or can be completely excluded from CAP schemes (Pradziadowicz 2014).

The area of agricultural parcels declared by farmers in payment applications and the reliability of LPIS data are controlled in all EU Member States. According to the report 25/2016 of the European Court of Auditors (ECA), the reliability of procedures and data stored in the LPS was verified in Austria, Germany (Saarland and North Rhine-Westphalia), Ireland, Poland and the United Kingdom (Scotland) between July 2015 and April 2016. More than 400 reference parcels were checked on-screen, of which more than 100 were visited on-site. The results of the inspections revealed that ortho-imagery was mostly up to date, but photo-interpretation was not always reliable or conclusive (European court of auditors 2016). The level of error for payments awarded by the European Agricultural Guarantee Fund (EAGF) is estimated each year. In 2014, the level of error was estimated at 2.9% (2% materiality threshold) based on 183 audited transactions. Area-related errors accounted for 44% of the estimated EAGF error rate, but half of these errors were below 2% (European court of auditors 2016).

5 Conclusion

The Common Agricultural Policy was developed to support rural development. Area-based payments are one of the CAP instruments available to the EU Member States. Various procedures (European court of auditors 2016) have been implemented to control spending on area-based payments and to verify whether the beneficiaries comply with the requirements and standards under cross-compliance. The control procedures are similar in the EU Member States, and they are performed annually. The greatest errors are usually noted in the defective spatial structure of the land, but not every breach is intentional. In this study, an analysis of the differences between the parcel area declared in the payment application and the area measured on-site revealed that the distance between a parcel used and the farmstead (owner's address) does not affect the level of error. One may note that most differences occur in the case of parcels located the farthest, although this correlation is statistically weak. The defective spatial structure of land (allocation of parcels) can be remedied through land consolidation (Latruffe and Piet 2014; Hendricks and Lisec 2014) and the exchange of parcels. In the sample under study, the reasons behind the phenomenon discussed may be associated with the quality of documents used to complete applications. They vary in quality and sometimes they are of extremely poor quality. That is why the best way to avoid errors is to obtain professionally take measurements on-site prior to submitting each payment application.

ACKNOWLEDGEMENT: This research was financed by the Ministry of Science and Higher Education of the Republic of Poland under grant No. 28.610.015-300.

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Acta geographica Slovenica, 60-2, 2020, 21–31

WHY AND HOW CENTRAL EUROPE'S LARGEST LOGISTICS COMPLEX DEVELOPED ON A BROWNFIELD SITE

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Sosnowiec – Amazon Fulfillment Center under construction (2017). The biggest logistics facility in the largest logistics complex on a brownfield site in Europe.

DOI: https://doi.org/10.3986/AGS.7085
UDC: 911.375:711.553(438)
COBISS: 1.01

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Why and how central Europe's largest logistics complex developed on a brownfield site

ABSTRACT: The aim of the article is to explain the dependence on key factors and development path in the expansion process of the largest Central European logistics complex situated on postmining brownfield. Here, a highly original example is the city of Sosnowiec in the Katowice conurbation (Poland). In the article, the development of this complex and its model of spatial diffusion, with an indication of both facilitating and restricting aspects of its further expansion is discussed. The following issues are also brought to light: spatial location, urban policy, transport accessibility and local labour market. In the article, the development of this complex is discussed according to model of spatial diffusion.

KEY WORDS: logistics complex, brownfields, urban polycentricity, facility location, Poland

Zakaj in kako je potekal razvoj največjega srednjeevropskega logističnega kompleksa na degradiranem zemljišču

POVZETEK: Namen članka je pojasniti odvisnost od ključnih dejavnikov in razvojno pot širitve največjega srednjeevropskega logističnega kompleksa na nekdanjem rudarskem zemljišču v poljskem mestu Sosnoviec v somestju Katovic. V članku avtorji obravnavajo razvoj navedenega kompleksa in model njegove prostorske razpršenosti, pri čemer predstavijo tudi vidike, ki podpirajo ali omejujejo njegovo nadaljnjo širitev. Poleg tega proučujejo naslednja vprašanja: lokacijo v prostoru, urbanistično politiko, prometno dostopnost in lokalni trg dela. Gradnjo kompleksa obravnavajo na podlagi modela prostorske razpršenosti.

KLJUČNE BESEDE: logistični kompleks, degradirana zemljišča, urbana policentričnost, lokacija storitve, Poljska

This paper was submitted for publication on November 10th, 2018.
Uredništvo je prejelo prispevek 10. novembra 2018.

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1 Introduction

The growing role of logistics in the European and global economies is among the key attributes of modern globalisation. One of the results of this phenomenon is the growing number of logistics centres and their complexes in both developed and developing countries (De Ligt and Wever 1998; Hesse 2004; 2008; Skowron-Grabowska 2009; Dablanc and Ross 2012; van den Heuvel et al. 2013; Walker and Manson 2014; Sakai, Kawamura and Hyodo 2015; Verhetsel et al. 2015; Straka and Wyrwich 2015; Aljohani and Thompson 2016). Undoubtedly, the post-socialist countries of Central Europe can be classified to the latter group. In this region, the development of logistics based on vehicle transport has been characterised by factors already identified in highly developed countries: deindustrialisation; spatial centralisation of stockholding adopted by manufacturers and retailers to achieve cost savings in their supply chains or rapidly rising land prices and increasing traffic congestion in urban areas (Allen, Browne and Cherrett 2012; Kraft 2012; Szołtysek 2016). One should also note the strong regional contrast of wages in this sector between East-Central and Western Europe, the great surplus of jobseekers in this sector compared to offers of employment and a strong rise in GDP in the mentioned countries (Roudná 2011; Jurásková and Macurová 2013; Grondys and Dragolea 2016) However, the most important argument pertains here to the deficit of cutting-edge logistics centres that would meet modern freight requirements. At that time, the logistics centres were obsolete in terms of infrastructure and usually situated in the city centres or heavily built-up areas (Haywood 2001; O'Connor and Parsons 2001; Strauss-Wieder 2010; Burdzik et al. 2013; Cui, Dodson and Hall 2015). Currently large logistics complexes develop both in accordance with the logistics sprawl and with the logistics anti-sprawl model (Aljohani and Thompson 2016; Dablanc, Ogilvie and Goodchild 2014; Krzysztofik, Kantor-Pietraga and Spórna 2019). A facilitating factor in both models, meanwhile, is the availability of large derelict areas that offer space for locating even several dozen facilities. However, the availability of brownfields in urban cores is not the only condition for development of large logistics complexes. The article aims to explain – the complicated origins and unique development path of the largest logistics complex in Central and Eastern Europe located on a post-mining brownfield. This goal is important because research on such large logistics complexes is a research gap in the literature. Furthermore, the case of the »Bór« logistics zone in Sosnowiec in Poland presented in the article is unique due to its location within a former sandpit.

2 Methods

2.1 Study area

The Bór logistics complex is situated in southern Poland in a convenient location at the intersection of major communication routes of Poland and Central and Eastern Europe, i.e., motorways A1 and A4, and S1 (Figure 1). In the vicinity, there is also an international airport (Katowice Airport). The travel from Krakow and Ostrava to the logistics site takes 1 hour, whereas the travel time from Wrocław is 2 hours (Figure 1).

The specificity of this area also manifests in its previous usage. Until the end of the 20th century it served as an industrial area (filling sand mining), whereas from the beginning of the 21st century, it has been a place of dynamic development of the largest logistics area on brownfield land in Central Europe, complemented with other service and productions functions substantially related to transport (HGV servicing, car body production) (Figure 1).

2.2 Data collection

The studies on the development of »Bór« logistics complex were based on three sources. The first, concerning data of Sosnowiec City Council and companies engaged in the development of this area allowed construction dates of each facility to be determined with regard to the exact month and year. This pertained also to outward extension of the already existing facility. Moreover, information on the area of construction plots and facilities themselves were also collected. Regarding the subject of the article, the analysis also covered all planning and strategic documents pertaining to the analysed area with particular focus on the *Master plan for Sosnowiec* (2016). In order to obtain a full picture of the changes that are taking place and to make an attempt to develop future projections, the authors also interviewed 12 the key figures operating in this area (i.e., the local authorities, Panattoni, Goodman, NGO).

The article uses two main research methods. First, desk research focused on analyzing facts and processes related to logistics development in the region (see subchapter 3.2). The second group of methods consisted of 12 interviews with the key stakeholders (representatives of municipal authorities, logistics companies, the Katowice Special Economic Zone and NGOs), since certain flows of information between individual entities operating in the analysed area, both direct and indirect, formal and informal, also proved to be significant. Two interviews were conducted as a telephone conversation (kind of CATI method), while the others were – face to face. All of them had a free-form review.

The use of desk research analysis as well as a interview (soft method) was aimed at confirming the correctness of treating the studied phenomenon in terms of diffusion of innovation. The model of spatial diffusion distinguishes 4 stages of diffusion of a new type of socio-economic feature or phenomenon and 5 groups of adopters of diffusion (see in brackets): penetration (innovators, early adopters), expansion (early majority), consolidation (late majority), full saturation (laggards) (Sanders ed. 2007; Rogers 2003. Because the number of facilities that have been established or may still be established in this area is less than 30, we refrained from using a rigid percentage range to define the boundaries between individual stages. We only adopted guidelines for the penetration stage – the innovator group, and the boundary of around 50% of all facilities between the expansion (early majority) and consolidation (late majority) stage.

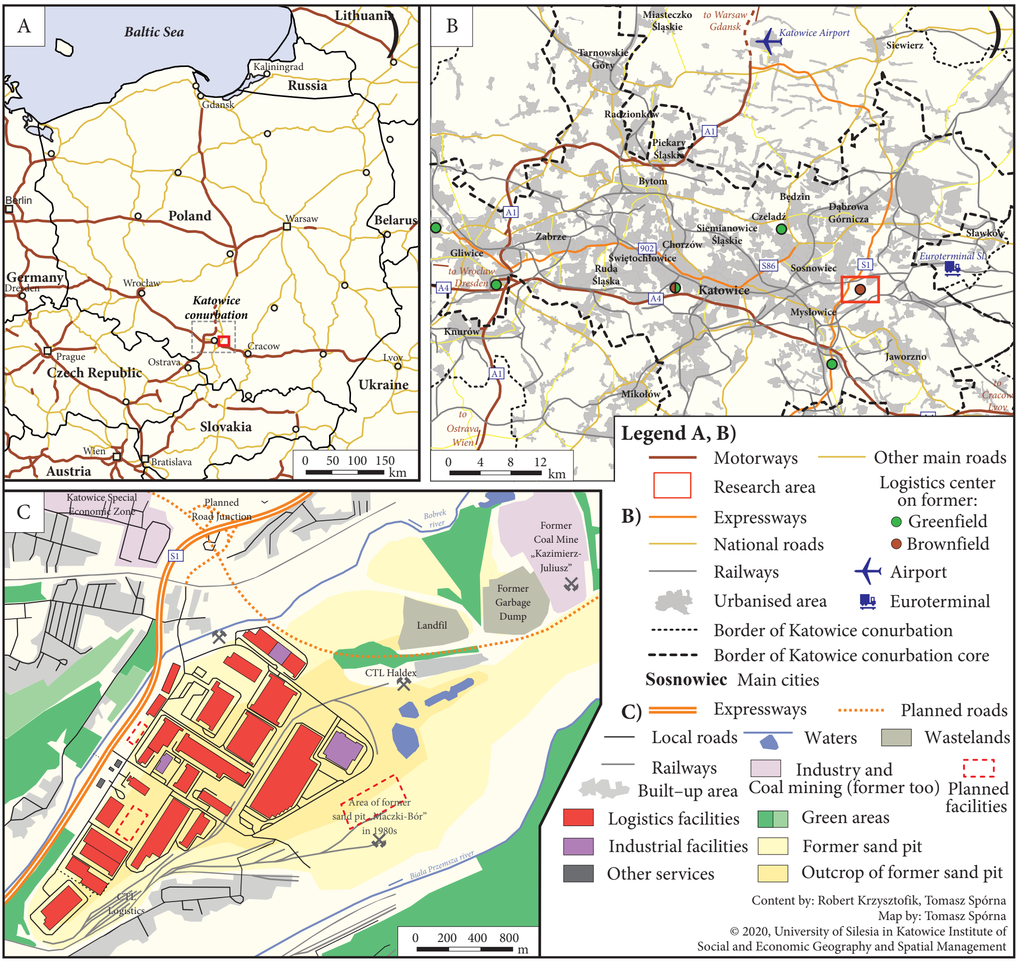

Figure 1: Study area. A) Location of the study area in Central and Eastern Europe; B) Katowice conurbation; C) local scale (the city of Sosnowiec)

3 Results

3.1 Pre-logistics stage of development

The development of the Bór logistics complex in Sosnowiec has an exceptionally atypical background. This exceptional nature stems not only from the fact that it was founded on a brownfield site but also because only 15–20 years earlier, the area was located as much as 30 metres lower than in the present day. This location was related to the existence of one of the few larger sandpits in southern Poland. On the eastern boundaries of the Katowice conurbation (the Upper Silesian Industrial Region), sand was excavated on a total area of over 20 square kilometres (Dulias 2010). Of these largest sandpits, the smallest was »Maczki-Bór« filling stone quarry (FSQ) in Sosnowiec (Figure 1). The sandpit was divided into two exploitation areas: Bór Wschód (East) and Bór Zachód (West). This logistics complex is situated at present within the former Bór Zachód (West) exploitation area.

3.2 Stimulators and destimulators of development for the Sosnowiec logistics complex

It was no accident the largest logistics complex in Central and Eastern Europe developed in a former sandpit. An analysis of the chart in Figure 2 demonstrates that around 2010, positive effects of many factors conducive to development accumulated. They had a trans-regional nature (development of expressways and airports in southern Poland, decrease in greenfields, expansion of large logistics companies and increase in demand for modern logistics facilities). However, the success of the area in question was determined by a combination of several causes with a decidedly local nature (providing a very large, 2 km^2 brownfield for the investment, strong pro-investment policy of the city and the company administrating the brownfield, very good accessibility that was competitive compared to post-coalmining brownfields, high unemployment rate, strong social acceptance of new companies and diminishing possibilities for location of logistics centres on brownfields) (see Szołtysek 2016; Krzysztofik, Kantor-Pietraga and Spórna 2013; Krzysztofik et al. 2019). The accumulation of the above drivers caused a dynamic development of logistics functions, which

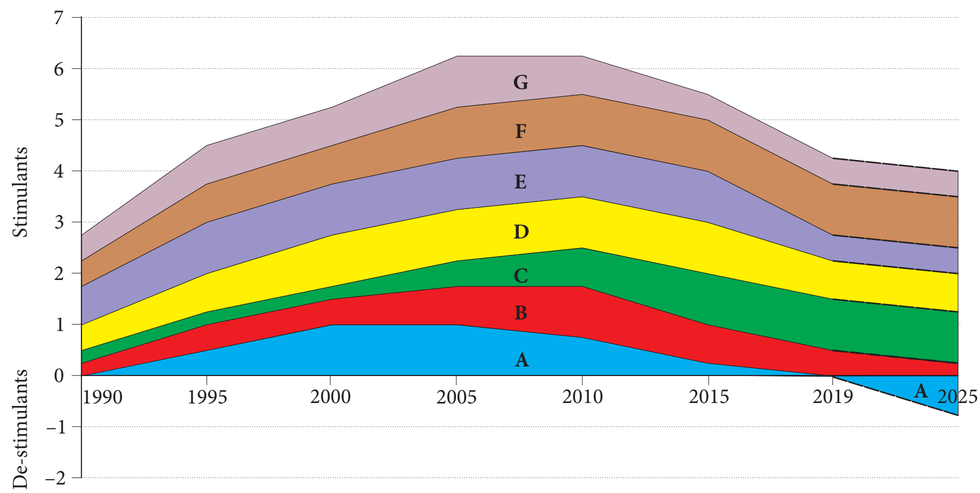

Figure 2: Emergence of the biggest logistics complex on a postmining brownfield site in Central and Eastern Europe. Explanations: A – labour market; B – accessibility of brownfield (considered); C – national system of expressways; D – local policy; E – acceptance of local community; F – expansion of foreign capital; G – regional system of expressways and air cargo.

to some extent surprised even the local authorities. From another perspective, it bears mentioning that the key investor in this area – Panattoni – did not decide to balance its activities on brownfield sites compared to those performed on greenfield sites on a broader scale in Poland until 2016. Though it had already pursued such investments earlier, it was not until 2017 that well-localised brownfields were recognised as not only a means for balancing greenfields but in many cases as the only option.

Full development of the former sandpit is also accompanied by changes that only several years ago could have slowed or even stopped the process under discussion. The most painful of them is the change on the labour market: a noticeable lack of workers, caused by rapid depopulation. In the years 2000–2019, Sosnowiec lost around 50,000 inhabitants (a fall from 235,000 to 185,000). Furthermore, social opposition is on the rise, focused on criticism of such a high density of trucks and road traffic problems in districts neighbouring logistics complexes. Not insignificant is also the change in urban policy: from the stage of »investment euphoria« still visible in the years 2015–2017, to the stage of »financially beneficial approval«.

3.3 Diffusion model in the logistics site development

The first investor (innovator) did not appear at the site until 2008. It was a branch of the German company Salzgitter Mannesmann, who erected steel product warehouses. For over 5 years their facility stood »alone« surrounded by the re-cultivated sandpit (Figure 3). On the one hand, the said facility was a symbol of attempts to reuse this area for business purposes, which were extensive though ineffective for a long time. On the other, it symbolised the investor's struggle with all the restrictions mentioned in the previous subchapter. When referring this investment to the concept of the diffusion of innovations, one ought to consider it a stage of penetration (Sanders 2007).

The breakthrough in the development of the discussed logistics and service complex discussed in the article took place in the years 2012–2015 . At that time, CTL Logistics sold a considerable part of its property to large developer companies Goodman, Panattoni and Raben (early adopters). They all decided to create their logistics parks there. This factor had an unquestionable impact on the synergy of the advances development of this area (cf. Verhetsel et al. 2015). The said synergy was additionally reinforced by the factor of a short geographic distance between the logistics facilities and end delivery sites (cf. Allen et al. 2012; Cidell 2010). It should be noted that this period was linked to a clear growth of the role of individual pro-investment drivers in the logistics sector (Figure 2). This growth was visible both with respect to internal factors (labour market, urban policy, new local road investments and airport expansion), and supralocal factors (FDI inflow to Poland, extension of the road network in south Poland, shrinkage of greenfields, greater interest of global businesses in the Katowice region).

In the 2012–2015 period, investments in the former sandpit site were made by: Raben – two facilities, Jeronimo Martins – distribution centre, Panattoni Park I, II, Goodman – 3 facilities (Figure 3). In terms of infrastructure, this was complemented by the construction of 3 new internal roads within the complex areas. Moreover, several minor infrastructural investments were made within the area. In the view of the spatial diffusion model it should be noted that the discussed phenomenon resulted in the formation (expansion and early majority) of logistics facilities on various sites of the said area.

The new development stage, i.e., consolidation (late majority), occurred in the years 2016–2017. In that period, new facilities were founded by Panattoni Park III, Goodman (Eurocash) and DBK The total area of facilities commissioned throughout this stage is over 200,000 m². This period consolidated 3 key cores of development – northern (dominated by Panattoni Parks), central (dominated by Panattoni Parks and other companies) and southern (dominated by Goodman Park and Raben).

Until the beginning of 2018, were commissioned: an ambulance assembly plant of the Polish company Auto Form, Swedish HAGS and also two Panattoni Parks V and VI. The last (2019) investor in the discussed area is developer – 7R. In mid-2019, it was building 3 BTS logistics centres directly next to the S1 expressway.

By the end of 2019, the total surface of logistics facilities (»under the roof«) in the analysed area will exceed around 550,000 m² (Figure 4), and will total approximately 1,000,000 m² including accompanying infrastructure (parking lots, docks, roads, greenery and others). CTL Logistics is also preparing a new investment site near the Amazon facility. Total area of all facilities (manufacturing, other services) in this area is more than 580,000 m² (Figure 4).

The next stage in the development of the discussed investment area began in 2018 and will probably last until 2020–2022. Regarding the model of spatial diffusion of innovation, this stage is referred to as the stage of full saturation (Sanders 2007).

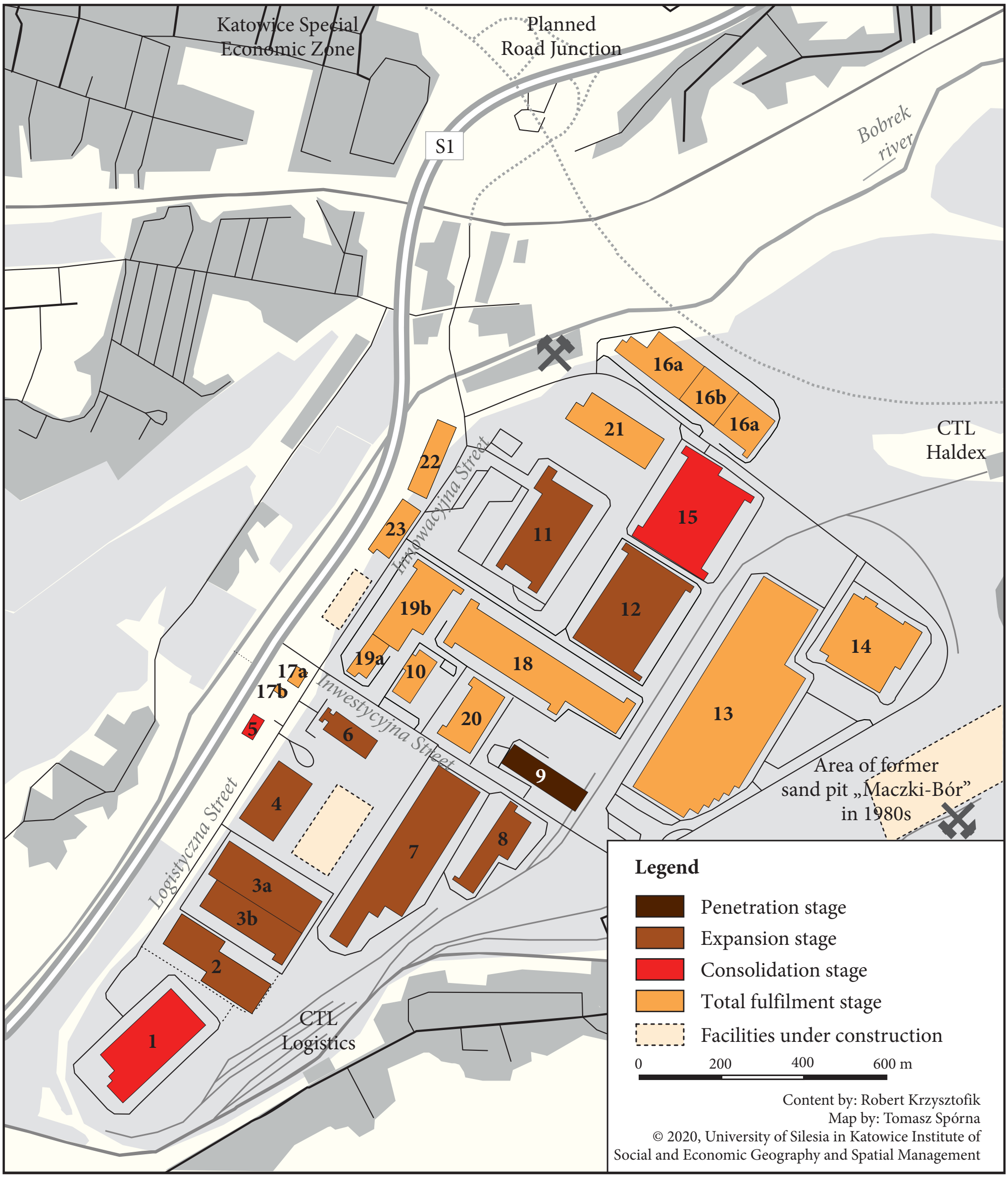

Figure 3: Logistics site development stages (Sosnowiec, Poland – former sand pit). Markings: I – penetration stage; II – expansion stage; III – consolidation stage; IV – full saturation stage; Numbers: 1 – Goodman Poland (Eurocash); 2 – Goodman Poland (DSV Solutions); 3a,[b – expansion] – Goodman Poland (Inter Cars); 4 – Raben II; 5 – DBK Truck Center; 6 – Raben I; 7 – Panattoni Park II A; 8 – Pannatoni Park II B; 9 – Salzgitter Mannesmann Stahlhandel; 10 – Auto Form; 11 – Jeromino Martins; 12 – Pannatoni Park I (A,B); 13 – Amazon Fulfillment Poland; 14 – Hags; 15 – Panattoni Park III; 16a – Panattoni Park IV (DSV Solutions; Corenso); 16b – Amazon (manufacturing); 17a – Orlen Oil Station; 17b – Mc Donalds &; 18 – Panattoni Park V A; 19 – Panattoni Park V B; 20 – Panattoni Park V C ; 21 – Panattoni Park VI; 22 – 7R (InPost); 23 – 7R.

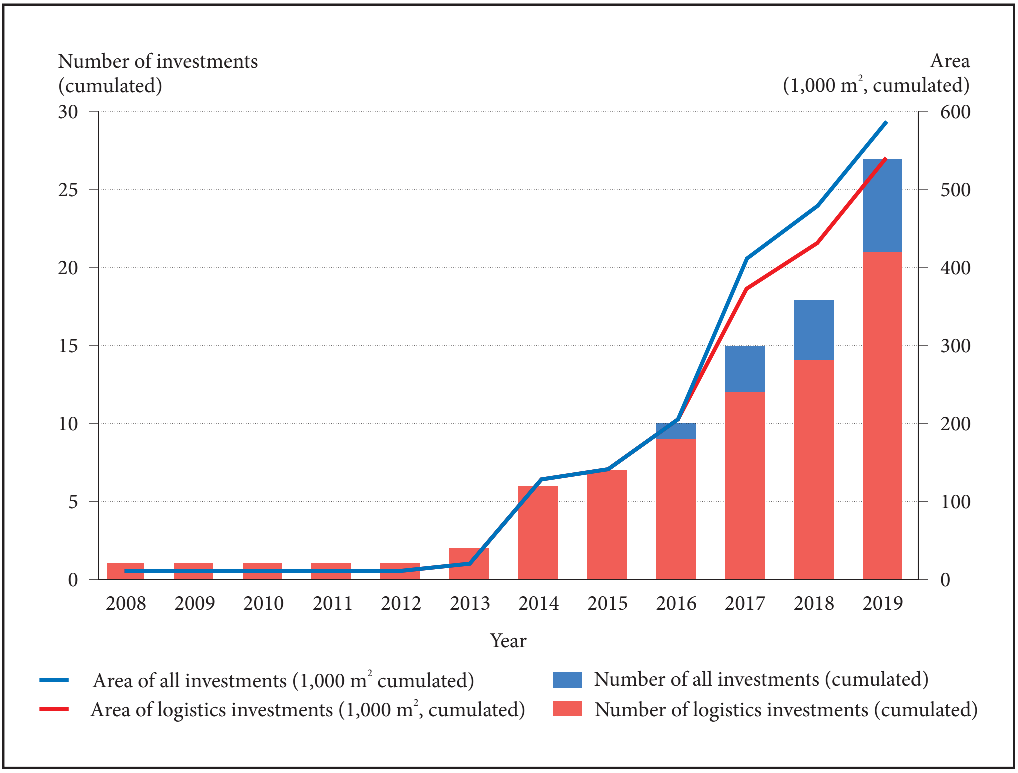

Figure 4: Dynamics of investments inside of the logistics complex »Bór« in Sosnowiec, Poland

4 Discussion

The development of economic complexes, such as the one discussed in the article, can be considered in terms of both diffusion and synergy. In the analyzed case, due to specific backstage development (no cooperation, we are building because we have already built here, and not because we are counting on measurable benefits from the existence of other objects', the existence of competing companies) it was assumed that the diffusion attribute prevails. In this case, a large investment area was a location niche for many independent investments of different companies that at the same time built their facilities in other parts of the region (cf. Sheffi 2012; Krzysztofik et al. 2019).

Given proper conditions, i.e., the polycentric nature, low land prices in core cities, the specific course of expressways, such a niche could be located within the agglomeration core and not in the suburbs, contrary to the popular belief (Davoudi 2003; Heitz and Dablanc 2015). Moreover, relatively low land prices are also significant in this matter. Another important argument supporting the location of mega centres is the absence of the need to invest in micro urban consolidation centres (MUCC) and urban logistics spaces (ULS), which are subcentres that facilitate good deliveries in high-density urban monocentric metropolitan areas (cf. Dablanc, Ogilvie and Goodchild 2014; Janjevic and Ndiaye 2014; Woudsma, Jakubicek and Dablanc 2015). Regarding logistics investments, this fact is to some extent contradictory to the sprawl processes that have been observed worldwide (Krzysztofik et al. 2019).

A no less important problem is the relationship between logistics centre expansion and brownfield redevelopment. This relationship is in keeping with the policy of sustainable development and reindustrialisation of brownfields well-known in Eastern and Central Europe (cf. e.g. Wirth, Černič Mali and Fischer 2012; Frantal et al. 2013; Perić 2016). In the case of this particular logistics complex there is another important question:

why did it develop on the site of a defunct sandpit, and not one of the post-coalmining brownfields that are very numerous in this region? When answering this question, attention should be drawn to the following facts. First, active policy of the defunct sandpit's owner is by far more expansive than the actions of the state company – SRK (Company for Restructuring of Coalmining) that controls most post-coalmining brownfields in the Katowice region. A model in which two expansive private entities cooperate is far more effective than the more difficult relationship between logistics company and state mining restructuring company. Projects in which a third partner, the Katowice Special Economic Zone or city authorities appear, are the exception.

In the investigation of the phenomenon of the investment area in question, it should also be noted that the area developed was a very large, compact site of a defunct open-cast, and the numerous underground coal mines of the region have smaller surfaces. Furthermore, post-coalmining brownfields in the city of Sosnowiec are not always very accessible from the main expressway.

Also very significant was the periodisation of development, underlined in the article. Since the end of the 1990s, the best locations on post-coalmining brownfields were redeveloped by industrial investments. At that time, the logistics sector was more focused on suburban greenfields (Krzysztofik et al. 2019). Logistics companies interested in good accessibility of large urban cores were thus limited to brownfields. As P. Kociołek, environmental director at Panattoni, stated in an interview (December 2017), »*brownfields are a natural stage of expansion of this sector in cities*«.

Taking the above into account, also the possibilities of establishing such complexes in the future should be discussed. Especially as there exist more post-sandmining sites that could potentially become new areas for investment. However, due to their distance from the conurbation core and the emerging strong social need for turning defunct sandpits into leisure areas, the analysed case of Sosnowiec will probably be unique. Dispersion of logistics investments among complexes that are more numerous but smaller than the Sosnowiec one is also brought about by the most important destimulant for the development of logistics: lack of employees caused by depopulation of the Katowice region. Some large logistics companies reacted rapidly, creating their own bus lines to bring in employees from up to 50–60 km away. The trend of locating new logistics centres in greater dispersion is confirmed among others by a new phenomenon observed in the Katowice conurbation. It involves building logistics centres in intraurban greenfields and in the place of demolished 19th century industrial plants that are slightly less accessible in terms of transport. In both cases (postindustrial brownfields and intraurban greenfields) the key factor is low prices and lack of the legal and ownership problems so common for many greenfields in suburban areas. In such cases it is also relatively easier to find employees.

5 Conclusion

The founding of the logistics complex on the former sandpit site in Sosnowiec is quite an unusual phenomenon. The trend aims to locate giant investment clusters of this sort primarily towards the suburban area situated at a distance from core cities of agglomeration, which are in general greenfield-type investments. Although the discussed investment area was not formed in the very city centre, it lies in an urban area within the administrative boundaries of a 2-million urban area core. This example is therefore one of the most significant examples of the phenomenon of anti-sprawl in logistics (Krzysztofik et al. 2019). The unique nature of this area stems also from the fact that it is the first case of this type and size in Europe to be founded on a former sandpit site.

The article also indicates that the development of large clusters of logistics centres on brownfield sites, as pointed out in the article, will have more advantageous conditions in polycentric and post-industrial agglomerations. However, the most advantageous conditions would come together with overlapping polycentric and post-industrial attributes. Because new niches for location of logistics facilities exist, also within post-coalmining brownfields, further development of the logistics anti-sprawl phenomenon should be expected in the region under study, although it will probably not concern former sandpits. The existence of a large defunct sandpit in Sosnowiec thus had, in addition to several other more egalitarian drivers, a particular significance in the process of development of the largest logistics complex on a brownfield in Europe.

The article also emphasizes that the development of this type of logistics complexes can be considered in terms of diffusion. Regardless of the noticeable aspect of the synergy. The size of the analyzed area allows even competing companies whose free development is based on the idea – »I build where others build, but I develop business regardless of neighbors«.

ACKNOWLEDGEMENT: We would like to thanks management of CTL Logistics, Panattoni Europe, Raben Logistics Polska sp. z.o.o. and Goodman Poland for all information that deepened explanations presented in paper. Our special thanks for Piotr Kociołek – Environmental Director – Panattoni Europe and Anita Petrykowska – Marketing and Communication Director – Panattoni-Poland.

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Acta geographica Slovenica, 60-2, 2020, 33–55

THE CORRELATION BETWEEN DEMOGRAPHIC DEVELOPMENT AND LAND-USE CHANGES IN SLOVENIA

Uroš Horvat, Igor Žiberna

Overgrowth on former terraced vineyards between Dravinjski Vrh and Majski Vrh
in eastern Haloze region (northeastern Slovenia).

DOI: https://doi.org/10.3986/AGS.7611
UDK: 911.3:711.14:314(497.4)
COBISS: 1.01

Uroš Horvat[1], Igor Žiberna[1]

The correlation between demographic development and land-use changes in Slovenia

ABSTRACT: The paper focuses on determining the degree of correlation between land-use changes and demographic development in Slovenia. The authors conclude that there is still insufficient evidence in the literature for a correlation between these two processes, because quantitative studies addressing these links are very rare and mostly cover small and specific areas. In the case of Slovenia, Spearman's correlation coefficients are quite low, which confirms that land-use change processes are complex and not dependent solely on individual demographic and socioeconomic factors. Despite the low correlation coefficients, our findings indicate that changes in land use are significantly influenced by changes in age structure and population growth. In areas with population growth the share of arable land is shrinking, whereas in areas with depopulation and a rising aging index the share of partially overgrown land is growing. In the following analysis, the authors focus their analysis on a case study of the Mura and Central Slovenia statistical regions, which lie on opposite poles with regard to development, and thus show differing trends in land-use changes.

KEY WORDS: land use, arable land, afforestation, demography, age structure, Slovenia

Povezanost med demografskim razvojem in spremembami rabe zemljišč v Sloveniji

POVZETEK: Avtorja se osredotočata na ugotavljanje stopnje povezanosti sprememb v rabi zemljišč in demografskim razvojem v Sloveniji. Ugotavljata, da v literaturi ni dovolj dokazov o povezavi med obema procesoma, saj so kvantitativne študije, ki obravnavajo te povezave, zelo redke in večinoma vezane na proučevanje prostorsko majhnih in specifičnih območij. Tudi na primeru Slovenije so Spearmanovi koeficienti korelacije precej nizki, kar potrjuje da so procesi spreminjanja rabe zemljišč kompleksni in niso odvisni le od posameznih demografskih in socio-ekonomskih dejavnikov. Kljub nizkim korelacijskim koeficientom pa rezultati nakazujejo, da na procese spreminjanja rabe zemljišč pomembno vplivajo spremembe v starostni sestavi prebivalstva in rast prebivalstva. V območjih z rastjo prebivalstva se obseg obdelovanih površin zmanjšuje, v območjih depopulacije in višanja indeksa staranja pa narašča delež zemljišč v zaraščanju. V nadaljevanju analize se avtorja osredotočita na analizo primera v Pomurski in Osrednjeslovenski statistični regiji, ki glede na stopnjo razvitosti ležita na nasprotnih polih, in kažeta različne trende v spremembah rabe zemljišč.

KLJUČNE BESEDE: raba zemljišč, obdelovalne površine, ogozdovanje, demografija, starostna sestava, Slovenija

This paper was submitted for publication on September 17th, 2019
Uredništvo je prejelo prispevek 17. septembra 2019

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1 Introduction

Land use is an element that most distinctly characterizes a specific landscape. It refers to land exploitation through human activity and is a good indicator of landscape structures and processes (Kladnik 1999). It reflects the mutual effects between natural, historical, and socioeconomic factors (Gabrovec and Kladnik 1997). Land use and its changes also reflect changing social values, as well as the impact of various decisions on the transformation of farm production and land use in the past (Bičík, Gabrovec and Kupková 2019). From the very beginning, one of the most important land-use functions has been land cultivation and food production, which ensures the survival of individuals and the human race as a whole.

Harmony between life satisfaction, health, lifelong learning opportunities, feeling of safety, and an appropriate environment is required to ensure appropriate prosperity within a given society (Vrabič and Kek 2012; Tiran 2017). Providing high-quality and healthy food in adequate quantities is an important quality-of-life indicator. One of the most important causes of food shortages is also land-use changes, especially shrinking areas of arable land either due to construction, grass overgrowth, or afforestation (Gabrovec and Kladnik 1997; Gabrovec and Kumer 2019). These processes reduce food security in underdeveloped countries, but in altered economic conditions they may also threaten developed countries (Cuff and Goudie 2009).

Compared to other EU countries, land-use changes in Slovenia show unfavorable self-sufficiency trends. EU land-use data are collected by Eurostat, which in 2009 began issuing annual statistical reports as part of the LUCAS project (Internet 1). The first report covered only twenty-three EU member states, leaving out Bulgaria, Romania, Cyprus, and Malta (Gallego, Palmieri and Ramos 2015). This method differs slightly from the one the Slovenian Ministry of Agriculture uses for its regular online reports on agricultural land use, with the Slovenian method being significantly more detailed (Interpretacijski ključ … 2013), but it nonetheless provides sufficiently good insight into the current state of land use in the EU.

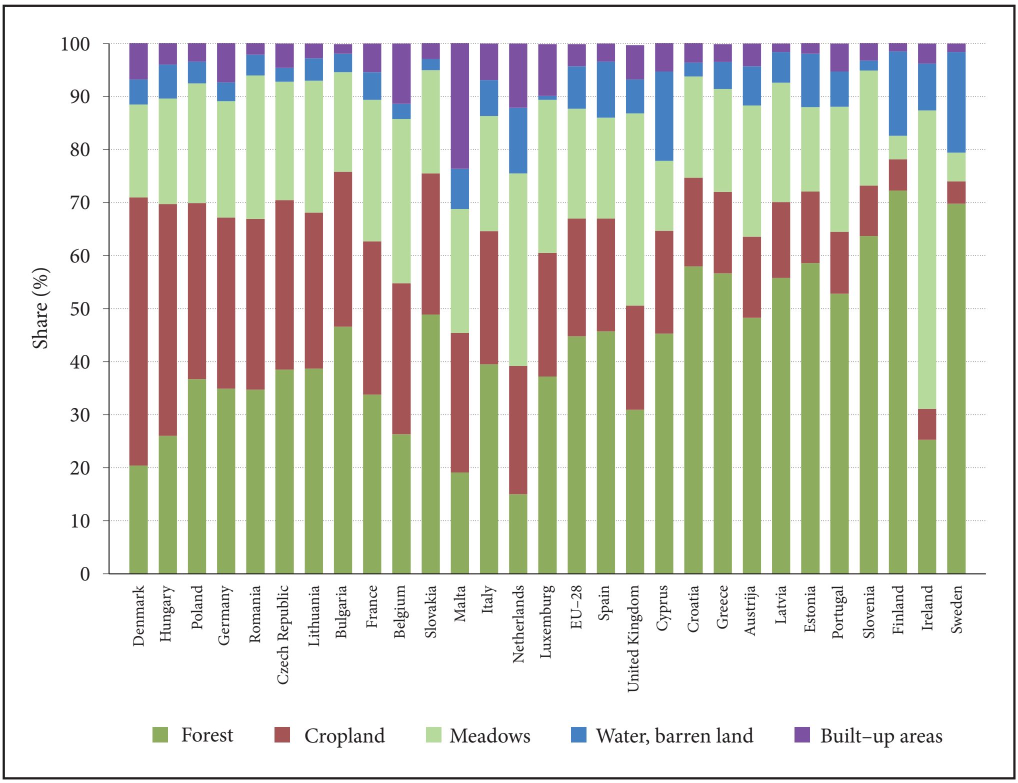


Figure 1: Breakdown of land use in the EU-28 in 2015 (% of total area).

According to the 2015 Eurostat data, woodland predominated among the land-use types in the EU-28 (44.9%), followed by cropland (22.2%), grassland (20.7%), water areas and wetlands (8%), and built-up and other anthropogenically modified land (4.2%; Figure 1). Scandinavia had the largest share of woodland and Slovenia was in third place (63.7% wooded). As a rule, the share of cropland (Figure 2) is inversely proportional to the share of woodland. Less than 6% of cropland was typical of Sweden, Ireland, and Finland, followed by Slovenia (9.5%). Denmark and Hungary had by far the highest shares (50.6% and 43.7%, respectively). The average share of cropland in the EU-28 was 22.2%.

Compared to other EU member states, Slovenia has an above-average share of woodland and a below-average share of cropland. A high share of woodland can be an advantage because forests function as carbon sinks and, in terms of energy industry and economics, wood is an important renewable resource and a raw material whose added value should be increased by the wood industry. However, the high share of woodland in Slovenia also results in a decrease in cropland. According to Plut (2012), a wood cover of approximately 50% would suffice for a stable balance between food production, ecosystem, and wood in Slovenia.

The area of cropland per capita is an even better self-sufficiency indicator (Figure 3). It is estimated that in the EU climate zone, c. 0.3 hectares of cropland per capita would be required to ensure food independence (Perpar and Kovačič 2006). Conditions in the EU member states are not favorable in this respect.

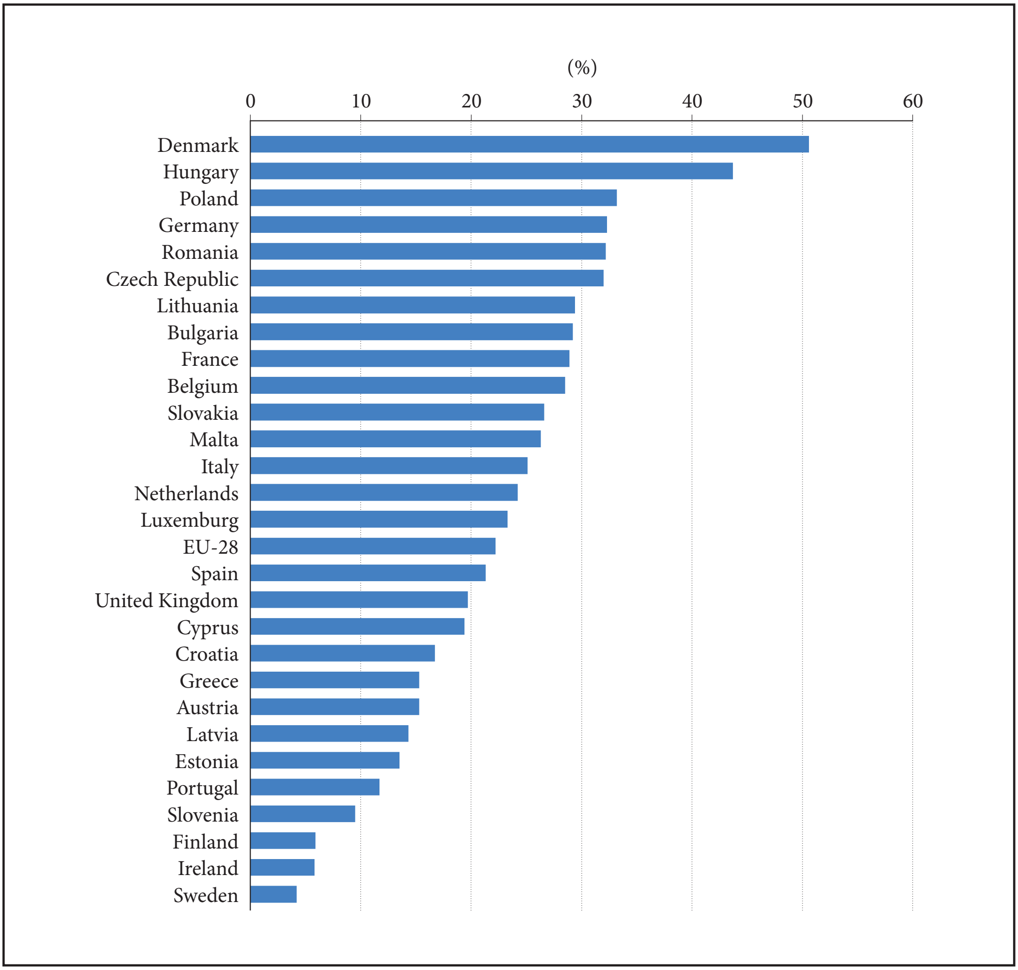


Figure 2: Breakdown of cropland in the EU-28 in 2015 (% of total area).

Only twelve countries fulfilled this condition in 2015. Compared to other countries, Slovenia is practically in last place, having only 0.0355 hectares per capita (the EU average being 0.1903 hectares). The problem of food security is thus shared by most EU countries, in which the situation in Slovenia is one of the worst. Monitoring the changes in Slovenia's cropland and maintaining a minimum that still guarantees food security are key factors of future development. It is alarming that in Slovenia cropland is shrinking in the areas with the highest production potential (Žiberna 2018).

Land use and its changes have been relatively well covered in literature. Focusing on Slovenia alone, land-use changes have been examined by many authors, such as Gabrovec and Kladnik (1997), Petek (2002), Petek and Urbanc (2004), Paušič and Čarni (2012), Lisec, Pišek and Drobne (2013), Ribeiro, Ellis Burnet and Torkar (2013), Gabrovec and Kumer (2018), Žiberna (2018), and Ribeiro and Šmid Hribar (2019).

At the same time, the impact of demographic change on land-use change has been relatively poorly covered in quantitative studies. Studies dealing with these correlations are very rare and mostly cover small and specific areas. Rajan and Shibasaki (2000) examined the correlations between population and economic power on the one hand and land-use changes on the other in Thailand. They highlighted the correlations between rural-urban migration and the decline in arable land resulting from an increase in built areas. Shi et al. (2010) analyzed the impact of population dynamics on land-use changes in the Tarim Basin and

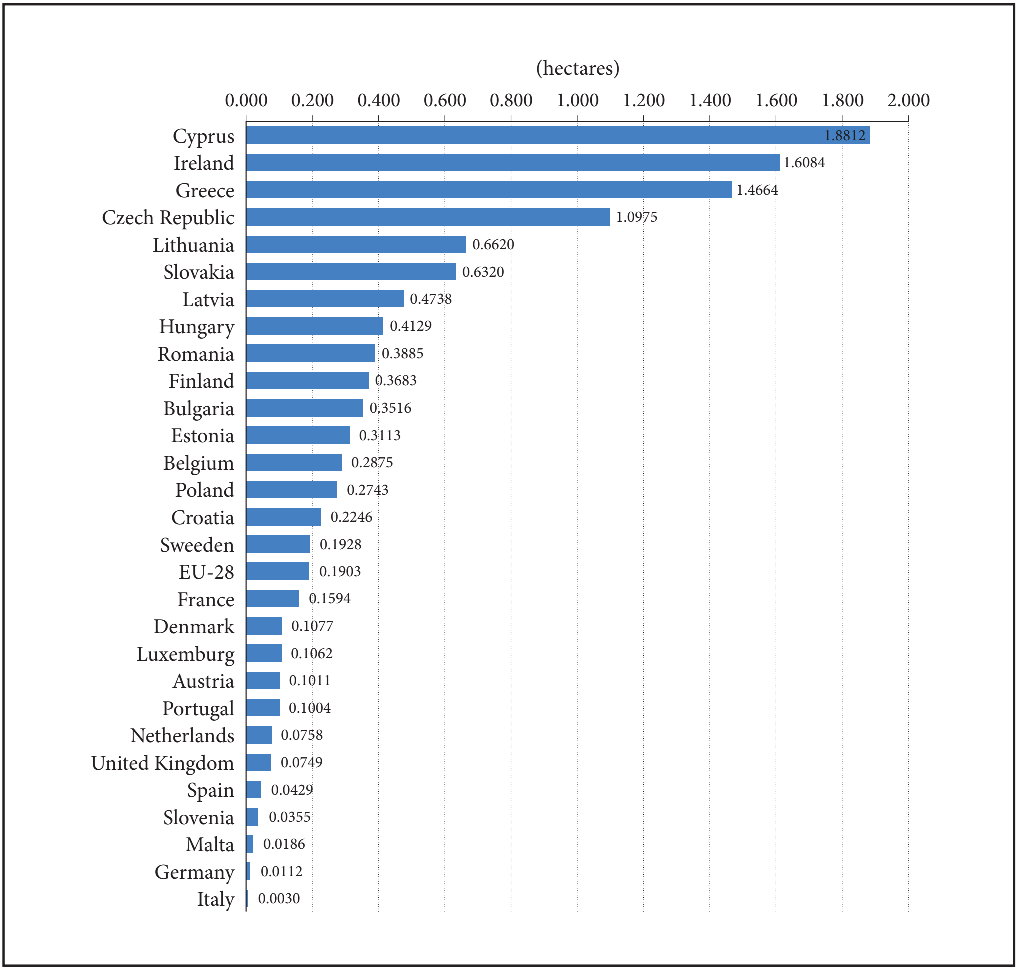


Figure 3: Cropland per capita in the EU-28 in 2015 (in hectares).

established that population growth drives increases in farmland, primarily to provide the required quantity of food. Gould, Martinuzzi and Parés-Ramos (2012) analyzed the impact of urban population growth on the decrease in arable land in Puerto Rico, whereby they also examined changes in ecosystem services. Hansen et al. (2002) studied the western part of the US to establish that it is not completely clear why the population growth rate, economic conditions, and land-use patterns change faster in some areas than others. Certain areas with similar land use are growing quickly, whereas others in the same region are losing its population. Something similar was also determined by Kroll and Haase (2010), who report that recent demographic change, characterized by a decreasing and aging population, is a main factor influencing future land-use change in Europe. They found a correlation between land use, natural population dynamics, and net migration in most of the growing regions in western Germany, whereas in the eastern German regions with a shrinking population, economic variables are a more important factor influencing land-use change. Their cluster analysis further showed that areas of growth and depopulation in Germany are connected with both urbanization and demographic change, and that neither a decreasing nor an aging population imply reduced land consumption for housing and transportation.

Also relevant to Slovenia is the study by Ferreira and Petek (2005), who defined changes in land use and the socioeconomic structure of the population in northwest Upper Carniola. Their analysis showed that the extensive social changes after the Second World War (i.e., demographic growth, depopulation, abandonment of farming, and intense economic development) caused extensive grass overgrowth and afforestation, which continue today. Ribeiro (2017) also partly examined land use and demographic characteristics at the local level.

This article analyzes the degree of correlation between land-use indicators and selected demographic indicators in Slovenia or, in other words, it uses a quantitative analysis to determine the correlation between land-use change and selected demographic indicators.

2 Methods

The 2000 and 2018 land-use data were taken from reports by the Slovenian Ministry of Agriculture, Forestry, and Food, which annually posts land-use data online in .shp format (Internet 2). The vector data for each land-use category was converted into raster data with 5 × 5 m cell size. The method for land-use data capture changed between 2000 and 2018, and so the land-use types for 2000 are divided into twenty-one categories and for 2018 into twenty-six. Merging these categories into clusters for analysis yields the following eleven land-use categories: tilled fields and gardens, vineyards, orchards, other perennial plantings, meadows, partially overgrown land, mixed land use, built-up and similar areas, forest, other, and water areas. Following this, land-use structure (in %) was determined by individual Slovenian municipalities for 2000 and 2018, and the indices of changes in the area of various land-use types between the two years.

After this, the relevant demographic and socioeconomic data were added at the municipal level for 2000 and 2018 (or 2017 if the 2018 data were not yet available at the time of the analysis) from the SiStat SURS database (Internet 3). The focus was on the following indicators: the population change index between 2000 and 2018, average population age, population aging index, old-age dependency ratio, share of population by large age groups, general birth rate, rate of natural increase, net migration rate, and share of population with tertiary education. An additional synthetic indicator was included in the end: the municipal development ratio calculated by the Slovenian Statistical Office (SURS), which also includes certain demographic indicators; the average municipal development ratio is 1.00 (Internet 4).

A table with all the data collected was used as the basis for calculating Spearman's correlation coefficients. The final analysis focused on correlation coefficients with $p < 0.0001$.

3 Demographic development and land-use changes in Slovenia over the past two decades

Abandonment of farming, industrialization, and urbanization had a key impact on Slovenia's demographic development and settlement network after the Second World War. Klemenčič (1996) reports that three types of areas formed in terms of settlement characteristics and population development: areas of greater population density with ongoing population growth, depopulation areas with ongoing declines in population, and intermediate areas. Ravbar (1997) adds that like most other European countries during the 1970s Slovenia gradually stepped into a post-industrial industrialization phase characterized by stagnation or decline in the urban population growth, with a simultaneous population growth in the wider peri-urban area.

By 1991, the average annual urban population growth fell to 1.4%, which was lower than the total Slovenian growth rate. To a smaller degree, suburbanization was already present during the 1970s, when it was mainly typical of the settlements closest to Ljubljana; it heavily intensified during the 1980s, and even more during the 1990s. The urban population in Slovenia began to move to increasingly more remote peri-urban settlements, which was related to the spatial transformation of peri-urban areas and urban depopulation (Rebernik 1999; Rebernik 2008).

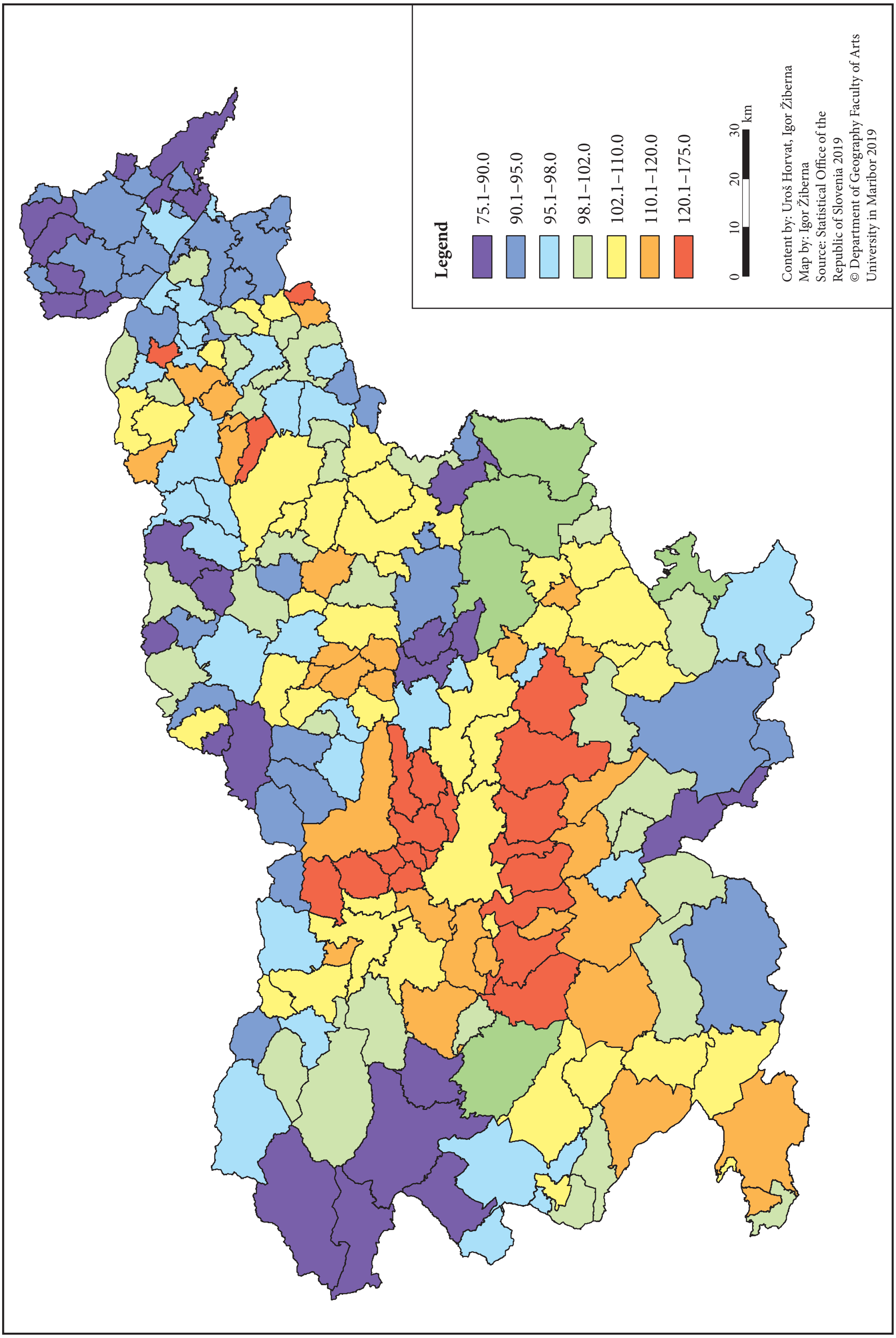
Suburbanization was influenced by several factors, especially the shortage of appropriate housing in cities, lower land prices in peri-urban settlements, good transport connections between cities and their surroundings, a higher vehicle-ownership rate, development of modern telecommunication devices, more urban pollution, relocation of production and service companies from cities to the surrounding areas, bankruptcy of large industrial businesses, and the consequent higher urban unemployment rates. From 1991 to 2002, the population of Ljubljana decreased by 3%, of Celje by 7.1%, Kranj by 2.4%, Koper by 4%, and Maribor by 9.7% (Horvat 2006). The 2009–2018 data show a slightly different situation. The population in Ljubljana has increased (by 4.7%) due to the growing centralization of all activities in the country. In Maribor, the population has decreased (by 1.8%), although recently the population has been decreasing more rapidly especially in peripheral medium-sized cities, such as Murska Sobota (4.9%), Velenje (3.8%), Slovenj Gradec (3.7%), and Ptuj (2.9%; Horvat 2019).

Over the past two decades there have also been certain changes in rural population development. After a long period of decline, after 1991 rural settlements recorded slight growth. According to Ravbar (2007), the rural population decreased by approximately 15% from 1961 to 1991 and increased by 1.7% from 1991 to 2002. This trend has continued since then. However, it should be highlighted that demographic growth has only been recorded in rural areas with relatively good access to larger regional centers. Klemenčič (2005) thus distinguishes between two types of rural areas: urbanized and stable rural areas with a high share of non-farming population, and rural areas in risk of dying out or extensive areas of depopulation, rapid shrinking of farmland, and disintegration of cultural landscape. Here, only farmland in the village or close to the village is being cultivated, whereas meadows and pastures outside the villages are partly or fully overgrown with forest.

Data on changes in the population by municipality between 2000 and 2018 (Figure 4) confirm the processes described above. On the one hand, they show areas of greater population density and population growth, which typically occur in suburbanized areas near large cities, and on the other hand areas of depopulation typical mostly of Slovenia's hilly, peripheral, and border areas. Population has only increased in four urban municipalities: Novo Mesto, Ljubljana, Kranj, and Koper. Municipalities in the Central Slovenia Statistical Region stand out with the highest growth indices (120–173), with as many as fourteen municipalities out of the twenty-one in Slovenia where the population has grown by over 20%. Municipalities in the Drava and Upper Carniola statistical regions also stand out in this regard, with each having three municipalities of this type. A population growth of over 30% has been recorded in the municipalities of Brezovica, Grosuplje, Ig, Komenda, Dol pri Ljubljani, and Škofljica (all part of the Central Slovenia Statistical Region). In turn, the highest depopulation index (75–90) has been recorded in municipalities in the northeast (especially the Mura Valley), west (the Soča Valley), and south and north (along the border with Croatia and Austria). The twenty-five municipalities with the greatest population decrease include nine in the Mura Statistical Region, five in the Gorizia Statistical Region, and four in the Carinthia Statistical Region. In the municipalities of Šalovci, Grad, Cankova, Gornji Petrovci (all in the Mura Statistical Region), Podvelka, and Kanal, the population increased by over 15%.

Slovenia has an older population. Ever since 1961, the share of young people (0–14 years old) has been rapidly decreasing and it nearly halved by 2018 (i.e., it decreased from 27.3% to 15.0%), whereas the share of the elderly (age 65 or more) has been rapidly increasing and it nearly doubled from 2000 to 2018 (i.e., it increased from 7.8% to 19.4%). The average age of the population is also increasing: it rose from 39.5 years in 2002 to 43.2 years in 2018. This is largely the result of longer life expectancy and low birth rates (Slovenia

Figure 4: Population change index by municipality from 2000 to 2018 ($Index_{(2000)} = 100$). ➤ p. 40


Legend
75.1–90.0
90.1–95.0
95.1–98.0
98.1–102.0
102.1–110.0
110.1–120.0
120.1–175.0
0 10 20 30 km
Content by: Uroš Horvat, Igor Žiberna
Map by: Igor Žiberna
Source: Statistical Office of the Republic of Slovenia 2019
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is among the countries with a very low birth rate). The share of younger population is higher in areas with a relatively high birth rate and a positive net migration rate, which are primarily areas of pronounced suburbanization. Population aging has recently also been evident in urban centers: in large cities the share of elderly population has increased significantly, exceeding the values in the surrounding area (Horvat 2019). Pelc (2015) also reported that in 2011 the share of young people was higher in non-urban settlements and the share of the elderly was higher in large cities.

In 2018, among the twenty-three municipalities with an aging index higher than 170, ten belonged to the Mura Statistical Region and three to the Gorizia Statistical Region (Figure 5). All urban municipalities had an index higher than 100, with the municipalities of Maribor and Murska Sobota recording the highest values (i.e., 178). On the other side of the spectrum there are municipalities with aging indices lower than 95. There are nineteen of these; eleven of them belonged to the Central Slovenia Statistical Region, followed by four in the Southeast Slovenia Statistical Region and three in the Drava Statistical Region.

Slovenia's landscape diversity also causes significant land-use differences. Forests predominate in the Alpine and Dinaric landscapes of western Slovenia, grassland predominates in the hills of eastern Slovenia, intensive farmland is typical of Pannonian lowlands, and built-up areas predominate on the coast and in the Alpine basins (Gabrovec et al. 2020).

In Slovenia, the area covered by arable land (tilled fields, gardens, vineyards, orchards, and other perennial plantings) decreased by 29,847.4 hectares (or 1.5 percentage points) from 2000 to 2018, which amounts to a decrease of 30.21 hectares per week. During the same period, the increase in the area covered by forest was nearly the same (i.e., 27,581.3 hectares or 1.4 percentage points) or 27.92 hectares per week (Table 1). In 2018, the share of arable land was unevenly distributed among municipalities (Figure 6). The highest shares were recorded in lowland municipalities in northeast Slovenia (the Drava, Ptuj, Apače, and Mura basins), of which some even had over 50% of arable land (between 60 and 70% in the municipalities of Odranci, Turnišče, Tišina, Beltinci, and Kidričevo). A high share was also typical of municipalities in the Littoral (Izola), Ljubljana Basin (Šenčur, Mengeš, and Komenda), the Gorizia Hills, and the Krško-Brežice Basin (Brežice).

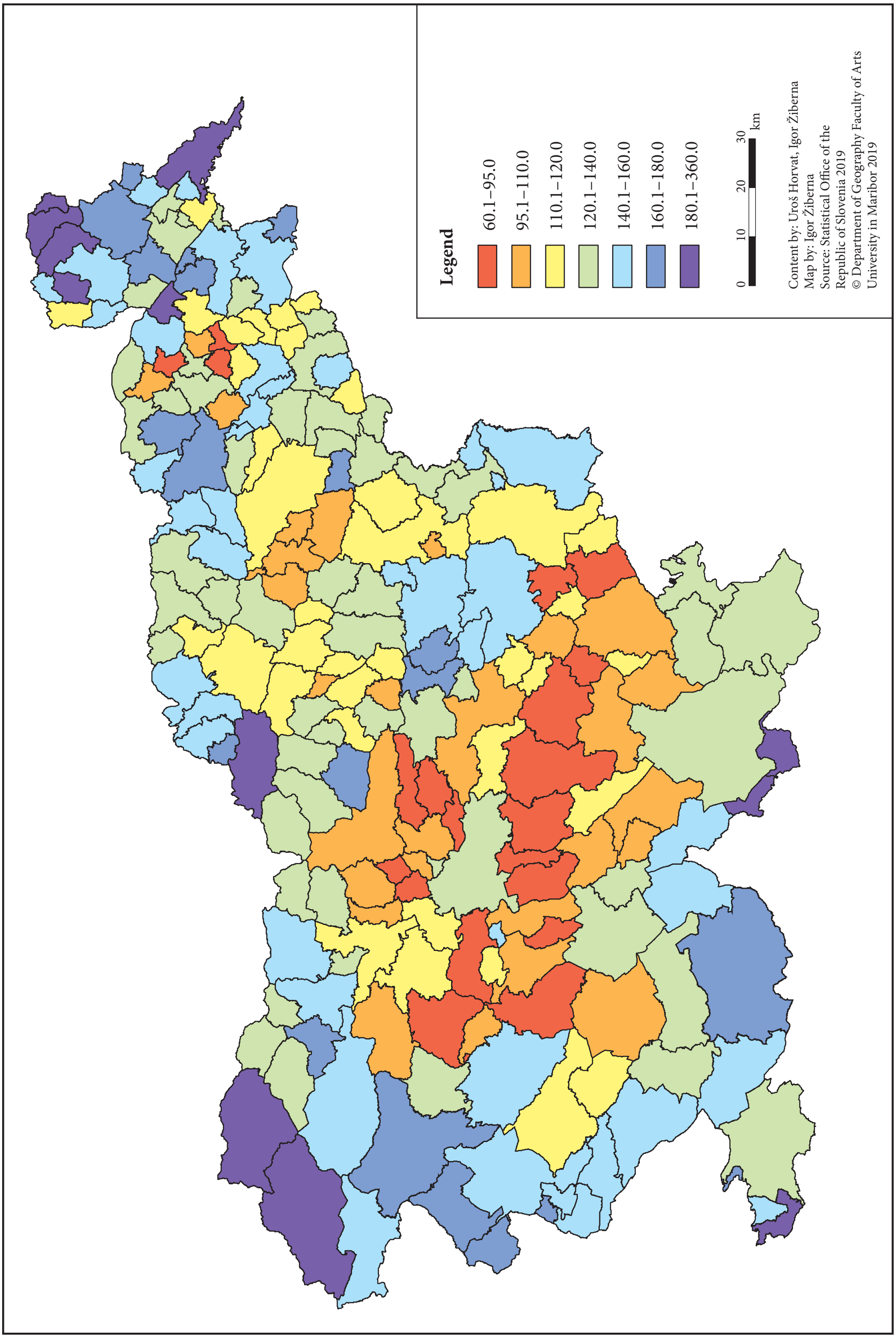
In his analysis of trends in land-use change, Žiberna (2013) reports that from 2000 to 2012 Slovenia acquired 87,614.1 hectares in the process of intensification, but it also lost twice as much (167,610.0 hectares) due to extensification. Only 73.2% of tilled fields and gardens were preserved during this period. The remaining fourth turned into meadows (45,470.9 hectares or 21.0%), built-up and similar areas, partially overgrown land, forests, and other land-use types. According to Žiberna (2018), abandonment of arable land is characterized bybifurcation: high-quality arable land is either turning into built-up areas (this is primarily evident in the suburbs), or into meadows, partially overgrown land or forest (in marginal areas with often unfavorable demographic conditions). Indices of changes in partially overgrown land are the highest in areas with the greatest shares of arable land – that is, northeast Slovenia (Figure 7).

In central and western Slovenia, indices of changes in the size of built-up land (Figure 8) are higher than in northeast Slovenia. The built-up areas around cities spread primarily due to suburbanization (Gabrovec

Table 1: Land-use types in Slovenia by area and percentage, 2000 and 2018.

Land-use type/Year	Area (hectares), 2000	Area (hectares), 2018	Change in area (hectares), 2000–2018	% 2000	% 2018	Index, 2000–2018
Tilled fields and gardens	216,471.9	183,983.0	−32,488.9	10.7	9.1	85.0
Vineyards	25,292.7	18,668.2	−6,624.5	1.2	0.9	73.8
Orchards	24,891.7	32,518.0	+7,626.3	1.2	1.6	130.6
Other perennial plantings	1,182.8	2,822.2	+1,639.4	0.1	0.1	238.6
Forests	1,202,285.5	1,229,866.8	+27,581.3	59.3	60.7	102.3
Meadows	350,570.1	354,766.5	+4,196.4	17.3	17.5	101.2
Built-up areas	108,156.9	112,285.0	+4,128.1	5.3	5.5	103.8

Figure 5: 2018 population aging index by municipality. ➤ p. 42
Figure 6: Share of arable land by municipality in 2018 (%). ➤ p. 43
Figure 7: Index of changes in partially overgrown land by municipality, 2000–2018 (2000 = 100). ➤ p. 44
Figure 8: Index of changes in built-up areas by municipality, 2000–2018 (2000 = 100). ➤ p. 45


Legend
60.1–95.0
95.1–110.0
110.1–120.0
120.1–140.0
140.1–160.0
160.1–180.0
180.1–360.0
0
10
20
30
km
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Map by: Igor Žiberna
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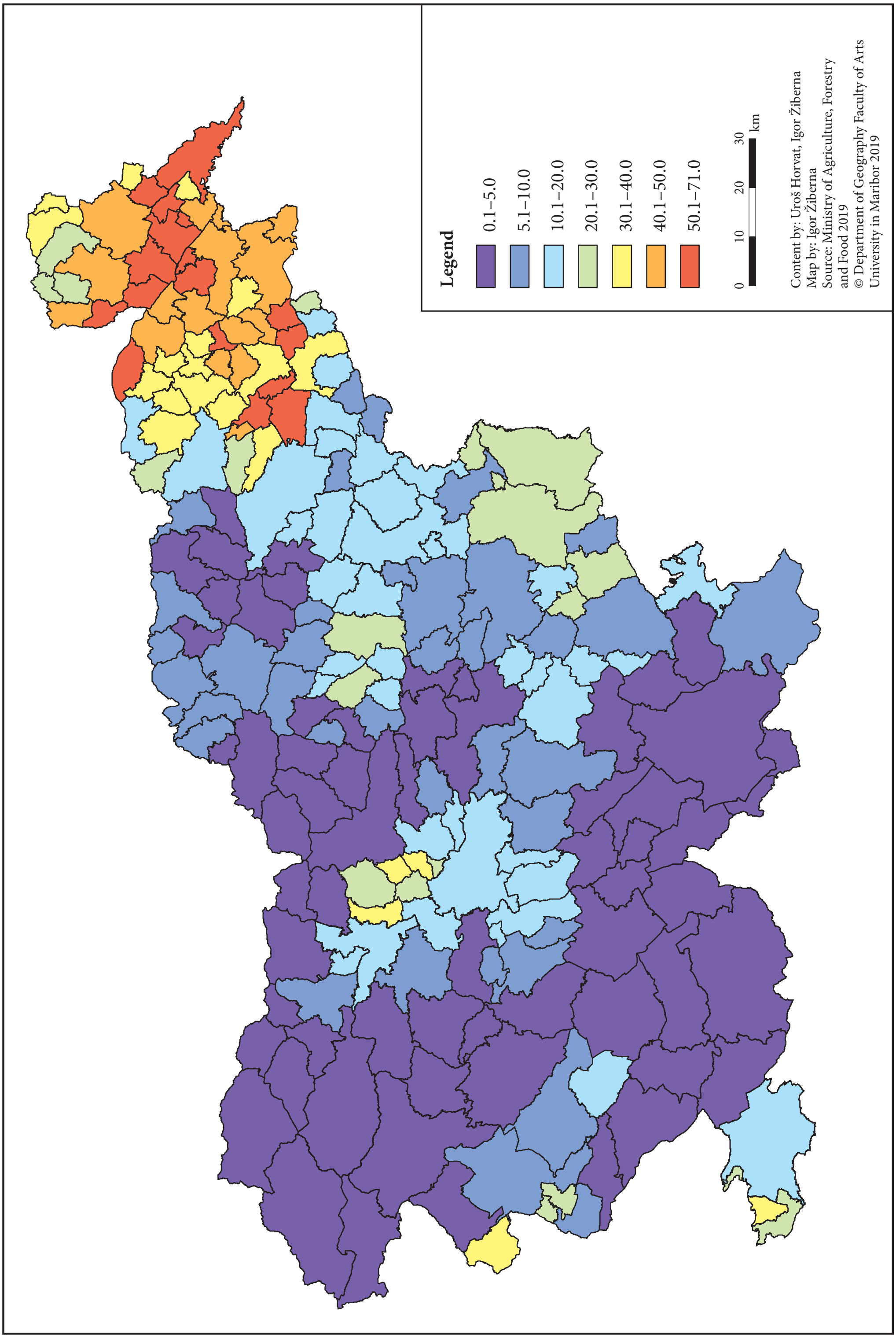
Legend
0.1–5.0
5.1–10.0
10.1–20.0
20.1–30.0
30.1–40.0
40.1–50.0
50.1–71.0
0
10
20
30
km
Content by: Uroš Horvat, Igor Žiberna
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Source: Ministry of Agriculture, Forestry and Food 2019
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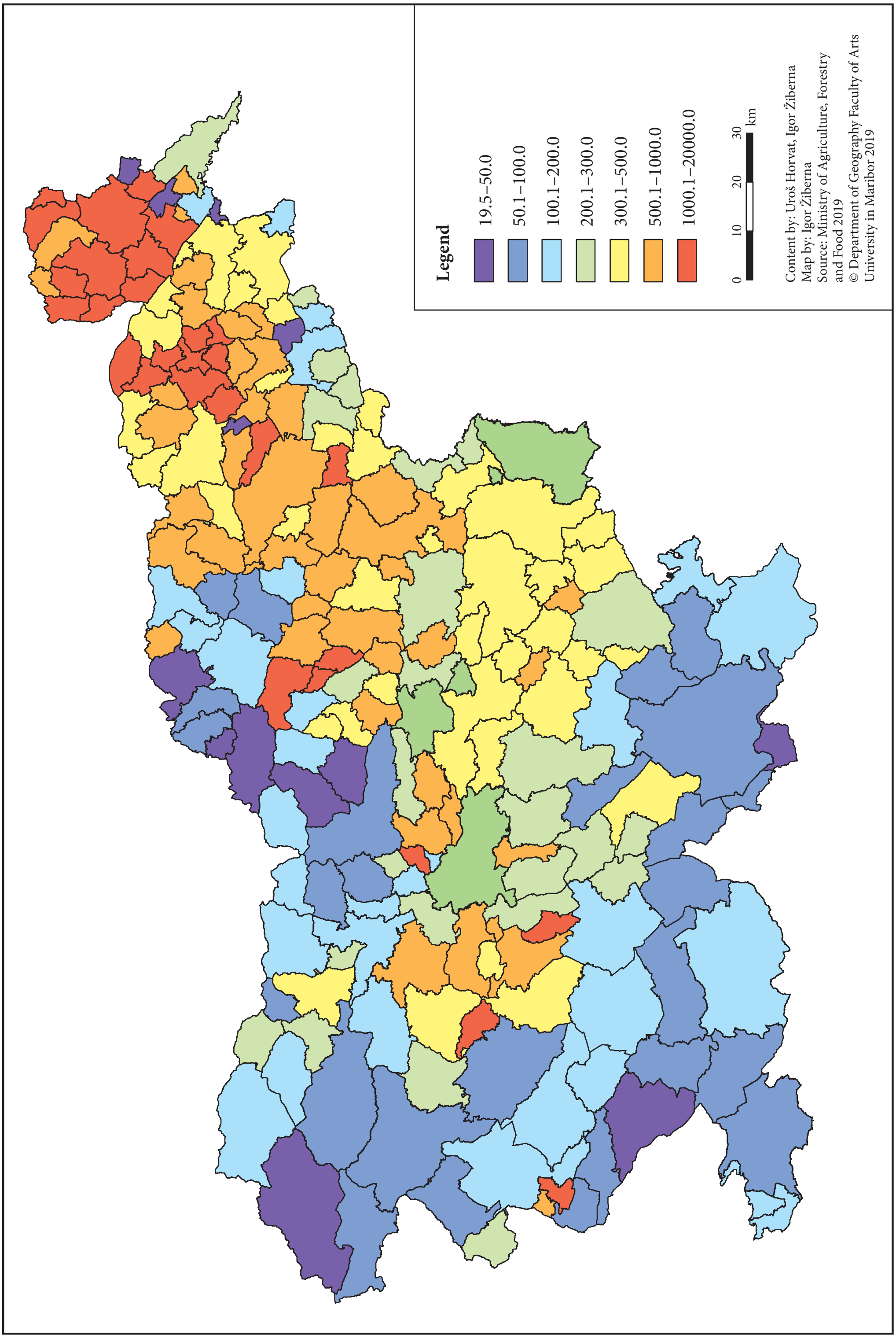
Legend
19.5–50.0
50.1–100.0
100.1–200.0
200.1–300.0
300.1–500.0
500.1–1000.0
1000.1–20000.0
0 10 20 30 km
Content by: Uroš Horvat, Igor Žiberna
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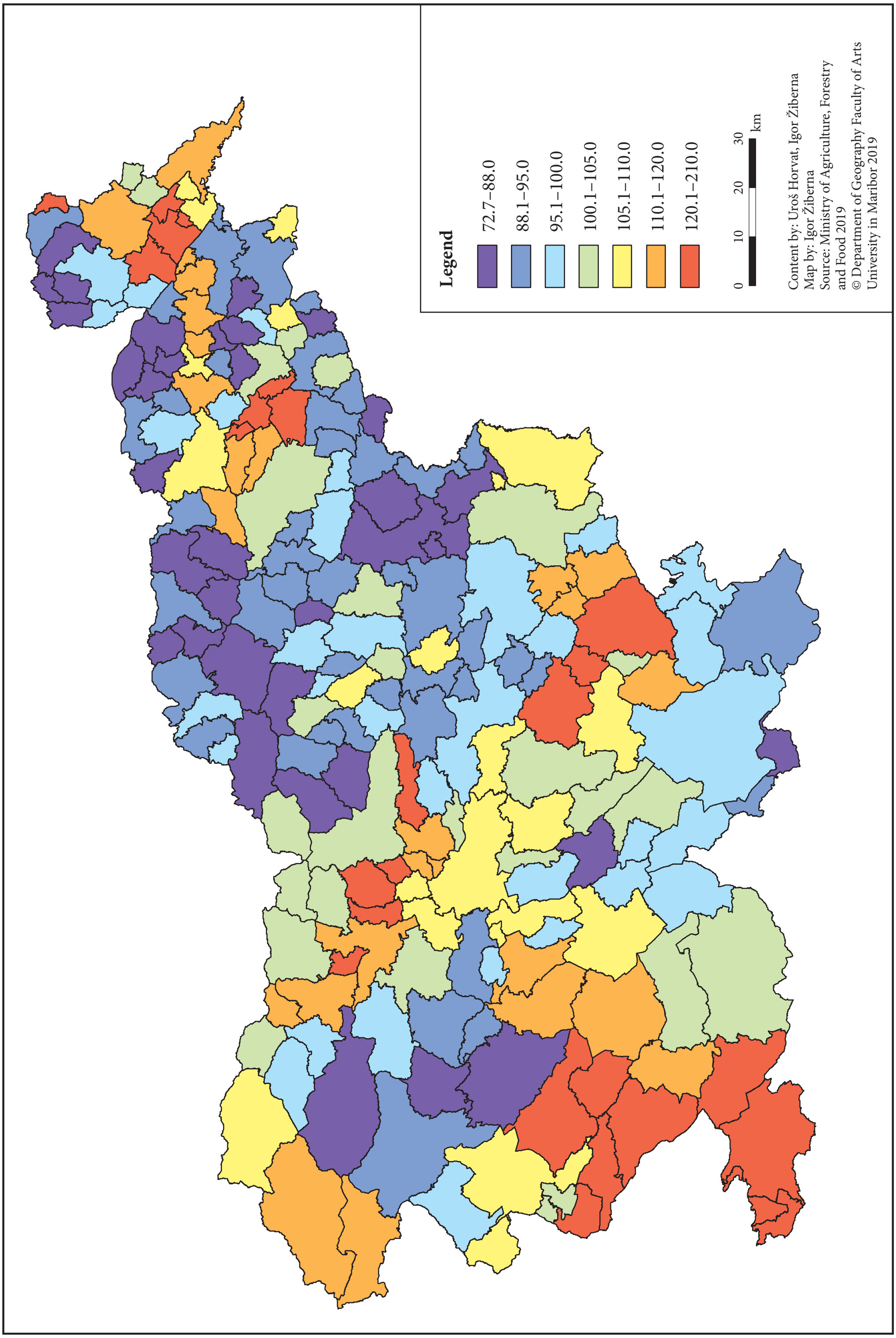
Legend
72.7–88.0
88.1–95.0
95.1–100.0
100.1–105.0
105.1–110.0
110.1–120.0
120.1–210.0
0
10
20
30
km
Content by: Uroš Horvat, Igor Žiberna
Map by: Igor Žiberna
Source: Ministry of Agriculture, Forestry and Food 2019
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and Kumer 2018). During the period studied, high positive indices were observed in municipalities in the Ljubljana Basin (Komenda: 154.4, Cerklje na Gorenjskem: 152.6, Lukovica: 135.6, and Naklo: 132.1), southwest Slovenia (Piran: 209.7, Ankaran: 152.9, Vipava: 140.4, Hrpelje-Kozina: 137.5, and Sežana: 128.8), and individual municipalities in Lower Carniola (Mirna Peč: 156.8, Novo Mesto: 133.4, and Miren-Kostanjevica: 128.0) and northeast Slovenia (Turnišče: 149.8, Hodoš: 144.8, Starše: 136.1, and Kidričevo: 126.0).

As anticipated, the analysis of Spearman's correlation coefficients for selected indicators by municipality showed high coefficients between various interconnected demographic indicators that define the population's age structure (mostly over ±0.80). The coefficients of correlation with other demographic indicators are lower and do not exceed ±0.80. Hence, the correlation coefficient between the population change index and the share of young people (younger than fourteen) is 0.63, and the coefficient between the population change index and the population aging index is –0.61. The general birth rate and the population aging index have a negative correlation coefficient (i.e., –0.73). It is interesting that the share of population with tertiary education does not show a high correlation with most indicators (it is below ±0.50); the only exceptions are the population change index (0.55) and the municipal development ratio (0.62), which shows a trend of highly educated population moving to areas with high population density.

Spearman's correlations coefficients are also somewhat higher between indicators defining various land-use types and changes. There is an exceptionally high negative correlation between the share of forest and the shares of tilled land (–0.89) land built-up areas (–0.72). Among the indicators demonstrating changes in land use between 2000 and 2018, the highest positive correlations are typical of the index of changes in partially overgrown land, showing that this land is increasing in areas with a higher share of arable land (0.52) and tilled fields (0.50), and the highest negative correlation is in areas with a higher share of forest (–0.50). There is also high correlation between the index of changes in forest and the index of changes in partially overgrown land (0.68), indicating that afforestation is still ongoing.

Spearman's correlation coefficients are significantly lower between the demographic and land-use indicators (Table 2), which confirms the initial premise that the land-use change processes are complex and not dependent solely on individual demographic and socioeconomic factors. The 2018 share of tilled fields and gardens is negatively correlated with the share of people eighty years old or more (–0.30). The share of partially overgrown land has a weak positive correlation with the aging index (0.25) and the average age of the population (0.24), and consequently a negative correlation with the share of people in the 0–14 age group (–0.36). The share of built-up areas is positively correlated with the changes in the population over the 2000–2018 period (0.33) and negatively correlated with the share of people eighty years old or more (–0.25). Differences in the share of arable land between 2000 and 2018 are negatively correlated with the population change index during the same period (–0.35). The index of changes in arable land is negatively correlated with the share of people in the 0–14 age group (–0.26). Despite low correlation coefficients, the results indicate that the processes of land-use change largely depend on changes in the age structure of the Slovenian population and changes in the population, considering that in areas where the population is growing the amount of arable land is decreasing (the correlation coefficient between the two is –0.46).

4 Case study: Central Slovenia and Mura statistical regions

The data above refer to Slovenia as a whole but, as mentioned above, there are significant differences between individual areas due to Slovenia's pronounced geographical diversity. To further elucidate these differences, the focus hereafter is on the analysis at the level of statistical regions, which proved to be sufficiently large territorial units. The analysis is limited to the Mura and Central Slovenia statistical regions, where the bifurcation of land-use change mentioned above is the most pronounced. These two statistical regions are complete opposites in terms of their municipal development ratios (Figure 9) and most demographic indicators.

A comparison between the population change index from 2000 to 2018 and the municipal development ratio in the two statistical regions (Figure 10) shows two typical clusters: during the study period, in nearly all municipalities in the Mura region the population change index was lower than 100, and the municipal development ratio was also at the lower end. The municipalities of Hodoš (0.4) and Šalovci (0.5) had the lowest municipal development ratios in Slovenia. In the Central Slovenia region, the population change index was above 100 in all municipalities, with the highest ones recorded in the municipalities of Škofljica (172.5), Dol pri Ljubljani (144.3), and Komenda (142.2). All top eleven municipalities with the highest

Table 2: Spearman's correlation coefficients for selected indicators in Slovenian municipalities (≥ ±0.25, $p < 0.0001$).

Indicator	Population change index (2000–2018)	Average age (2018)	Average age change (2000–2018)	Aging index (2018)	Share of population 0–14 (2018)	Shae of population 65+ (2018)	Shae of population 80+ (2018)	Old-age dependency ratio (2018)	Share of population with tertiary education (2017)	Unemployment rate (2017)	Live births per 1,000 (2017)	Rate of natural increase per 1,000 (2017)	Net migration per 1,000 (2017)	Municipal development ratio (2017)
% tilled lands and gardens (2018)							–0.30	–0.27		0.27				
% vineyards (2018)					–0.30			–0.32	–0.27	0.30				–0.28
% orchards (2018)								–0.37	–0.27	0.31				
% meadows (2018)	0.38	–0.44		–0.43	0.33	–0.43	–0.26	–0.27			0.32		0.25	0.31
% partially overgrown land (2018)				0.25	–0.36				–0.25	0.32		–0.25		–0.31
% forests (2018)							0.28	0.27						
% built-up areas (2018)	0.33						–0.25		0.29					0.38
% arable land (2018)							–0.27	–0.27		0.28				
Area change index: tilled fields and gardens (2000–2018)					–0.30			–0.25		0.31				
Area change index: vineyards (2000–2018)					–0.34					0.34	–0.25			–0.30
Area change index: partially overgrown land (2000–2018)							–0.27	–0.26						
Area change index: forests (2000–2018)		0.33		0.32	–0.38						–0.30	–0.31		–0.34
Area change index: built-up areas (2000–2018)	0.31								0.48					0.28
Area change index: arable land (2000–2018)	–0.46	0.27	0.28		–0.26				–0.29				–0.28	–0.26
Change in % arable land (2000–2018)	–0.35												–0.25	

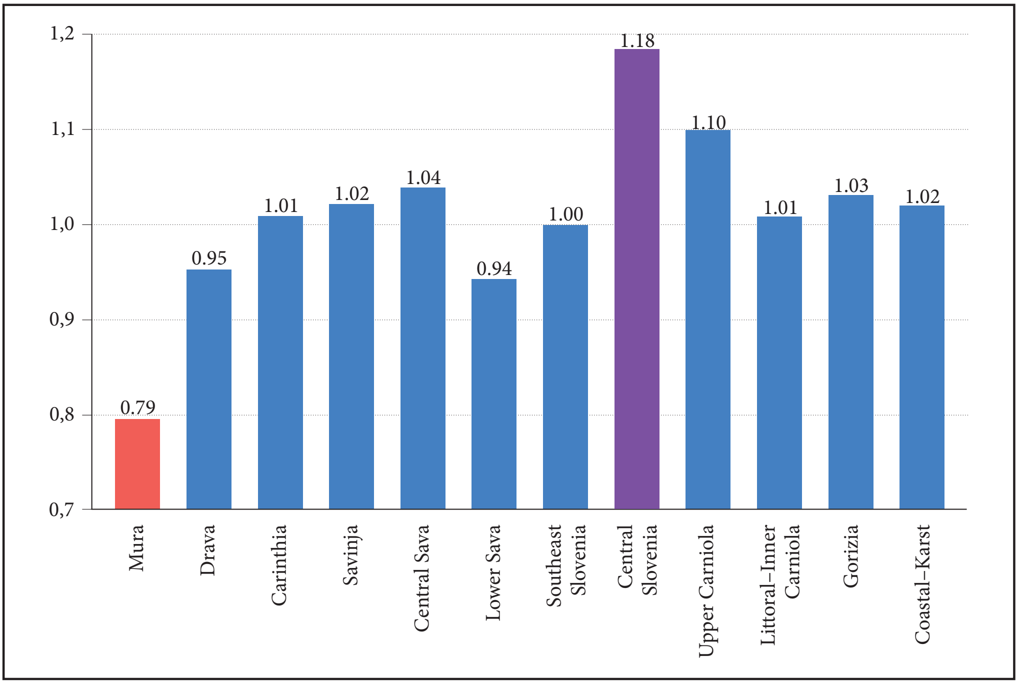

Figure 9: Municipal development coefficient by statistical region in 2018.

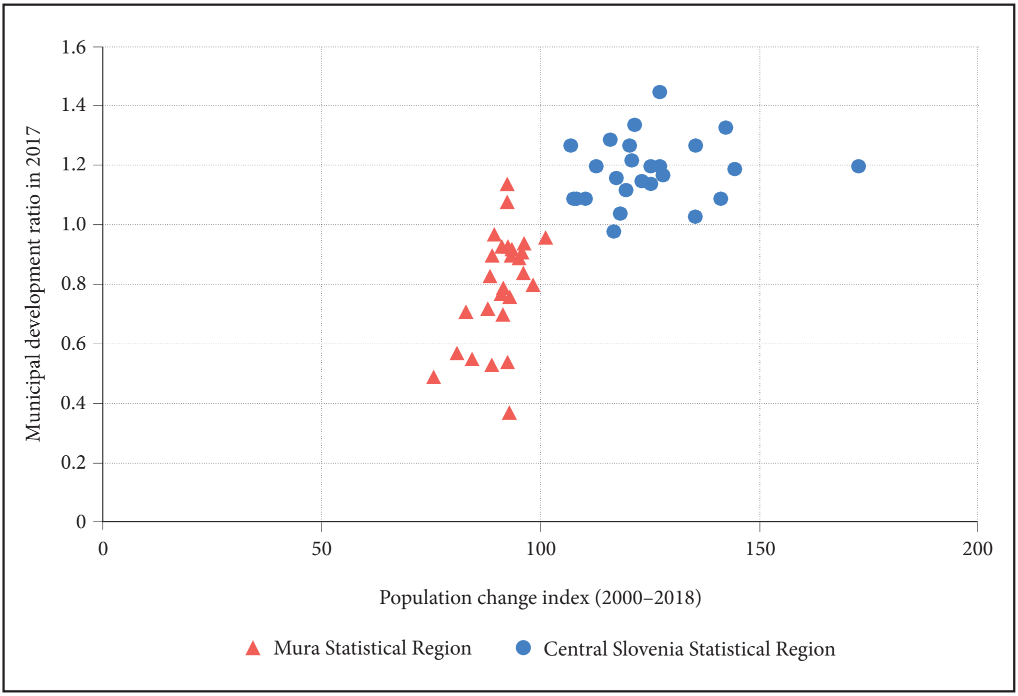

Figure 10: Population change index (2000–2018) and the municipal development ratio in the Mura and Central Slovenia statistical regions.

population change index can be found in the Central Slovenia region, whereas the municipalities of Šalovci (75.5) and Grad (80.9) can be found at the very bottom (both from the Mura region).

A contrast between the two statistical regions can also be identified by comparing the population change index between 2000 and 2018 and the index of arable land change (Figure 11). In addition to population change indices lower than 100, the municipalities in the Mura region are characterized by arable land change indices between 90 and 100. In the Central Slovenia region, the population change indices are above 100 and the indices of arable land change are below 90, which shows that, in parallel with suburbanization, population growth in this region causes significant shrinking of arable land.

In the Mura region, the shrinking of arable land due to grass overgrowth is more pronounced than in other parts of Slovenia. Half of the ten municipalities with the highest index of change in partially overgrown land between 2000 and 2018 (Figure 12) can be found in this region, which reconfirms the thesis that unfavorable processes of arable land extensification are present in areas with the highest production potential. In Central Slovenia region this shrinking is significantly less common. Even though the average age of Slovenia's population is increasing, the intensity of this process is not evenly distributed across regions. The share of partially overgrown land increases with the increase in the aging index (Figure 13), in which this correlation is more pronounced in the Mura region. The reasons for arable land being overgrown thus can be sought not only in depopulation, but also pronounced population aging.

Spearman's correlation coefficients for all of Slovenia showed a relatively weak correlation between the selected indicators. Through further analysis, the correlation coefficients were also calculated at the level of selected statistical regions (Tables 3 and 4). Due to smaller scales, less landscape diversity, and lower impacts of various other factors, Spearman's correlation coefficients by statistical region showed significantly higher correlations, which in some cases can even be over ±0.80. The Mura region shows clear positive correlations (0.30–0.60) between indicators revealing population growth, a younger age structure, and a higher share of population with tertiary education, and indicators revealing a higher share of built-up areas. On the other hand, a positive correlation (0.30–0.60) is also shown between indicators revealing population aging and depopulation, and indicators revealing a higher share of partially overgrown land and forest.

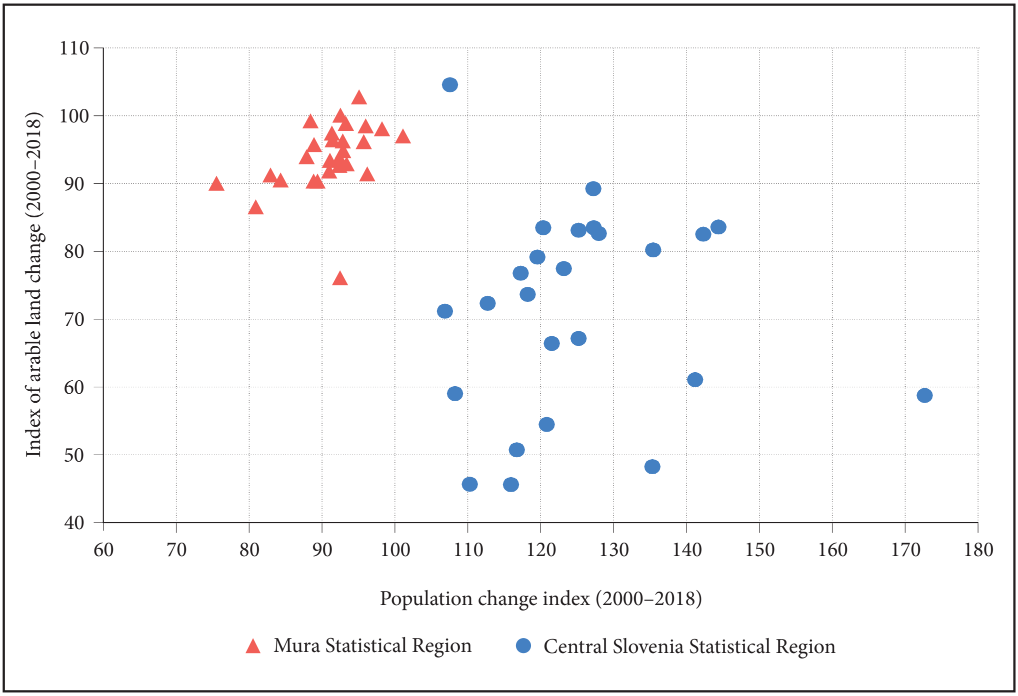

Figure 11: Population change index and index of arable land change in municipalities of the Mura and Central Slovenia statistical regions, 2000–2018.

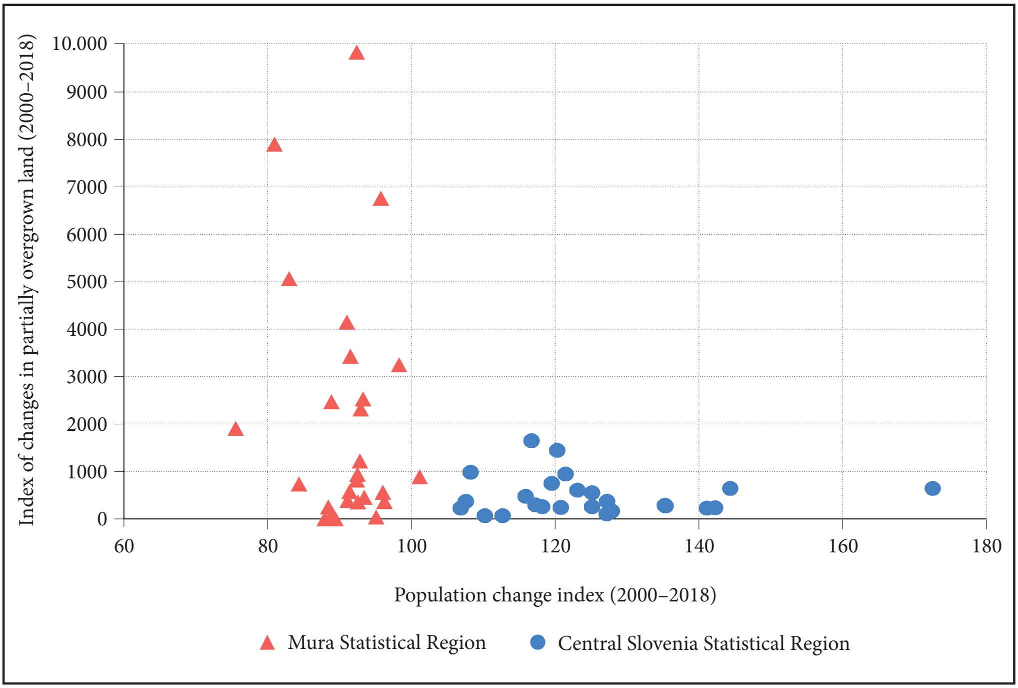

Figure 12: Population change index (2000–2018) and index of changes in partially overgrown land in municipalities of the Mura and Central Slovenia statistical regions.

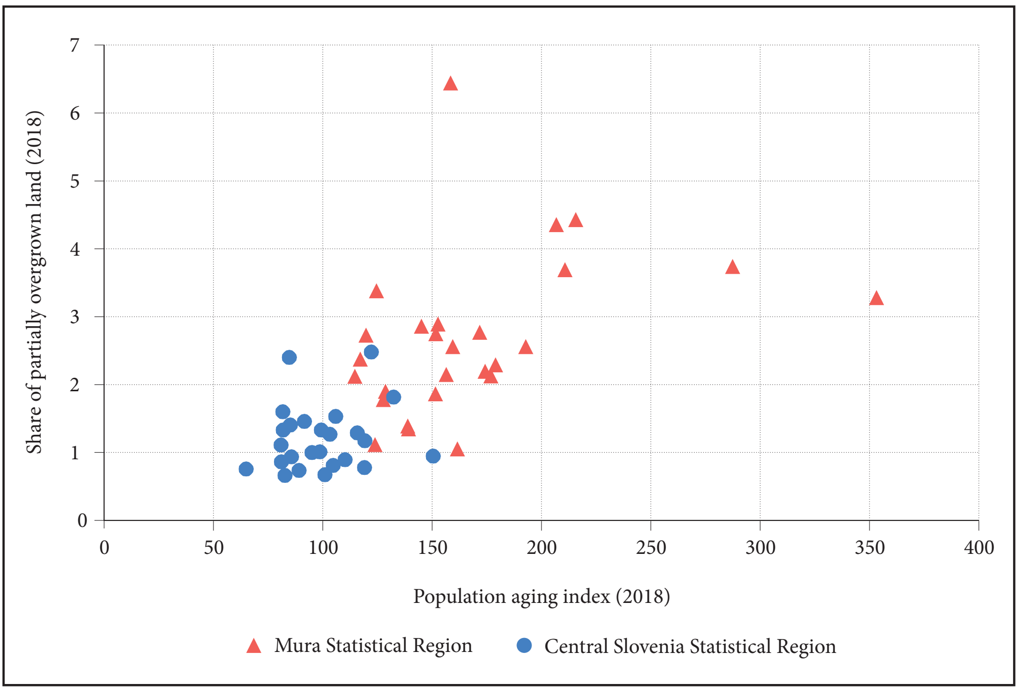

Figure 13: Population aging index (2018) and the share of partially overgrown land in municipalities of the Mura and Central Slovenia statistical regions.

Table 3: Spearman's correlation coefficients for selected indicators in municipalities of the Mura Statistical Region ($\geq \pm 0.30$, $p < 0.0001$).

Indicator	Population change index (2000–2018)	Average age (2018)	Average age change (2000–2018)	Aging index (2018)	Share of population 0–14 (2018)	Shae of population 65+ (2018)	Shae of population 80+ (2018)	Old-age dependency ratio (2018)	Share of population with tertiary education (2017)	Unemployment rate (2017)	Live births per 1,000 (2017)	Rate of natural increase per 1,000 (2017)	Net migration per 1,000 (2017)	Municipal development ratio (2017)
% tilled lands and gardens (2018)		–0.43		–0.45	0.34	–0.50	–0.56	–0.35	0.35			0.43		0.67
% vineyards (2018)							0.33							
% orchards (2018)			–0.36											
% meadows (2018)												–0.39		–0.49
% partially overgrown land (2018)	–0.45	0.49		0.50	–0.51	0.40	0.58		–0.30	0.43		–0.61	0.35	–0.52
% forests (2018)	–0.33	0.41	–0.40	0.42	–0.33	0.45	0.54	0.34	–0.49					–0.81
% built-up areas (2018)	0.39	–0.36	0.47	–0.38	0.42	–0.30	–0.47		0.62					–0.86
% arable land (2018)		–0.42		–0.44	0.33	–0.49	–0.55	–0.35	0.41			0.40		0.72
Area change index: tilled fields and gardens (2000–2018)	0.45								0.30					
Area change index: vineyards (2000–2018)	0.33													
Area change index: partially overgrown land (2000–2018)										0.31				
Area change index: forests (2000–2018)														
Area change index: built-up areas (2000–2018)														0.42
Area change index: arable land (2000–2018)	0.53								0.36					
Change in % arable land (2000–2018)	0.39													

Table 4: Spearman's correlation coefficients for selected indicators in municipalities of the Central Slovenia Statistical Region (≥ ± 0.30, $p < 0.0001$).

Indicator	Population change index (2000–2018)	Average age (2018)	Average age change (2000–2018)	Aging index (2018)	Share of population 0–14 (2018)	Shae of population 65+ (2018)	Shae of population 80+ (2018)	Old-age dependency ratio (2018)	Share of population with tertiary education (2017)	Unemployment rate (2017)	Live births per 1,000 (2017)	Rate of natural increase per 1,000 (2017)	Net migration per 1,000 (2017)	Municipal development ratio (2017)
% tilled lands and gardens (2018)	0.40						−0.41		0.69		−0.37			0.40
% vineyards (2018)								−0.31						
% orchards (2018)				−0.30					−0.39		0.39	0.35		
% meadows (2018)		−0.34		−0.33	0.33						0.46			
% partially overgrown land (2018)														
% forests (2018)	−0.32						0.41		−0.67					−0.56
% built-up areas (2018)									0.80		−0.38			0.64
% arable land (2018)	0.39						−0.41		0.69		−0.37			0.37
Area change index: tilled fields and gardens (2000–2018)									0.37					0.42
Area change index: vineyards (2000–2018)														
Area change index: partially overgrown land (2000–2018)													0.39	
Area change index: forests (2000–2018)				0.33		0.31				0.38				
Area change index: built-up areas (2000–2018)									0.36					0.50
Area change index: arable land (2000–2018)														
Change in % arable land (2000–2018)0									−0.38				−0.38	

It is interesting that the population change and arable land change indices show a high correlation (0.53), being negative in most all the municipalities. As a rule, the scale of arable land in the Mura region is shrinking less in municipalities with a lower rate of depopulation. In the Central Slovenia region, the correlation coefficients between certain indicators are even higher (ranging from ±0.60 to 0.80). Standing out the most is the positive correlation between the share of population with tertiary education and indicators revealing a higher share of arable land, tilled fields, and gardens, whereas the population aging and depopulation indices are correlated with a higher share of forests and areas that are becoming increasingly overgrown with forest.

Attention should also be drawn to the fact that the correlation coefficients are higher with indicators showing the shares of individual land-use types, whereas correlations between land-use change processes and demographic indicators are relatively weak. Thus, only a positive correlation between demographic growth and an increase in the arable land can be highlighted in the Mura region and a positive correlation between an increase in forests and indicators revealing population aging and a higher unemployment rate in the Central Slovenia region.

5 Conclusion

Demographic changes in Europe, characterized by a decreasing and aging population, are a key factor influencing land-use changes. However, there is still insufficient evidence of the correlation between demographic changes and land-use changes, because quantitative studies dealing with such correlations are very rare and mostly cover small and specific areas. This study used land-use data and demographic and socioeconomic data at the level of Slovenian municipalities to calculate Spearman's correlation coefficients.

The coefficients for the whole of Slovenia are fairly low, confirming that land-use change processes are complex and not dependent solely on individual demographic and socioeconomic factors. Despite the low correlation coefficients, the results indicate that land-use change processes are significantly influenced by changes in the population's age structure and population growth. In areas where population is growing, the scale of arable land is decreasing, and in areas characterized by depopulation and an increasing aging index the scale of partially overgrown land is increasing. The highest positive correlation (0.48) was established between the share of population with tertiary education and an increase in the share of built-up areas, and the highest negative correlation (–0.46) was determined between population growth and a decrease in arable land.

Because Slovenia has very heterogenous landscapes, the analysis then focused on a case study of the Mura and Central Slovenia statistical regions, which lie on opposite poles in terms of the municipal development ratio. In this case, correlation coefficients were significantly higher and sometimes even reached ±0.50–0.60; in terms of the municipal development ratio they even exceeded ±0.80. The Mura region shows fairly clear positive correlations (0.30–0.60) between indicators revealing population growth, a younger age structure, and a higher share of population with tertiary education, and indicators revealing a higher share of built-up areas. On the other hand, there are also positive correlations (0.30–0.60) between indicators revealing population aging and depopulation, and indicators revealing a higher share of partially overgrown land and forest. In the Central Slovenia region, the correlation coefficients between certain indicators are even higher (ranging from ±0.60 to 0.80). Standing out the most is the positive correlation between the share of population with tertiary education and indicators revealing a higher share of arable land, tilled fields, and gardens, whereas the population aging and depopulation indices are correlated with a higher share of forests and areas that are becoming increasingly overgrown with forest.

Despite a weaker correlation than anticipated at the beginning of the study, the results show that demographic conditions should also be taken into account in addressing the abandonment of arable land, grass overgrowth, and afforestation. Similar future studies should also focus on other parts of Slovenia and expand the selection of relevant indicators. In this sense, it would be interesting to analyze the impact of migration on land-use change.

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Acta geographica Slovenica, 60-2, 2020, 57–70

DAILY MOBILITY OF THE ELDERLY: AN EXAMPLE FROM ŁÓDŹ, POLAND

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Figure caption Public transport in Łódź.

DOI: https://doi.org/10.3986/AGS.7490
UDC: 911.375:331.556-053.9(438)
COBISS: 1.01

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Daily mobility of the elderly: An example from Łódź, Poland

ABSTRACT: Recently, numerous countries have been facing the issue of population ageing, which poses a formidable challenge for many sectors, including transportation. Alas, there are no detailed or insightful studies that involve the analysis of the elderly, which is why the authors of this paper decided to research the issue to determine which features of mobility are common among senior citizens (aged 60+). In our study, we focused on Bałuty, a district located in Łódź. The applied research tool was an interview questionnaire which consisted of eight questions. Since transportation is a fundamental human need, maintenance of the mobility of the elderly at an acceptable level is crucial as it directly impacts the quality of their life. What is more, a change of motivation and mode of transport is recommended for this age group.

KEY WORDS: daily mobility, the elderly, questionnaire, Lodz, Poland

Dnevna mobilnost starejših: primer Lodža na Poljskem

POVZETEK: V zadnjem času se številne države spopadajo s problemom staranja prebivalstva, ki mnoge sektorje, tudi promet, postavlja pred velik izziv. Kljub temu do zdaj še ni bilo opravljenih podrobnih študij, ki bi analizirale mobilnost starejših. Avtorji članka so se zato odločili proučiti glavne značilnosti mobilnosti pri posameznikih, starejših od 65 let, ki živijo v okrožju Baluty v poljskem mestu Lodž. V raziskavi so uporabili anketo z vprašalnikom, sestavljenim iz osmih vprašanj. Ker je prevoz temeljna človekova pravica, je ključno ohranjati mobilnost starejših na zadovoljivi ravni, saj to neposredno vpliva na kakovost njihovega življenja. Poleg tega je za to starostno skupino priporočljivo, da spremenijo motivacijo in način prevoza.

KLJUČNE BESEDE: dnevna mobilnost, starejši, vprašalnik, Lodž, Poljska

The paper was submitted for publication on July 2nd, 2019.
Uredništvo je prejelo prispevek 2. julija 2019.

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1 Introduction

Recently, numerous countries have been facing the issue of population ageing, which poses a formidable challenge for many sectors, including transportation (Hildebrand 2003; Coughlin 2009; Kim 2011; Haustein and Siren 2015; Saboor et al. 2015; Stjernborg, Wretstrand and Tesfahuney 2015), since transport is one of people's fundamental needs at various stages of their life and is inseparably connected with independence, autonomy and a good quality of life (Carp 1988; Kaplan 1995; Tacken 1998; Metz 2000; Dickerson et al. 2007; Hjorthol, Levin and Sirén 2010; Li et al. 2012). Changes due to aging populations bring new challenges related to the provision of transportation services, mainly due to the fact that the travel habits and needs of the elderly differ substantially from those of other social groups (Rosenbloom 2001; Alsnih and Hensher 2003). Existing studies indicate that elderliness is directly related to a reduction in mobility (Hanson 1977; Alsnih and Hensher 2003; Tiitta 2003) and that senior citizens are more accepting of the fact that they may need to use modes of transport other than the car and to travel noticeably shorter distances (Schwanen, Dijst and Dieleman 2001; Rosenbloom 2004; Páez et al. 2007; Mercado and Páez 2009; Roorda et al. 2010). Despite certain common effects regarding age-related journeys, it is clearly emphasised in the literature that the mobility of senior citizens is not of a homogeneous nature (Schwanen and Páez 2010). The studies conducted by Schwanen, Dijst and Dieleman (2001), Páez et al. (2007), Roorda et al. (2010) indicate that there are considerable differences among the elderly in terms of frequency of travel, distance and means of transport. Factors determining these differences include social status, their financial situation, current health condition and mobility, lifestyle, and motivations at various stages of senectitude (Kałuża-Kopias 2014; Raczyńska-Buława 2017). The wide diversity of mobility patterns observed among the elderly poses an complex problem and has become a significant challenge for transportation planning and policy (Metz 2003; Páez et al. 2007; Schwanen and Páez 2010), This is particularly noticeable in cities where the process of population ageing is exceptionally dynamic and is, at the same time, related to the phenomenon of depopulation, as illustrated by the example of Łódź used here. Alas, there are no detailed or insightful studies that involve the analysis of the elderly, which is why the authors of this paper decided to research the issue to determine which features of mobility are common among senior citizens (aged 60+).

In our study, we focused on Bałuty, a district located in Łódź. In line with the perception of daily mobility presented in the literature (Bartosiewicz and Pielesiak 2014), the research described in this article concentrates on the totality of daily and recurring trips taken. Since the target group is the elderly, however, the set of analysed trip motivations was expanded and adjusted to the specificity of this individual social group. In this case, »dailiness« of mobility is not perceived literally as a feature which determines that trips must be taken on a daily basis, but as a characteristic indicating that such trips are, by assumption, quite common and frequent, and thus, recurring. The mobility of the elderly was studied in terms of differences in trip destinations and frequency, preferred modes of transport, length and duration of trips, time of their occurrence, and types of spatial mobility limitations. Management of an urban transport system in a manner that meets the needs of local residents must directly entail studies of their daily transport behaviours (including spatial mobility). Moreover, in the face of dynamic population ageing, it is also vital to conduct activities that promote mobility for the benefit of the elderly and their quality of life.

2 Study area and methods

Łódź, one of the largest Polish cities, was selected for the purposes of this study to illustrate the daily mobility behaviours of senior citizens, and this was by no means an accidental choice. Having analysed the 2016 data obtained from the Central Statistical Office (2019), the authors determined that the issue of population ageing afflicts all voivodeship capitals in Poland, and yet, the situation is worst in Łódź, which is interesting not only since its population is ageing, but also because it is in decline. These processes can be observed elsewhere in cities of the central and eastern EU (e.g., eastern parts of Germany – Magdeburg, Halle, and Romania – Arad) and some peripheral areas of Western Europe (e.g., Southern Italy, Northern England, and Northern Scandinavia) (Labus 2013). Łódź was chosen as a case study and an example of a city that is both »shrinking« and ageing at the same time, as, in all probability, the habits of its elderly citizens regarding the differentiation of trip destinations and frequency, preferred modes of transport, and length and duration of trips will be similar to other urban units of this kind. Łódź is classified among those cities whose situation is most difficult, i.e., their authorities must focus on redefining and renewing directions of development, including the sphere of transportation. Within the borders of Łódź, the percentage of people aged 60 or more has already exceeded 30%, and of those who are 65 and above amounts to 21%. Having conducted our questionnaire survey, we selected Bałuty (Figure 1).

An analysis of the percentage of older adults in individual districts reveals that by 2016, markedly the largest percentage of inhabitants aged 60 and above could be found in the Bałuty district (34.5%) (Borowska-Stefańska and Wiśniewski 2019). That is why the district in which the most elderly people live has just been selected for research.

The process of population ageing in Łódź stems from both the slowing growth rate of the young population and the relatively rapid growth rate of the older population, as ageing takes place both at the base of the population pyramid and at its top. It is worth stressing that of all Poland's provincial cities, the ageing demographic process in the area in question is at its greatest, which is why it is so important to carry out research into this particular group of inhabitants here.

As of 2016 the district of Łódź-Bałuty was populated by over 65,000 people, 63% of whom were women (Central Statistical Office 2019).

Figure 1: The division of Łódż into individual districts.

As for employment-population ratios, 13.7% of Łódź-Bałuty's population are in the pre-working economic age group, which is lower than that for the overall city (about 14.3%). In turn, 58.3% are of working age (compared to 59.9% for Łódź as a whole). The remaining 28% are of post-working age (25.8% for Łódź overall). Bałuty's situation would appear to be particularly unfavorable, i.e. a small young population accompanied by a very large older population.

The demographic dependency ratio calculated for the analyzed district is over 71%, which is higher than the value for the city as a whole (nearly 67%). The ratio of post-working age inhabitants per 100 inhabitants of pre-working age comes to a staggering 205 in the analyzed area, compared to 181 for the whole of Łódź. The process of population ageing in Bałuty is clearly more visible than in the other districts (Central Statistical Office 2019).

On the basis of the presented data it may be concluded that the population of Bałuty is ageing, as further indicated by the population pyramid (Figure 2). It is of a regressive character, indicating that reproduction is at a level which does not ensure generational renewal, which is the case in the whole of the city (although the process is even more pronounced in Bałuty). The pyramid extends in its upper part while it narrows at the bottom (illustrating the decline in the number of children and teenagers, i.e. inhabitants under 20). These changes are characteristic of the long-term transformations in the number of inhabitants in all districts of Łódź.

The applied research tool was an interview questionnaire which consisted of eight questions regarding private car ownership (question one), the availability of a private car to the household (question two), the frequency of trips (question three) related to professional activity, visiting public offices and institutions, religious purposes, everyday (grocery) shopping, meeting friends/relatives, seeking medical assistance, participating in cultural events and entertainment, using services provided by hairdressers and beauticians, and attending meetings, classes and events organised by the 3rd age university, day care centres or senior citizen clubs. The respondents were to determine whether they are engaged in such types of daily mobility, and if so, they were also asked to specify whether such trips were taken on a daily basis, several times a week or a month, once a month, or no such trips had been made the previous month. The

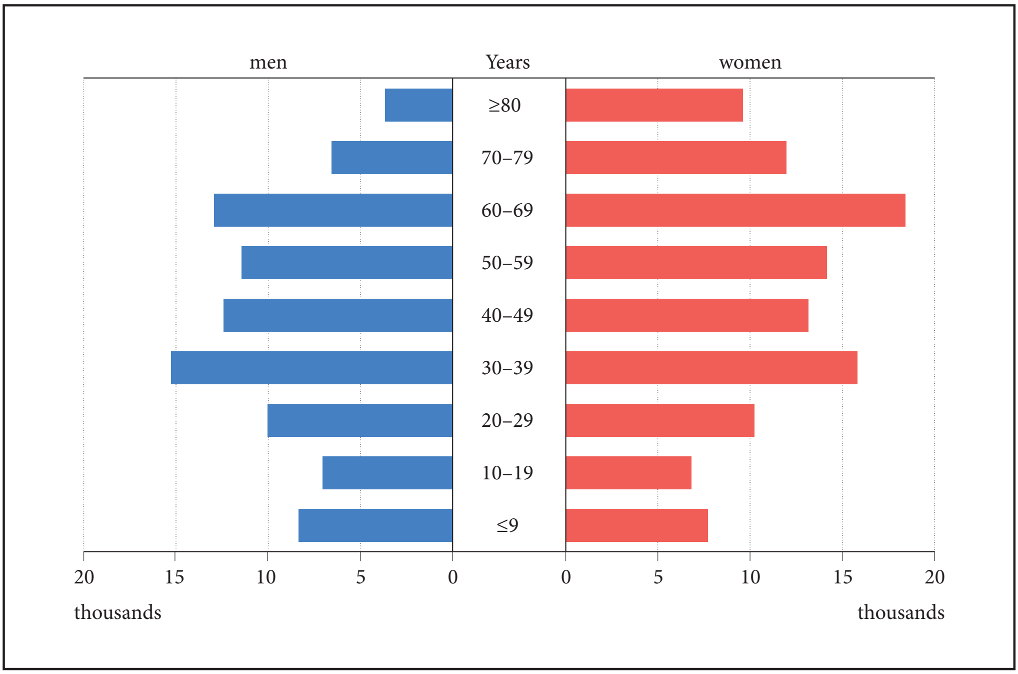

Figure 2: Population pyramid of Bałuty in 2017.

next (question fourth) question focused on the most popular modes of transport used to carry out the aforementioned tasks (the list of available options included: private car owned either by the respondent or by any relative/neighbour, bicycle, taxi, public bus or tram, train, plane, going on foot, coach, or buses provided by shopping centres – the respondents could choose more than one option if their trip involved stops or changes). In the fifth question (question five), those surveyed were asked to specify the distance they covered to reach the destinations they had selected earlier in the questionnaire (this referred to a single trip, and the following distance ranges were provided: up to 400 m, 401–800 m, 801–1200 m, 1201–1600 m, 1601–2000 m, and >2000 m). Another question (question six) focused on the average one-way travel time required to complete the intended tasks (the options included: up to 5 min, 5–10 min, 11–15 min, 16–20 min, 21–25 min, and >25 min). In question No. 7 (question seven), the respondent was to indicate how much time they needed to fulfil the selected tasks (with a choice of up to 15 min, 15–30 min, 31–60 min, and >1 hr). The last question (question eight) concerned the limitations of respondents' mobility. If there were any, the surveyed were asked to specify their nature (a semi-open question). These are all crucial constituents of mobility in terms of transport planning and policy. The final part of the questionnaire was the respondent's particulars.

It was elaborated on by the applicants on the basis of works by El-Telbani (1993), Taylor (1999), Wyszomirski (2008), Komornicki (2011), Sierpiński (2012), and Model of sustainable public transport in Łódź (*Model zrównoważonego transportu zbiorowego w Łodzi 2020+*,2019).

Personal interviewing techniques were used to carry out the research, using computer assisted personal interviewing (CAPI) or via a mobile device (MOBI). Both CAPI and MOBI are quantitative in character and involve direct communication between the interviewer and the respondent. They involve conducting a short interview during which the interviewer uses a dedicated system which displays questions on the screen of the mobile device used. The responses which are given and ticked in the system are recorded on an ongoing basis in the form of an electronic set of data. A questionnaire composed of a list of questions grouped into thematic sections was used as a research tool to structure and standardize the interviews.

The research was conducted among 400 inhabitants of the Bałuty district aged 60 and over as of November/December 2018 and concerned their daily mobility in the previous four-week period. In order to increase data reliability and gain a fuller picture of their mobility in the analyzed part of the city, the structure of the research sample took into account all the main administrative districts of Bałuty, i.e. Bałuty-Zachodnie, Bałuty-Centrum, Bałuty-Doły, Julianów-Marysin-Rogi, Łagiewniki, Osiedle Wzniesień Łódzkich, Radogoszcz, and Teofilów-Wielkopolska. 50 surveys were conducted in each designated area. The research used three channels to reach respondents: **(1)** door-to-door research, i.e. conducting a survey at the respondent's home after establishing the main age criterion, **(2)** conducting street surveys in the vicinity of places frequented by older persons, such as healthcare centers, churches and market places, **(3)** snowball sampling, i.e. recommendations by respondents of people who may be willing to participate in the research and who meet the age criteria (neighbors, friends etc.).

3 Results

3.1 Characteristics of respondents

Consent to take part in the research was more often given by women than men: just over 69% of the interviews were conducted with women and almost 31% with men. For the purposes of the analysis, the respondents were divided into age groups. People aged 65-69 constitute the largest group (20%), followed by those aged 75-79 (18.5%), then those aged 60-64 (just over 17%). Approximately one third of the research participants received a vocational education (33%), while another third of respondents completed secondary education with school-leaving examinations (just over 29%). Due to the demographic characteristics of the research participants, the overwhelming majority of respondents indicated a retirement pension as their main source of income (nearly 85%). Approximately 24% of respondents declared that they live on a gross income of between 500 and 1,000 PLN. This was followed by earnings of between 1,000-1,500 PLN and 2,000-2,500 PLN (with slightly over 13 per cent in each case).

The majority of people taking part in the research share their household with another person (nearly 61%), with just under a third of respondents living alone.

The vast majority of respondents live in multi-family housing (73.5%).

3.2 Activity types and mobility ranges for people aged 60+

The results of the study on types of activities and ranges of mobility among those aged 60 and above indicate that:

- such people are already excluded from the majority of regular activities (Figure 3);
- within the last 4 weeks, their main daily out-of-home activity has been grocery shopping;
- more than 50% of those researched are excluded from such »higher order« activities as entertainment, culture, going to the hairdresser or beautician;
- older Bałuty residents do get involved in such activities as the 3rd age university, courses, and senior citizen clubs;
- commuting to work involves mainly the youngest age group, i.e., citizens aged 60–64 (on weekdays, approximately 1/3 of them commute to work on a daily basis, with slightly below 6% commuting a few times during the week).

The study, when referring to levels of motorisation among senior citizens, indicates that:

- a vast majority (71.5%) of those surveyed do not possess their own private car;
- among the elderly, car ownership is considerably more common for men (46%) than for women (21%);
- the tendency to own a car diminishes with age (Figure 4).

When we take into account the data describing the destination of trips and car ownership, it should come as no surprise that those surveyed use their private car primarily to commute to work (Table 1).

Public transport is, however, equally popular (regardless of trip motivation). Despite the fact that the percentage of trips taken on foot is relatively high, there is still quite a potential for modal shifting from trips made by private car.

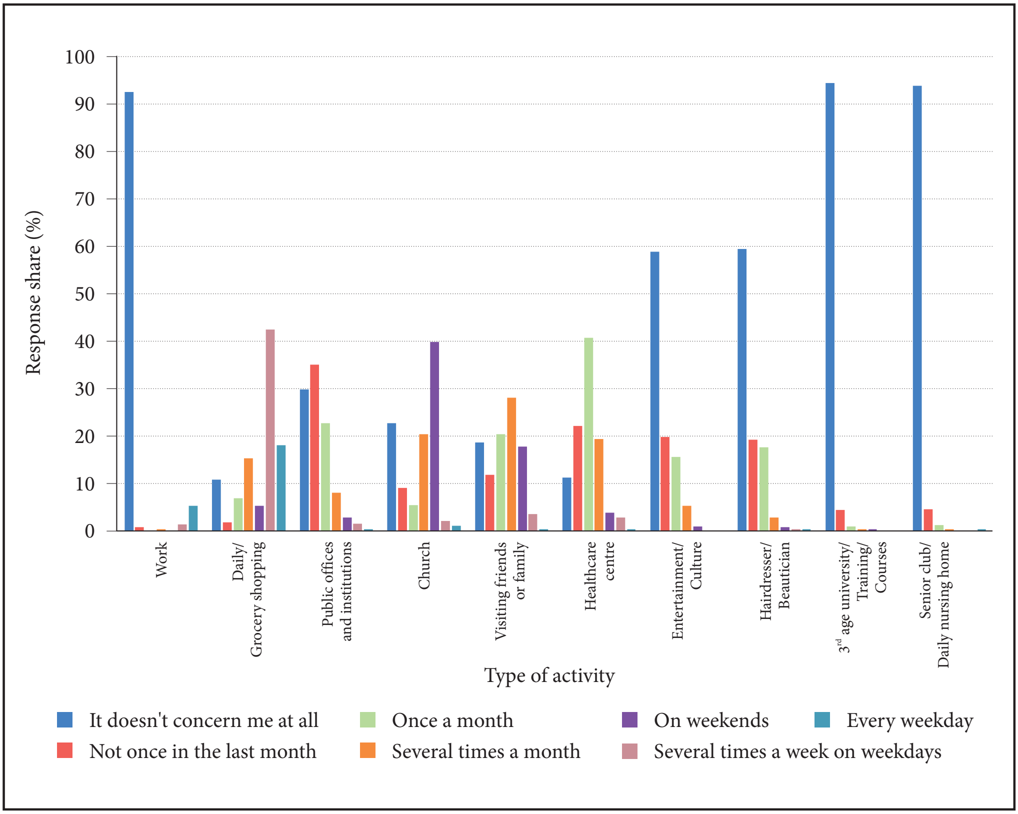

Figure 3: Frequency of activities for senior citizens.

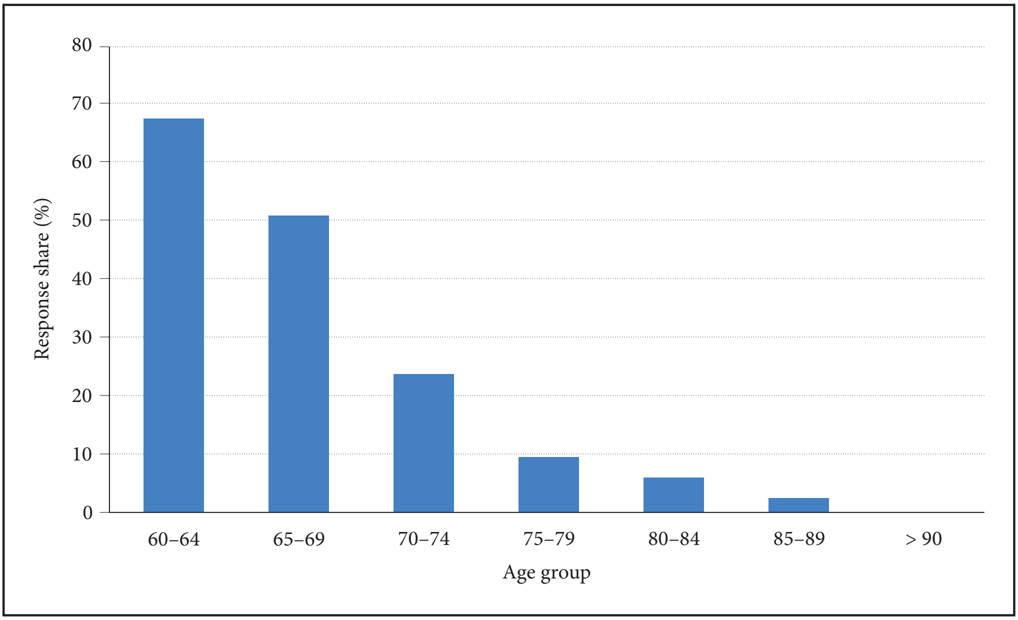

Figure 4: Car ownership versus respondent's age.

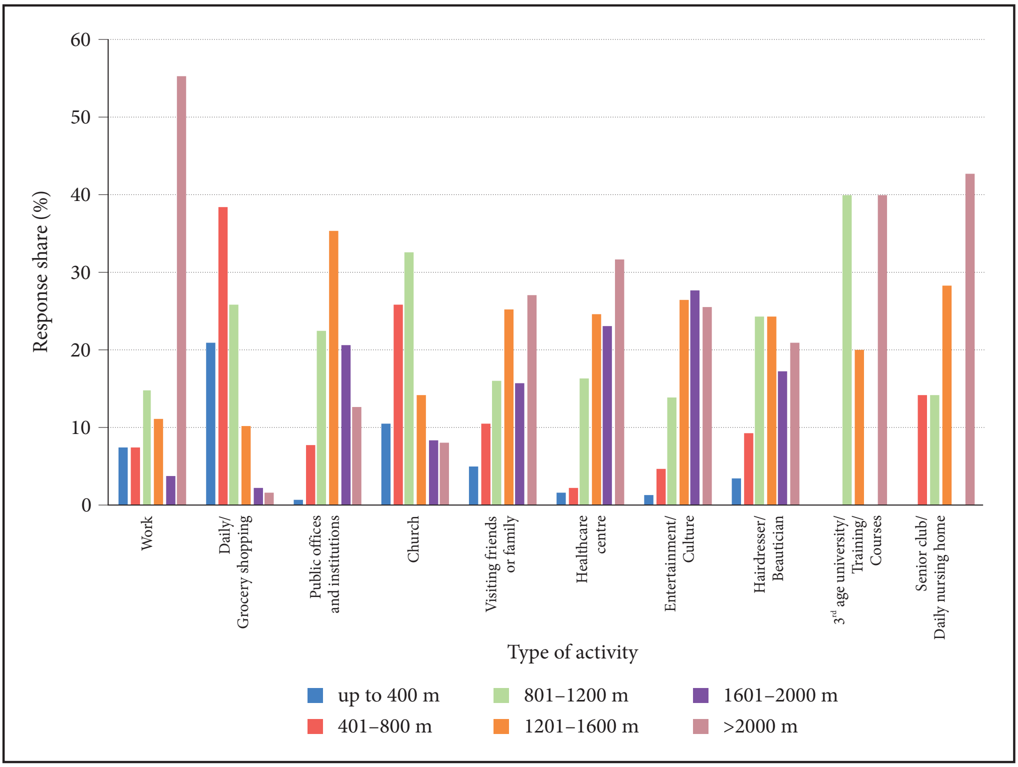

Figure 5: Travel distance versus trip motivation.

Table 1: Modal split of trip motivations.

	Work	Daily/Grocery shopping	Public offices and institutions	Church	Visiting friends or family	Healthcare centre	Entertainment/ Culture	Hairdresser/ Beautician	3rd age university/ Training/ Courses	Senior club/ Daily nursing home
Own car	48.1%	27.1%	32.6%	19.0%	28.3%	23.2%	40.7%	36.0%	20.0%	42.9%
Car of someone with family/friends	0.0%	7.7%	10.6%	9.5%	11.5%	20.6%	9.3%	8.1%	0.0%	14.3%
Bike	0.0%	0.3%	0.0%	0.7%	0.4%	0.4%	0.0%	0.0%	0.0%	0.0%
Taxi	0.0%	1.1%	1.4%	0.7%	1.1%	4.9%	1.2%	1.2%	0.0%	0.0%
Bus (MPK)	22.2%	13.4%	28.4%	15.4%	19.7%	21.0%	15.1%	15.1%	40.0%	14.3%
Shopping mall bus	0.0%	0.0%	0.0.%	0.0%	0.0%	0.7%	0.0%	0.0%	0.0%	0.0%
Tram	18.5%	14.0%	24.1%	15.8%	25.8%	25.1%	23.3%	22.1%	20.0%	14.3%
Plane	0.0%	0.0%	0.0%	0.0%	0.4%	0.0%	0.0%	0.0%	0.0%	0.0%
On foot	7.4%	36.3%	2.1%	38.5%	12.5%	3.0%	9.3%	16.3%	20.0%	14.3%
Bus/intercity bus	3.7%	0.0%	0.7%	0.4%	0.4%	1.1%	1.2%	1.2%	0.0%	0.0%

Table 2: Travel time and trip motivation.

	Work	Daily/Grocery shopping	Public offices and institutions	Church	Visiting friends or family	Healthcare centre	Entertainment/ Culture	Hairdresser/ Beautician	3rd age university/ Training/ Courses	Senior club/ Daily nursing home
Up to 5 min	11.2%	17.4%	0.0%	6.2%	1.4%	0.0%	1.2%	2.3%	0.0%	0.0%
5–10 min	3.7%	35.7%	10.6%	25.6%	12.3%	4.9%	2.3%	14.0%	0.0%	0.0%
11–15 min	18.5%	29.7%	19.1%	35.2%	16.8%	13.9%	18.6%	23.3%	0.0%	0.0%
16–20 min	29.6%	9.7%	35.5%	15.4%	26.9%	26.6%	32.6%	33.7%	20.0%	28.6%
21–25 min	7.4%	4.9%	19.2%	8.1%	19.7%	25.8%	24.4%	17.4%	20.0%	14.3%
> 25 min	29.6%	2.6%	15.6%	9.5%	22.9%	28.8%	20.9%	9.3%	60.0%	57.1%

Table 3: Activity duration by type.

	Work	Daily/Grocery shopping	Public offices and institutions	Church	Visiting friends or family	Healthcare centre	Entertainment/ Culture	Hairdresser/ Beautician	3rd age university/ Training/ Courses	Senior club/ Daily nursing home
Up to 15 min	11.1%	20.0%	1.4%	15.4%	6.8%	1.2%	1.2%	7.0%	0.0%	14.3%
15–30 min	11.1%	43.7%	13.5%	16.5%	7.9%	7.5%	10.5%	19.7%	0.0%	0.0%
31–60 min	14.8%	26.0%	54.6%	44.7%	24.4%	41.9%	36.0%	50.0%	60.0%	42.9%
> 1 h	63.0%	10.3%	30.5%	23.4%	60.9%	49.4%	52.3%	23.3%	40.0%	42.9%

Trips taken by senior citizens usually last for over 15 minutes (Table 2), and it is particularly common for them to take up to 16–20 minutes (regardless of trip motivation).

The greatest timeframe in travel time is recorded for visits paid to family/friends and trips to healthcare centres.

The surveyed senior citizens devoted most time to commuting to work, visiting friends and family, to entertainment, and to going to healthcare centres (Table 3).

In the above four cases, duration time is over an hour, while – on average – going to public offices and institutions, and to church, as well as visiting a hairdresser/beautician takes up to an hour.

Clearly, the greatest distances are covered by senior citizens who still remain professionally active (Figure 5).

The spatial relationships between the place of residence and the destinations where senior citizens carry out their tasks (and in particular, fulfil their needs of higher order) seem to justify the still limited share of trips taken on foot within the modal split.

Over 50% of the surveyed senior citizens declared that they do not feel their mobility to be restricted in any way. The rest mentioned health as the main limiting factor (72%), which was followed by advanced age (57%), and inadequate adaptation of public transport vehicles to the needs of senior citizens (15%). Financial matters, however, do not seem to pose a significant transportation obstacle. The study showed that only one in twenty senior citizens when using public transport commented on an inadequate distribution of bus and tram stops.

4 Discussion

The research conducted on the selected group of senior citizens shows that the reasons for daily journeys undertaken by Łódź-Bałuty's older inhabitants are likely to be shopping, going to church and visiting family and friends. It may be inferred, therefore, that above all, they choose to satisfy their basic needs. Senior citizens less often spend time outdoors than young people; they rarely go to theatres or cinemas, and consequently they are less frequently encountered in public spaces, which is also confirmed by other research (Borkowska-Kalwas 2002; Halicka and Halicki 2002; Oliwińska 2009; Kubicki 2010; Borowska-Stefańska and Wiśniewski 2019). The results of a 2016 study conducted in Łódź show that senior citizens spend their leisure time in parks/forests (24.6%) and retail facilities (16.5%), meeting friends (13.8%), in the vicinity of their house/block of flats (13.2%), and in public squares (12.8%) (Pielesiak 2017). In addition, our research results show that together with population ageing, there is a decline in mobility levels, which is also confirmed by other research (Hanson 1977; Alsnih and Hensher 2003; Tiitta 2003). Analysis of the obtained data shows that with regard to mobility and activity, the turning point for the elderly comes between the age of 70 and 75. Up to this point »younger« senior citizens (i.e. aged 60 to 69/74) are characterized by relatively high mobility and involvement in different types of pursuits and activities. This is convergent with what can be concluded from the research conducted by Pielesiak (2017), which indicates that the elderly subjectively feel that younger senior citizens (aged 60–75) participate in urban life to a relatively substantial extent.

Noble (2000) points to the decrease in mobility with age, which notes that in addition to the decrease in the number of journeys, the distances traveled and types of transport also change. The increased opportunities to travel freely are affected by the relatively large number of people in these age groups who have access to their own car or a car belonging to somebody they live with. In addition, most of these people are already retired and usually it is the journey to work that takes most time. Unfortunately, a reduction in mobility can result in an increase in isolation, loneliness and depression (Fonda, Wallace and Herzog 2001; Windsor et al. 2007; Edwards et al. 2009; Ziegler and Schwanen 2011) which can have an impact on reducing social contacts and a deterioration of mental health and emotional wellbeing (Smith et al. 2002; Mollenkopf et al. 2004; Allen 2008; Ziegler and Schwanen 2011). A serious problem arises for the elderly when they cease to drive – an activity which is normally associated with a sense of greater independence. Research shows that although there is »life after giving up driving«, it is necessary to offer some help to older drivers (Adler and Rottunda 2006) which is particularly important among women as they more often tend to give up driving, as evidenced by various studies (Hakamies-Blomqvist and Siren 2003). Maintaining environmental justice requires the maintenance of mobility for senior citizens at as high a level as possible, and it should not merely entail the reactivation of their desire to be mobile (Tacken 1998). This may help reduce the aforementioned phenomenon of depression and keep the existing standards of living (Alsnih and Hensher 2003).

The significance of mobility and independence in that matter is evidenced by the research results indicating that, on the whole, senior citizens who travel more and are car or van owners evaluate the quality of their life far more positively (Banister and Bowling 2004). Moreover, relatively few respondents take advantage of the leisure or cultural facilities on offer, which may be a result of their low income and architectural and transport barriers (Błędowski and Kubicki 2009; Pielesiak 2017; Borowska-Stefańska and Wiśniewski 2019), or lack of information about current events in the vicinity, etc. The research also suggests that older people's mobility limitations result mainly from their age and health problems.

The number of elderly drivers is growing steadily among the population (Rosenbloom 2001), which stems from the base effect (each year, there are more drivers aged 60+). A perfect illustration of this phenomenon are the studies conducted in Australia, where an incremental increase in the number of (all) trips taken by car by senior citizens is recorded with a simultaneous drop in the number of trips taken by bus (Alsnih and Hensher 2003). Upwards of a third of the, relatively, younger respondents have access to a car to some extent, with most of them having their own transport. However, car use falls dramatically with age and a clear division becomes apparent: up to the age of 70, senior citizens use a car fairly often for the purposes of travelling longer distances; but then there is an increase in the number of public transport users. In general, it is beneficial for the oldest age groups to cease driving, since elderly drivers often pose a threat on the road, and the typical functional impairments associated with normal ageing and medical conditions which are usually manifested at old age often become causes of accidents (Dickerson et al. 2007). Therefore, a drop in car use should be expected with age, while use of public transport for daily journeys should increase. Yet, as it is revealed by both the research conducted in Łódź and, for instance, Sweden, public transport is described by the elderly as expensive and not particularly accessible or safe (while travelling unaccompanied), and passenger information is deemed to be poor (Mackett 2015; Pielesiak 2017; Raczyńska-Buława 2017). The elderly express a range of opinions on public means of transport, emphasising their positive and negative sides (Coughlin 2001). As indicated by Alsnih and Hensher (2003), the approach that allows us to avoid one of the most serious, negative aspect of conventional public transport (based on fixed route) is to provide an alternative in the form of a more flexible system, which may be economically viable in the evolving market conditions. The issue of public transport costs is addressed quite differently and with an intention to eliminate it as a factor that can contribute to the exclusion of senior citizens. Implementation of free-of-charge travel outside rush hours generates new trip motivations among the elderly and can even lead to the phenomenon of »Bus Roulette« (Andrews et al. 2012). In Łódź, people aged 70+ are entitled to use public transport free of charge at any time of the day, while younger pensioners are eligible for a 50% discount.

Furthermore, the distance to stops is of considerable importance for older citizens using public transport (Carp 1988). Regrettably, this study shows that the distance to stops was assessed as poor by respondents (mainly in the case of buses). Therefore, ceasing to drive a car may have an adverse effect on the well-being of the elderly (Metz 2000; Davey 2007), because, as shown by the conducted research, it has an impact on reducing mobility. Having your own car available at any hour, provides door-to-door transport, and is a symbol of independence and autonomy (Davey 2007), and the use of public transport is not yet able to replace the car.

5 Conclusion

The problems of senior citizens are crucial because the population of this age group is continuously growing in number, which poses a formidable challenge at a global and local scale. The increase in this social group exercises an incremental pressure on transportation, which becomes particularly noticeable in cities. And yet, the existing research on the matter remains scarce. Studies into the mobility of the elderly ought to be conducted regularly, and their results could be utilised to create a blueprint for transport policy. Since transportation is a fundamental human need, maintenance of the mobility of the elderly at an acceptable level is crucial as it directly impacts the quality of their life. What is more, a change of motivation and mode of transport is recommended for this age group. Namely, senior citizens are advised to use public transport more often than before and instead of the car, while the maintenance of mobility requires the portfolio of potential destinations to be expanded so as to fill the gap created by retirement and lack of necessity to commute to work. In the course of the study, it was found that part of mobility which in the case of the elderly can be perceived as common/daily does not really fit into this category. Another observation was that despite a theoretically greater amount of spare time, senior citizens do not undertake a longer list of everyday trips than younger social groups. The patterns of mobility among the elderly and professionally inactive differ, which is evidenced by the results presented in the articles reviewed. City authorities should pay greater attention to this social group, especially with regard to public transport. This approach fits squarely into the philosophy of sustainable urban transportation, and additionally, involves the issue of intergenerational equality.

ACKNOWLEDGEMENT: The article was prepared as a part of a research project financed by the National Science Center in Poland »The daily mobility of the elderly in Lodz«, No. 2018/02/X/HS4/00378.

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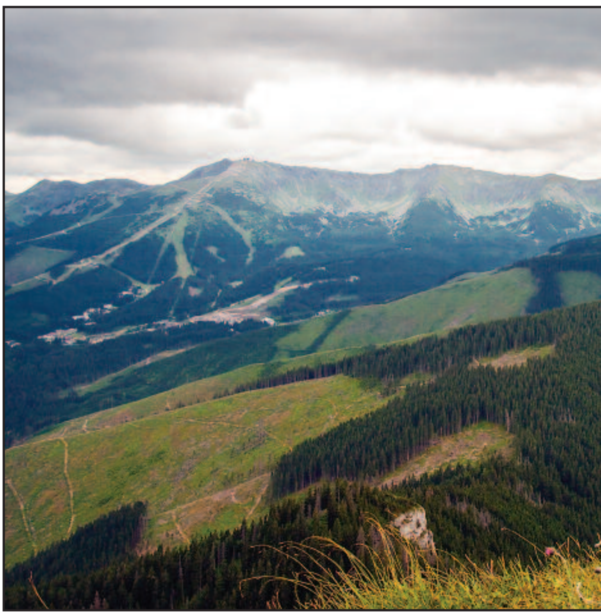
Acta geographica Slovenica, 60-2, 2020, 71–89

LAND COVER CHANGES IN PROTECTED AREAS OF SLOVAKIA BETWEEN 1990 AND 2018

Michaela Žoncová



MICHAELA ŽONCOVÁ

Manifestations of ongoing landscape changes in the National Park Nízke Tatry.

DOI: https://doi.org/10.3986/AGS.7996
UDC: 913:711.14(437.6)«1990/2018«
711.14:719(437.6)«1990/2018«
COBISS: 1.01

Michaela Žoncová[1]

Land cover changes in protected areas of Slovakia between 1990 and 2018

ABSTRACT: As a country with abundant natural resources, Slovakia has legislation to protect significant parts of nature and landscape. The paper aimed to identify the extent and nature of land cover changes in large protected areas in Slovakia and to determine how had these changes impacted the diversity and ecological stability of the landscape. We used the CORINE Land Cover data from 1990 and 2018 to identify landscape changes and analyzed them spatially and statistically. Overall, 21.7% of the total area was changed. In terms of landscape changes, nine dominant sub-processes within five »land cover flows« were identified. In terms of changes in landscape diversity and stability the most significant changes occurred in the NP Nízke Tatry.

KEY WORDS: landscape transformation, landscape protection, national park, protected landscape areas, CORINE Land Cover, landscape diversity, landscape stability, Slovakia

Spremembe rabe tal na zavarovanih območjih na Slovaškem med letoma 1990 in 2018

POVZETEK: Slovaška je bogata z naravnimi viri in ima zakonodajo, s katero so zavarovana pomembna naravna območja in pokrajine. V članku avtorica proučuje obseg in vrsto sprememb rabe tal na obsežnih zavarovanih območjih na Slovaškem ter ugotavlja, kako so te spremembe vplivale na raznolikost in ekološko ravnovesje pokrajine. Za določanje pokrajinskih sprememb ter njihovo prostorsko in statistično analizo je uporabila podatke CORINE Land Cover za obdobje med letoma 1990 in 2018. Spremenilo se je skupno 21,7 % celotne proučevane površine. Z vidika pokrajinskih sprememb je bilo določenih devet podprocesov znotraj petih tipov sprememb, do največjih sprememb v raznolikosti in ekološkem ravnovesju pokrajin pa je prišlo v Nacionalnem parku Nizke Tatre.

KLJUČNE BESEDE: pokrajinska preobrazba, varovanje pokrajin, narodni park, zavarovana pokrajinska območja, CORINE Land Cover, pokrajinska raznolikost, ekološko ravnovesje pokrajin, Slovaška

The paper was submitted for publication on April 19th, 2020.
Uredništvo je prejelo prispevek 19. aprila 2020.

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1 Introduction

Slovakia has undergone significant socio-economic changes over the last three decades (namely socialism 1980–1990, postsocialism 1990–2000, EU accession 2000–2006, EU membership 2004–today), which have also affected the land use (Pazúr and Bolliger 2017). The collapse of socialism throughout Eastern Europe was a natural experiment of rare magnitude that affected every aspect of societies, economies and land use practices (Radeloff and Gutman 2017). This rapid transformation is the key factor of understanding landscape changes in Central and Eastern Europe (Urbanc et al. 2004). Land use is determined by natural, socioeconomic, institutional, cultural, and legal factors (Jansen 2006). When the properties of the earth's surface, such as biota, soil, terrain, water, and settlement structure, are added to these factors, we speak of a land cover, which represents the intersection of natural spatial conditions and the current land use (Lambin et al. 2000).

Changes in the protected areas of Slovakia over the given period were manifested mainly in rural areas (Izakovičová 2012) by changes on agricultural land – extensification and abandonment of agricultural land and the decline of traditional land management (Šebo, Kopecká 2004; Lieskovský et al. 2015). Changes in land cover also occurred due to increased urbanization and suburbanization (Pazúr and Bolliger 2017). In protected areas, mostly covered by forests, the changes were caused mainly by natural factors – wind calamities and related problems with bark beetles (Sláviková and Slávik 2006).

Changes due to the increasing importance of tourism have also occurred. Recreational activities can thus be one of the main reasons for disruptions of landscape diversity and stability and increased fragmentation of the landscape caused by the development of tourism may lead to a decrease in biodiversity (Klaučo et al. 2012; Rušnák, Izsóff and Lieskovský 2017; Kňazovičová et al. 2018). Protected areas around the world are crucial to biodiversity conservation (Margules, Pressey and Williams 2002), while land use is a critical factor in providing food and other ecosystem services essential for human needs. The challenge is to identify management opportunities that preserve ecological functions while minimizing human land-use constraints (DeFries et al. 2007). Land cover changes in Europe's protected areas are a frequent research object studied mainly using GIS technologies (e.g., Gabrovec et al. 2013; Zafar 2014; Martinez del Castillo et al. 2015; Janík and Romportl 2018; Hamad, Kolo and Balzter 2018; Krajewski 2019; Martin et al. 2019; Rodríguez-Rodríguez, Martínez-Vega and Echavarría 2019; Ribeiro and Šmid Hribar 2019).

In Slovakia, nature and landscape protection is applied through the Act No.543/2002 Coll. on Nature and Landscape Protection (Zákon o ochrane … 2002). The Act aims to ensure the long-term preservation of natural balance, the protection of the diversity of conditions and forms of life, natural values and beauty, the creation of conditions for sustainable use of natural resources and ecosystem services, taking into account economic, social and cultural needs as well as regional and local conditions. The range of restrictions increases with the increasing degree of protection. Each type of protected area has a specific degree of protection within its territory. In Slovakia, large and small-scale protected areas are established. A specific degree of protection is applied in different protected areas (Table 1).

The degree of protection of the territory also determines land use and the number of ecosystem services provided. The most dominant industries in the protected areas of Slovakia are forestry, tourism, water management, and mining. The most significant revenues also flow from these industries (Janiga et al. 2012).

Table 1: Protected areas in Slovakia according to the Act No. 543/2002 Coll. on Nature and Landscape Protection.

Type of protected area		Degree of protection	Number	Area (ha)
Large-scale protected area	National park (NP)	3rd	9	317,889.90
	Protected landscape area (PLA)	2nd	14	522,581.50
Small-scale protected area	National Nature Reserve (NNR)	4th, 5th	219	84,188.97
	Nature Reserve (NR)	4th, 5th	217	13,347.35
	Protected Area (PA)	3rd, 4th, 5th	166	8307.54
	National Nature Monument (NNM)	4th, 5th	11	84,188.97
	Nature Moment (NM)	4th, 5th	217	1583.31
	Protected Landscape Feature (PLF)	2nd, 3rd, 4th, 5th	1	2.51

In our research, we have dealt only with the large-scale protected areas, which cover 22.65% of Slovakia. A **national park** is defined as an area of over 10,000 ha, predominantly with ecosystems substantially unchanged by human activity or in a unique and natural landscape structure, constituting the most important natural heritage, in which nature protection is superior to other activities. The protection objective of a national park is the conservation or gradual restoration of natural ecosystems, including ensuring the uninterrupted flow of natural processes in at least three-quarters of the area of a national park. A **protected landscape area** is defined as an area of over 1000 ha, with scattered ecosystems important for the conservation of biodiversity and ecological stability, with a characteristic landscape appearance or with specific forms of historical settlement (Act No. 543/2002 Coll. on Nature and Landscape Protection) (Zákon o ochrane … 2002). These areas thus constitute representative parts of the landscape that need to be protected by law and focus on their excellent management. Although the legislation protects a large part of the landscape, the protected areas are subject not only to anthropogenic influences but also to various natural disturbances. Protected areas are the cornerstone of forest protection, but during socio-economic and institutional crises, the protection of forests is not always adequate. Since 1990, Slovakia has undergone economic-institutional changes, including the break-up of socialism, accession to the European Union, and the rapid expansion of protected areas (Butsic et al. 2017).

It is very important to detect and analyze changes in protected areas, because they are not immune to biodiversity and habitat loss or increases in human-caused pressure (Geldmann, Joppa and Burgess 2014).

The paper aims to compare and evaluate the extent and the nature of land cover changes in protected areas of Slovakia between 1990 and 2018. Based on the research, we should be able to answer the following research questions:

- What was the extent of changes that took place in selected protected areas of Slovakia?
- What changes took place in protected areas of Slovakia?
- Which land cover classes were dynamic and which were static in protected areas?
- How did the landscape's diversity and stability of protected areas change in the last three decades?

2 Methods

2.1 Study area

In our research, we have dealt with landscape changes in large-scale protected areas of Slovakia, which include nine national parks and fourteen protected landscape areas (Figure 1).

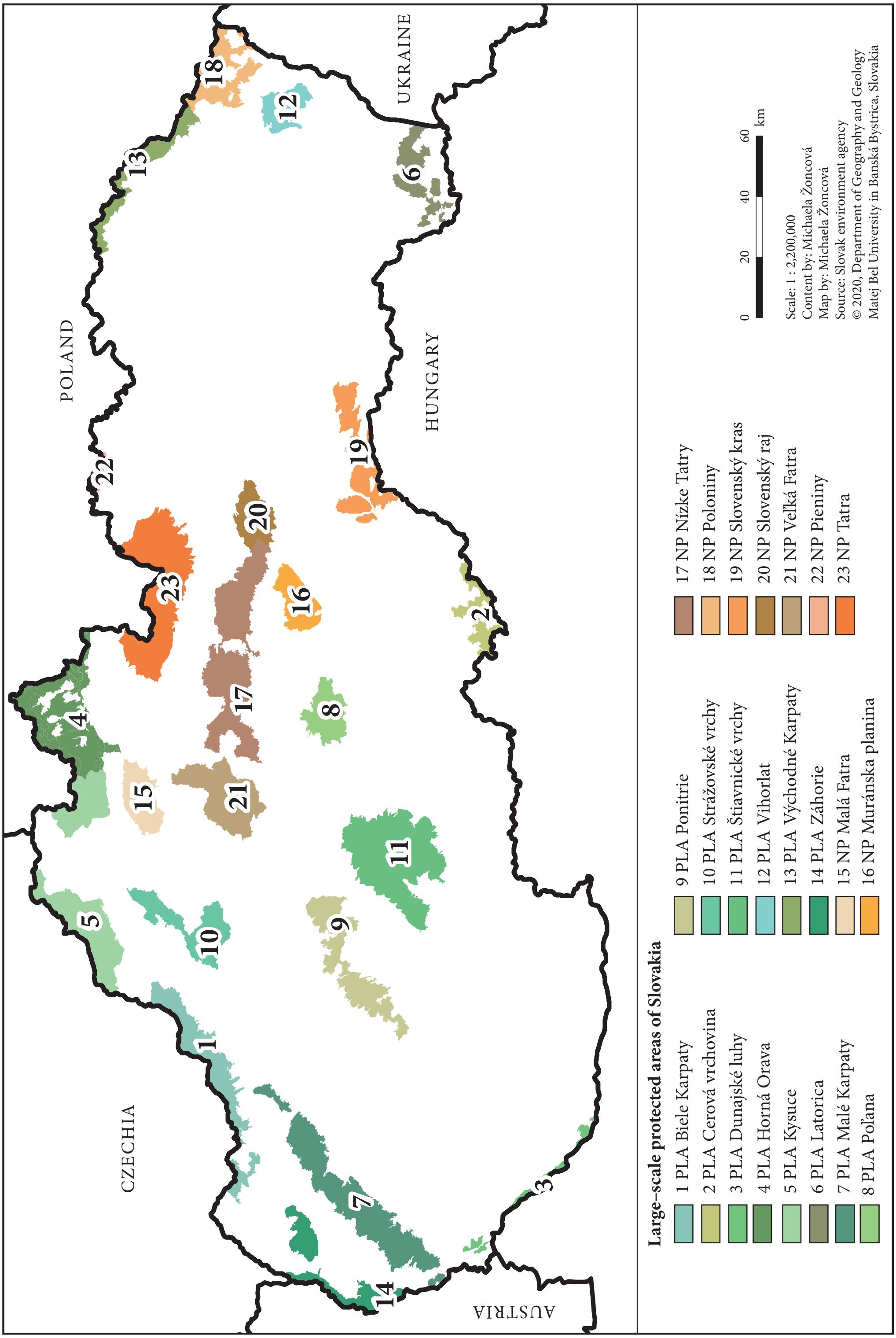
The oldest protected landscape area is the PLA Vihorlat, which was declared in 1973. All PLAs were established until 1990, except for the PLA Dunajské Luhy, which was established only in 1998 and is the youngest protected area in Slovakia. Some of the present national parks were firstly protected as protected landscape areas and had been transformed into national parks later (1964 – Slovenský raj, 1967 – Malá Fatra, 1973 – Slovenský Kras, 1974 – Veľká Fatra, 1977 – Muránska Planina). The oldest national park is the Tatra National Park (TANAP), which was proclaimed in 1948. This year was significant for the former Czechoslovakia, as it had been listed as the 49th state in the list of states that established national parks on their territory (Štátny zoznam osobitne … 2020). Some protected areas have changed their boundaries and area over time. In our research, we have observed areas delimited by their current borders.

2.2 Data and analyses

We have used CORINE Land Cover (CLC) data from 1990 and 2018 for the analysis of land cover changes in protected areas. Using analytical tools in ArcMap 10.5 software, we had been able to identify the extent and the nature of changes over a nearly 30-year period. Twenty-six CLC classes have been identified in large-scale protected areas of Slovakia (Table 2).

We have focused mainly on the comparative evaluation of changes in the individual land cover classes and analyzed them statistically and spatially. The output tables were subsequently transformed into contingency tables, from which we have obtained the proportional shares of land cover classes in 1990 and

Figure 1: Large-scale protected areas in Slovakia (National park – NP, Protected landscape area – PLA). ➤


POLAND
UKRAINE
HUNGARY
CZECHIA
AUSTRIA
Large-scale protected areas of Slovakia
1 PLA Biele Karpaty
2 PLA Cerová vrchovina
3 PLA Dunajské luhy
4 PLA Horná Orava
5 PLA Kysuce
6 PLA Latorica
7 PLA Malé Karpaty
8 PLA Poľana
9 PLA Ponitrie
10 PLA Strážovské vrchy
11 PLA Štiavnické vrchy
12 PLA Vihorlat
13 PLA Východné Karpaty
14 PLA Záhorie
15 NP Malá Fatra
16 NP Muránska planina
17 NP Nízke Tatry
18 NP Poloniny
19 NP Slovenský kras
20 NP Slovenský raj
21 NP Veľká Fatra
22 NP Pieniny
23 NP Tatra
0 20 40 60 km
Scale: 1 : 2,200,000
Content by: Michaela Žoncová
Map by: Michaela Žoncová
Source: Slovak environment agency
© 2020, Department of Geography and Geology
Matej Bel University in Banská Bystrica, Slovakia

2018 as well as the changes within the period observed. The next stage consisted of assessing landscape structure changes based on the calculation of landscape metrics using the Patch Analyst extension. The software offers analyses of several types of landscape-ecological indices. These metrics are often used as indicators of landscape fragmentation or diversity in Slovakia (Boltižiar 2010; Gajdoš, Klaučo and Škodová 2012; Olahová, Vojtek and Boltižiar 2013) and abroad (Li et al. 2004; Kumar et al. 2018; Deriaz et al. 2019). However, in our research we have focused mainly on the analysis of landscape diversity over time using the **Shannon Diversity Index (SDI).** It is an index determining landscape diversity calculated as the ratio of the size of different land cover classes over the total area. SDI increases by the number of patches in the land cover classes. The higher the index value, the greater the diversity of the land cover, i.e., the land cover is richer in the number of land cover classes and the number of patches (Klaučo et al. 2014). The index will be equal to 0 when there is only one patch in the landscape, and increases as the number of patch types or the proportional distribution of patch types increases. We analysed the landscape stability using the **Ecological Stability coefficient** (ESc), according to Míchal (1982). The coefficient reflects the proportion of relatively stable and unstable landscape areas. Stable areas include forests, non-forest tree vegetation, meadows, pastures (we have included CLC classes: 221, 222, 231, 311, 312, 313, 321, 322, 324, 331, 332, 333, 411, 412, 511, 512). Unstable areas include arable and built-up areas (we have included CLC classes: 112, 121, 131, 132, 133, 141, 412, 211, 242, 243). We have observed the values of the coefficient as well as their change between the years 1990 and 2018. The resulting values were interpreted as follows:

- ESc < 0.10 – an area with a maximal disruption of natural structures, essential ecological functions must be intensively and permanently replaced by technical interventions;
- ESc = 0.10–0.30 – an over-exploited area, with an apparent disruption of natural structures;

Table 2: CLC classes in large-scale protected areas of Slovakia.

Level 1	Level 3
1 Artificial surfaces	112 Discontinuous urban fabric
	121 Industrial or commercial units
	131 Mineral extraction sites 132 Dumpsites 133 Construction sites
	141 Green urban areas 142 Sport and leisure facilities
2 Agricultural areas	211 Non-irrigated arable land
	221 Vineyards 222 Fruit trees and berry plantations
	231 Pastures
	242 Complex cultivation patterns 243 Land principally occupied by agriculture, with significant areas of natural vegetation
3 Forest and semi-natural areas	311 Broad-leaved forest
	312 Coniferous forest
	313 Mixed forest
	321 Natural grasslands
	322 Moors and heathland
	324 Transitional woodland-shrub
	331 Beaches, dunes, sands 332 Bare rocks 333 Sparsely vegetated areas
4 Wetlands	411 Inland marshes 412 Peat bogs
5 Water bodies	511 Watercourses 512 Waterbodies

- ESc = 0.31–1.00 – an intensively used area, mainly for large-scale agricultural production, where weakening of self-regulatory processes causes their considerable ecological lability;
- ESc > 1,00 – an almost balanced landscape in which the technical objects are in relative balance with the preserved natural structures.

Within the framework of land cover structure changes between 1990 and 2018, we have also identified the dominant (not the prevailing) process using the »land cover flows« (LCF) identification method. Some authors (Stott and Haines-Young 1998; Feranec et al. 2010; Perdigao and Christensen 2000; Köhler, Olschofsky and Gerard 2006) have used this method, but they defined different types of processes. In our research, we used a land cover flow definition by Haines-Young and Weber (2006). They identified nine types of processes:

- **LCF1 Urban land management** – Internal transformation of urban areas;
- **LCF2 Urban residential sprawl** – Land uptake by residential buildings altogether with associated services and urban infrastructure from non-urban land;
- **LCF3 Sprawl of economic sites and infrastructures** – Land uptake by new economic sites and infrastructures (including sport and leisure facilities) from non-urban land;
- **LCF4 Agriculture internal conversions** – Conversion between farming types;
- **LCF5 Conversion from forested & natural land to agriculture** – Agricultural expansion;
- **LCF6 Withdrawal of farming** – Farmland abandonment and other conversions from agriculture activity in favor of forests or natural land;
- **LCF7 Forests creation and management** – Creation of forests and management of the forest territory by felling and replanting;
- **LCF8 Water bodies creation and management** – Creation of dams and reservoirs and possible consequences of the management of the water resource on the water surface area;

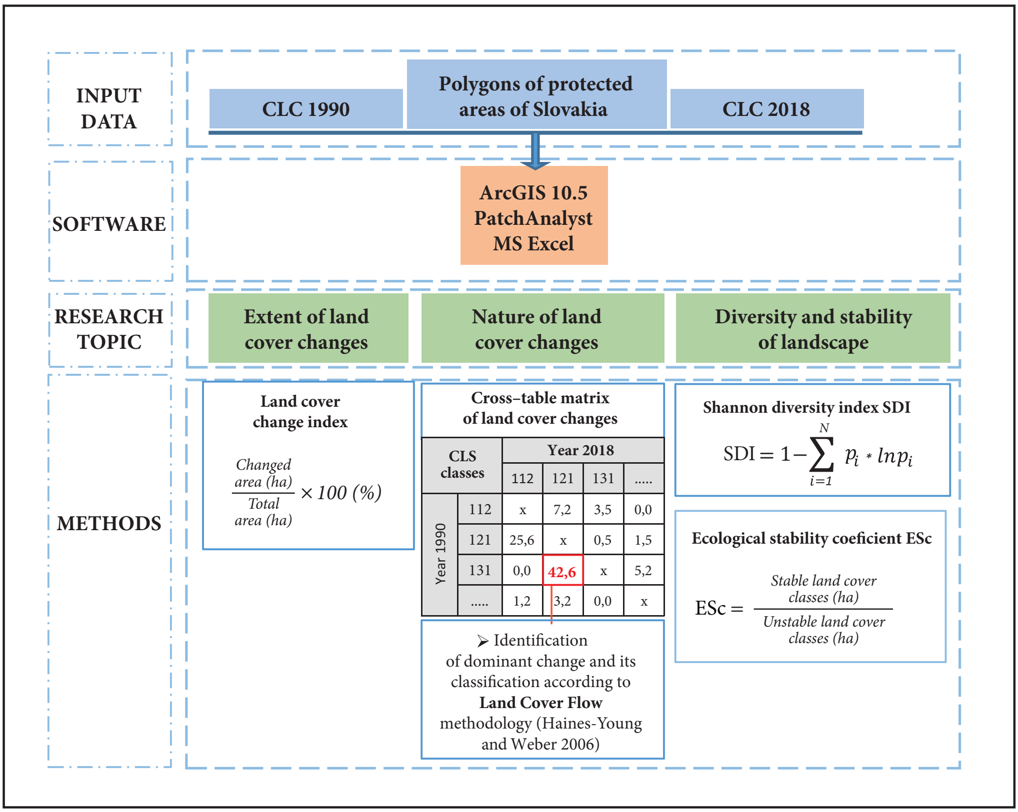


Figure 2: Schematically representation of the methodology followed by the research.

- **LCF9 Changes of land cover due to natural and multiple causes** – Changes in land cover resulting from natural phenomena with or without any human influence.

Additionally, Haines-Young and Weber (2006) defined sub-processes at detailed level. For complete list of sub-processes see Haines-Young and Weber (2006). We have identified the most dominant sub-process, i.e., the one with the highest proportional share in each protected area. We have focused on the figure with the highest numerical value, that is to say, which class of land cover was dominantly changing to another class, using the cross table matrix of the changes in the different land cover classes in the observed period. We have then assigned this change to a specific land cover flow. Although we could have assigned other sub-processes in the observed area (e.g., LCF71 includes changes from CLC 324 to CLC 311, CLC 324 to CLC 312, CLC 324 to CLC 313, and other), we have not deliberately addressed all the sub-processes, but only the most dominant sub-process (Figure 2).

3 Results

3.1 The extent of land cover changes

We could determine the extent of land cover changes by comparing the CLC data from 1990 and 2018 in each of the protected areas (Figure 3).

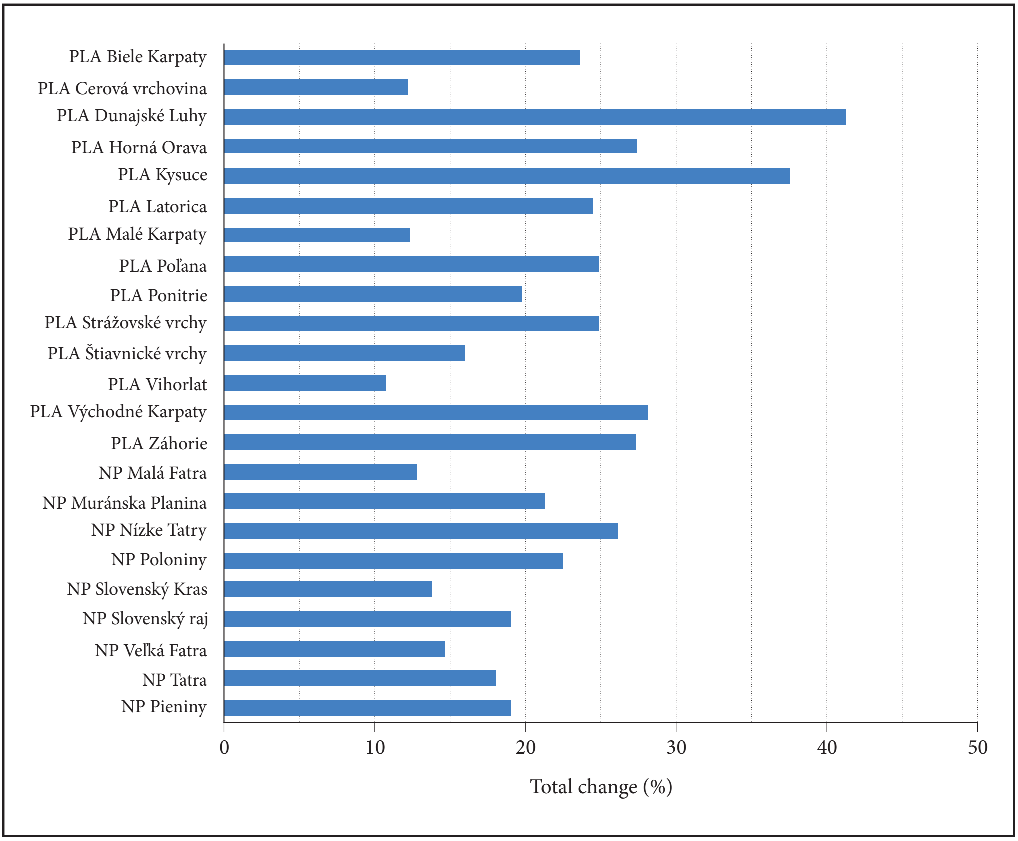
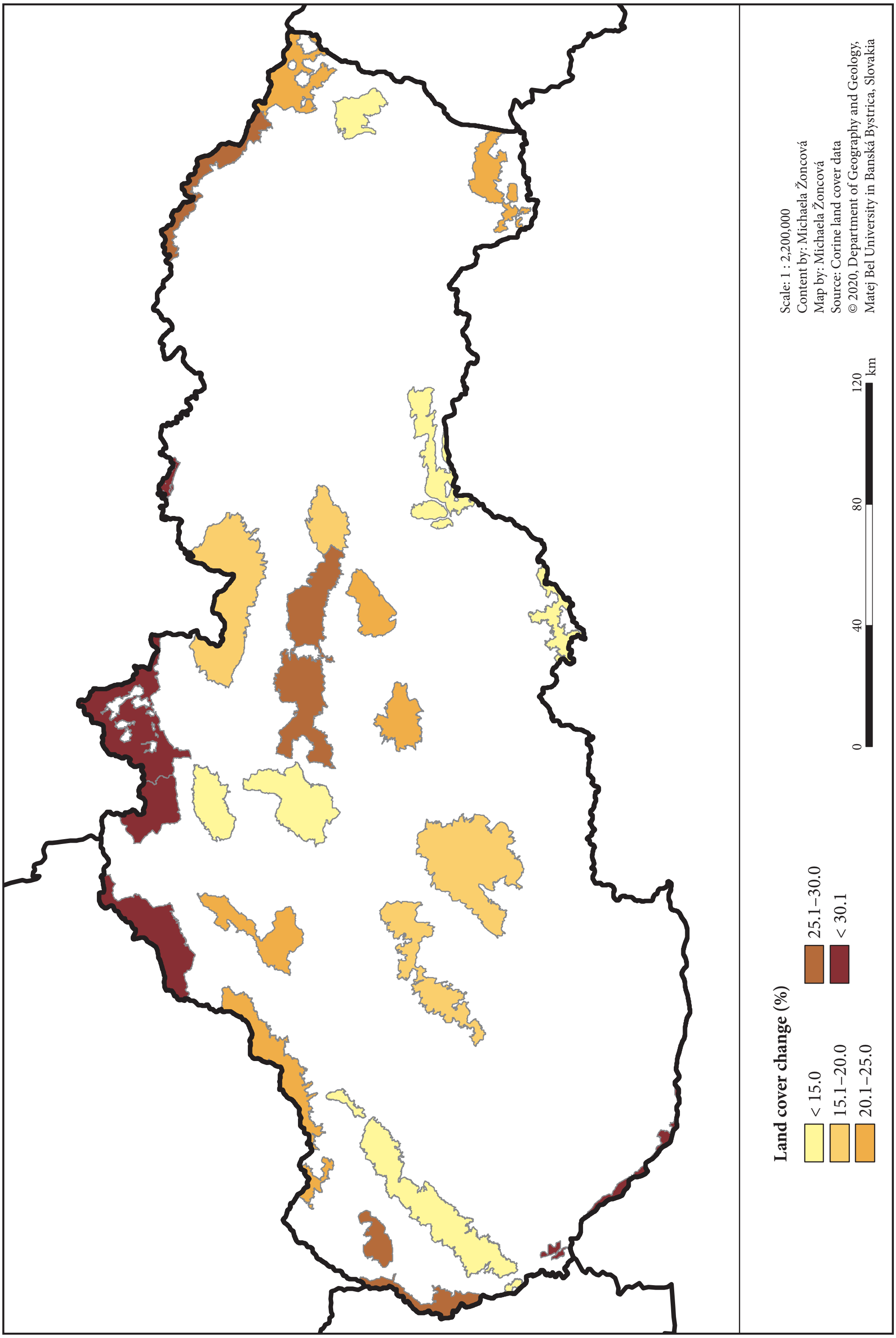


Figure 3: Extent of changes in large protected areas of Slovakia between 1990 and 2018.

Figure 4: Land cover changes in large-scale protected areas in Slovakia between 1990 and 2018 (in %). ➤


Land cover change (%)
< 15.0
15.1–20.0
20.1–25.0
25.1–30.0
< 30.1
0
40
80
120
km
Scale: 1 : 2,200,000
Content by: Michaela Žoncová
Map by: Michaela Žoncová
Source: Corine land cover data
© 2020, Department of Geography and Geology,
Matej Bel University in Banská Bystrica, Slovakia

In total, up to 21.7% of the area of the protected areas was changed. Land cover, and consequently the landscape, changed in the national parks as well as in the protected landscape areas. More than one third of the area was changed in the PLAs Dunajské luhy (41.3%) and Kysuce (37.6%). On the contrary, the least changes occurred in the PLAs Vihorlat (10.7%) and Cerová vrchovina (12.2%). Considering the national parks, the NP Nízke Tatry has changed the most, where up to 26.3% of its area has changed. On the contrary, the least changes were recorded in the NP Malá Fatra, where only 12.8% of the area has changed. In terms of spatial distribution, most changes occurred in protected areas located along the country's borders with one exceptions in the centre of the country in the Low Tatras National Park (Figure 4).

The most significant changes thus took place within CLC classes 231, 243, 311, 312, 313, 324, i.e., within forest stands and meadows. These classes can be considered very dynamic, with more than 20% decrease or increase in their areal extent. On the contrary, CLC classes 112, 121, 131, 132, 141, 142, 221, 222, 331, 332, 333, 412, i.e., urbanized areas, areas of permanent crops, areas with sparse vegetation and wetlands, can be described as static classes.

3.2 The nature of land cover changes

By comparing the percentage shares of land cover classes of protected areas in individual years, it is possible to define the nature of the main changes (Table 3).

The most significant increase in land cover class was recorded in the PLA Poľana, where up to 58% of the area was transformed into mixed forests (CLC 313). In particular, the forest land cover classes (CLCs 311, 312, 324) and agricultural land cover classes (CLC 211, 231, 243) were transformed. On the other hand, the most substantial proportional decrease occurred in the PLA Východné Karpaty, where the area of tran-

Table 3: The nature of land cover changes in large protected areas of Slovakia between 1990 and 2018 (x – no change observed).

Protected area	512	511	412	411	333	332	331	324	322	321	313	312
PLA Biele Karpaty	x	x	x	x	x	x	x	–5%	x	<0.5%	–1%	–1%
PLA Cerová vrchovina	–1%	x	x	x	x	x	x	–7%	x	x	7%	1%
PLA Dunajské Luhy	8%	4%	x	–5%	x	x	<0.5%	–44%	x	<0.5%	x	x
PLA Horná Orava	6%	x	<0.5%	–7%	x	x	x	–12%	1%	<0.5%	10%	11%
PLA Kysuce	1%	x	x	x	x	x	x	27%	x	<0.5%	16%	–27%
PLA Latorica	x	x	x	5%	x	x	x	–4%	<0.5%	x	x	x
PLA Malé Karpaty	<0.5%	<0.5%	x	<0.5%	x	x	x	–18%	x	–2%	–4%	7%
PLA Poľana	<0.5%	x	x	x	x	x	x	–25%	x	x	58%	–9%
PLA Ponitrie	x	x	x	x	x	x	x	–9%	x	x	29%	3%
PLA Strážovské vrchy	x	x	x	x	<0.5%	x	x	3%	x	x	10%	<0.5%
PLA Štiavnické vrchy	<0.5%	x	x	x	x	x	x	–5%	x	<0.5%	6%	<0.5%
PLA Vihorlat	2%	x	x	x	<0.5%	x	x	–16%	x	<0.5%	8%	<0.5%
PLA Východné Karpaty	x	x	x	x	x	x	x	–52%	x	x	21%	4%
PLA Záhorie	1%	5%	x	<0.5%	x	x	x	–10%	x	x	11%	7%
NP Malá Fatra	<0.5%	<0.5%	x	x	–2%	x	x	5%	2%	–8%	23%	–9%
NP Muránska planina	x	x	x	x	–1%	x	x	–8%	x	x	36%	–17%
NP Nízke Tatry	<0.5%	x	x	x	<0.5%	x	x	42%	4%	–9%	11%	–45%
NP Poloniny	<0.5%	x	x	x	x	x	x	–35%	x	x	27%	<0.5%
NP Slovenský Kras	<0.5%	x	x	x	2%	x	x	11%	x	<0.5%	21%	–1%
NP Slovenský Raj	<0.5%	x	x	x	–1%	x	x	17%	x	x	9%	–23%
NP Veľká Fatra	x	x	x	x	1%	x	x	8%	<0.5%	–5%	19%	–26%
NP Pieniny	x	x	x	x	x	x	x	1%	x	x	11%	17%
Tatra NP	<0.5%	x	x	x	<0.5%	–1%	x	48%	5%	–7%	1%	–44%

sitional woodland-shrub was transformed into deciduous and mixed forests. Both cases, correspond to **succession processes**, where over-harvested or degraded forest areas have overgrown over time and have been transformed into young forests. However, it does not have to be just a succession. Artificial reforestation is mainly used in habitats where the natural regeneration is slowed down, i.e. if the mother stand is missing or has an unsuitable species composition or poor quality, or on large calamitous areas. Artificial regeneration is often a tool to ensure the continuity of the forest in larger and more continuous calamitous areas. An obligation to afforest any clearing within two years from its origin, three years if protective forest stands are concerned, comes from the Act No. 326/2005 Coll. on forests (Zákon o lesoch 2005). The state authorities may extend this period by another two years in case of an expected natural renewal. Another obligation is to secure the forest stand from 2 to 10 years after the end of the afforestation period.

The same process, when the share of transitional woodland-shrub (CLC 324) decreases at the expense of forest land cover classes is also visible in the PLAs Dunajské luhy, Poloniny, and Poľana. Succession processes are also reflected by the increase of permanent grasslands in the NP Slovenský kras. The opposite process, when the share of transitional woodland-shrub increases and the share of forest decreases, was recorded in the PLA Kysuce, the NPs Nízke Tatry, Slovenský raj and Tatra. Transitional woodland-shrub is a class which contains young forest trees (deciduous and coniferous), planted after loggings or various calamities, as well as forest nurseries, forest formations with natural development, shrub formations on abandoned meadows, pastures and forest clearings under high-voltage power lines (Feranec and Oťaheľ 2001). Due to the loss of forest cover, this landscape ceased to fulfill its essential functions. Consequently, the ecological stability of the landscape is disrupted, which is manifested in various disturbances, including landslides, floods, and endangering of wild animals by the reduction of their natural habitats. The most significant **change in the urbanized (built-up) areas** was observed in the PLA Dunajské Luhy. However, it is necessary to note

Continuation of table 3.

311	243	242	231	222	221	211	142	141	133	132	131	121	112
15%	−8%	2%	1%	<0.5%	x	−4%	<0.5%	x	x	x	x	x	2%
26%	−6%	<0.5%	−19%	x	−1%	3%	x	x	x	x	<0.5%	x	−2%
52%	−6%	<0.5%	3%	−1%	x	1%	1%	x	−12%	−1%	x	<0.5%	<0.5%
6%	−7%	12%	−11%	x	x	−9%	<0.5%	x	x	x	x	<0.5%	<0.5%
1%	−4%	4%	−18%	x	x	−1%	<0.5%	x	<0.5%	x	x	<0.5%	1%
34%	−4%	−1%	−15%	x	<0.5%	−14%	x	x	x	x	<0.5%	<0.5%	−1%
22%	<0.5%	<0.5%	−1%	<0.5%	−1%	−3%	<0.5%	x	<0.5%	x	<0.5%	<0.5%	<0.5%
−13%	−2%	x	−9%	x	x	−1%	x	x	x	x	x	<0.5%	x
−17%	−1%	<0.5%	−2%	<0.5%	<0.5%	−4%	1%	x	x	x	<0.5%	x	<0.5%
−5%	−4%	−1%	−5%	x	x	1%	x	x	x	x	x	x	1%
12%	−13%	<0.5%	1%	<0.5%	<0.5%	−1%	<0.5%	<0.5%	x	<0.5%	<0.5%	<0.5%	<0.5%
11%	−2%	1%	−2%	x	x	−2%	x	x	x	x	x	2%	−1%
42%	−7%	<0.5%	−7%	x	x	−1%	x	x	x	x	x	x	<0.5%
−6%	−4%	<0.5%	8%	<0.5%	<0.5%	−12%	<0.5%	x	x	x	x	<0.5%	<0.5%
−6%	−3%	2%	−5%	x	x	<0.5%	<0.5%	x	x	x	<0.5%	x	<0.5%
1%	1%	x	−11%	x	x	<0.5%	x	x	x	x	<0.5%	<0.5%	<0.5%
−1%	<0.5%	x	−3%	x	x	<0.5%	1%	x	x	x	x	x	<0.5%
26%	−7%	x	−11%	x	x	<0.5%	x	x	x	x	x	x	<0.5%
<0.5%	−5%	<0.5%	−25%	x	−1%	−2%	x	x	x	x	<0.5%	<0.5%	<0.5%
10%	2%	x	−14%	x	x	−1%	−1%	x	x	x	x	x	<0.5%
10%	<0.5%	<0.5%	−6%	x	x	<0.5%	−1%	x	x	x	<0.5%	x	<0.5%
<0.5%	−22%	<0.5%	−7%	x	x	1%	x	x	x	x	x	x	<0.5%
<0.5%	<0.5%	<0.5%	−2%	x	x	<0.5%	<0.5%	x	x	x	x	x	<0.5%

that this area was not been categorized as a PLA in 1990. The construction of the Gabčíkovo waterworks was carried out in this area in the 1980s and 1990s. However, the system of aggradation embankments and accumulation depressions with a dense network of river distributaries was created before human interventions into the natural hydrological regime of the Danube River. The Dunajské Luhy was declared as Protected Landscape Area only in 1998, and the formerly built-up areas are nowadays mainly water bodies, permanent grasslands, agricultural areas, or deciduous forests (Feranec et al. 2002).

We have focused on the identification of processes taking place in the landscape within the dynamics of land cover classes, the so-called »land cover flows«. We have identified the dominant sub-processes based on the percentage of all changes in every protected area, i.e., the process with the highest percentage (Table 4).

Nine dominant sub-processes, which can be assigned to five land cover flows, have been identified (Figure 5).

LCF71 – is the most frequent dominant sub-process in Slovakian large protected areas. It represents the conversion of transitional woodland-shrubs to forests, i.e., **the secondary succession on forest clearings**. This sub-process was dominant in eight protected areas. Altogether three types of changes were observed: Transitional woodland-shrubs were dominantly transformed into deciduous forests in the PLAs Malé Karpaty (29.54%), Dunajské luhy (40.15%), Vihorlat (39.89%), Východné Karpaty (40.74%), and the NP Poloniny (37.98%). The transformation of transitional woodland-shrubs into coniferous forests was most evident in the PLAs Horná Orava (14.96%) and Záhorie (10.72%), and transformation to mixed forests was most evident in the PLA Poľana (28.49%).

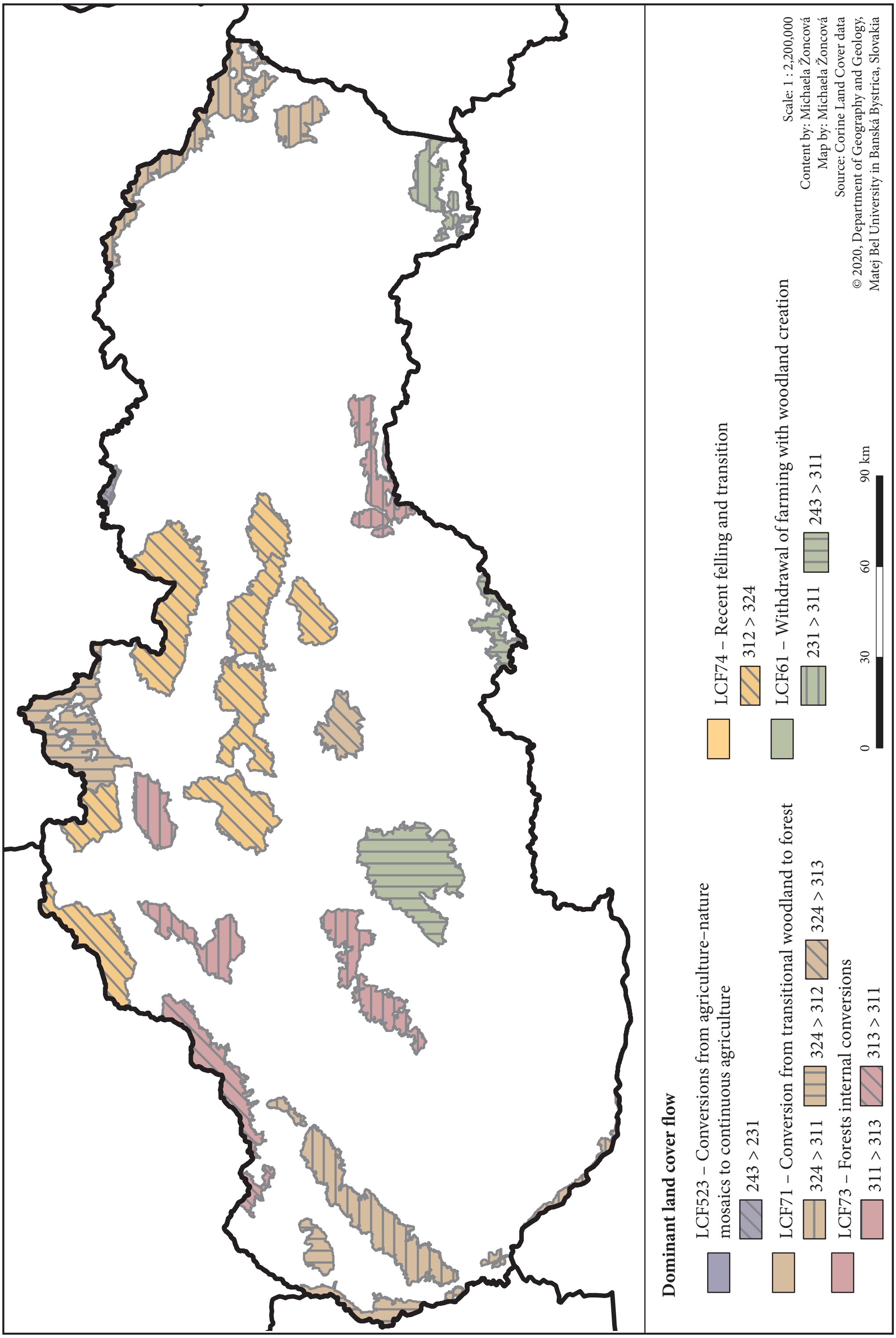
LCF73 – represents the internal transformations of forests, i.e., conversions of one forest type to another (among coniferous, deciduous and mixed). Overall, two types of changes have been identified, when mixed forests were converted to deciduous forests and vice versa. These sub-processes were identified in five protected areas, most notably in the NP Malá Fatra. Specifically, this involved the conversion of CLC 311 to CLC 313. Conversion of deciduous forests to mixed forests was also dominant in the PLAs Ponitrie (29.15%) and Strážovské vrchy (17.06%) and the NP Slovenský kras (16.36%).

LCF74 – the sub-process is most often caused by forest loggings or by natural forces resulting in subsequent logging. Only one sub-process was identified in the large protected areas, namely the transformation of coniferous forest into transitional woodland-shrub. This sub-process can also be described as a »transient state of the forest« and has been dominant in one PLA – PLA Kysuce and in five national parks – the Tatra NP, NP Nízke Tatry, NP Slovenský raj, NP Muránska planina and NP Veľká Fatra. The sub-process

Table 4: Dominant land cover flows in large protected areas.

Large protected area	Dominant LCF		Large protected area	Dominant LCF	
	%	LCF		%	LCF
PLA Biele Karpaty	16.12	LCF73	PLA Východné Karpaty	40.74	LCF71
PLA Cerová vrchovina	17.79	LCF61	PLA Záhorie	10.72	LCF71
PLA Dunajské Luhy	40.15	LCF71	NP Malá Fatra	32.54	LCF73
PLA Horná Orava	14.96	LCF71	NP Muránska planina	17.59	LCF74
PLA Kysuce	31.18	LCF74	NP Nízke Tatry	52.59	LCF74
PLA Latorica	14.62	LCF61	NP Poloniny	37.98	LCF71
PLA Malé Karpaty	29.54	LCF71	NP Slovenský kras	16.36	LCF73
PLA Poľana	28.49	LCF71	NP Slovenský raj	43.42	LCF74
PLA Ponitrie	29.15	LCF73	NP Veľká Fatra	16.17	LCF74
PLA Strážovská vrchy	17.06	LCF73	NP Pieniny	20.59	LCF523
PLA Štiavnické vrchy	9.28	LCF61	NP Tatra	53.55	LCF74
PLA Vihorlat	39.89	LCF71			

Figure 5: Land cover flows in large protected areas of Slovakia between 1990 and 2018 (%). ►


Dominant land cover flow
LCF523 – Conversions from agriculture–nature mosaics to continuous agriculture
243 > 231
LCF71 – Conversion from transitional woodland to forest
324 > 311
324 > 312
324 > 313
LCF73 – Forests internal conversions
311 > 313
313 > 311
LCF74 – Recent felling and transition
312 > 324
LCF61 – Withdrawal of farming with woodland creation
231 > 311
243 > 311
0
30
60
90 km
Scale: 1 : 2,200,000
Content by: Michaela Žoncová
Map by: Michaela Žoncová
Source: Corine Land Cover data
© 2020, Department of Geography and Geology,
Matej Bel University in Banská Bystrica, Slovakia

can be described as alarming, as the most significant parts of Slovakia's nature have lost a large amount of forest areas. These areas are often affected by wind disasters, with the most considerable damage being recorded in 2004 (Konôpka and Kunca 2016). The proportion of forests destroyed by wind calamities has been increasing over the past 55 years (Konôpka and Konôpka 2007).

LCF61 – This sub-process involves a secondary succession sub-process and the abandonment of agricultural land and its gradual transformation into transitional woodland-shrubs or forests. Two types of changes were identified: The class land principally occupied by agriculture, with significant areas of natural vegetation (CLC 243) was transformed into broad-leaved forest (CLC 311) in the PLA Cerová Vrchovina and the PLA Štiavnické Vrchy and pastures were transformed into broad-leaved forests (CLC 311) in the PLA Latorica. Abandonment of agricultural land is related to socio-economic changes in Slovakia and changes in traditional management (Lieskovský et al. 2015; Pazúr et al. 2014). Traditional mowing or goats and sheep grazing had prevented succession sub-processes in the past (Škodová and Gajdoš 2010).

LCF523 – the sub-process is characterized by the conversion of predominantly agricultural structures with natural elements into continuous agriculture. The sub-process was dominant only in NP Pieniny, where mainly CLC 243 was converted to CLC 231.

3.3 Diversity and landscape stability of the large protected areas

The landscape diversity in the observed years was calculated using the SDI. The variation of this index reflects the changes in the number of landscape feature classes and their abundance. We have also determined the level of ecological stability of the landscape (Figure 6).

SDI values ranged from 0.48 in the PLA Vihorlat to 1.84 in the PLA Záhorie in 1990. The minimum and maximum values were recorded in these areas in 2018 as well. The most significant decrease in the

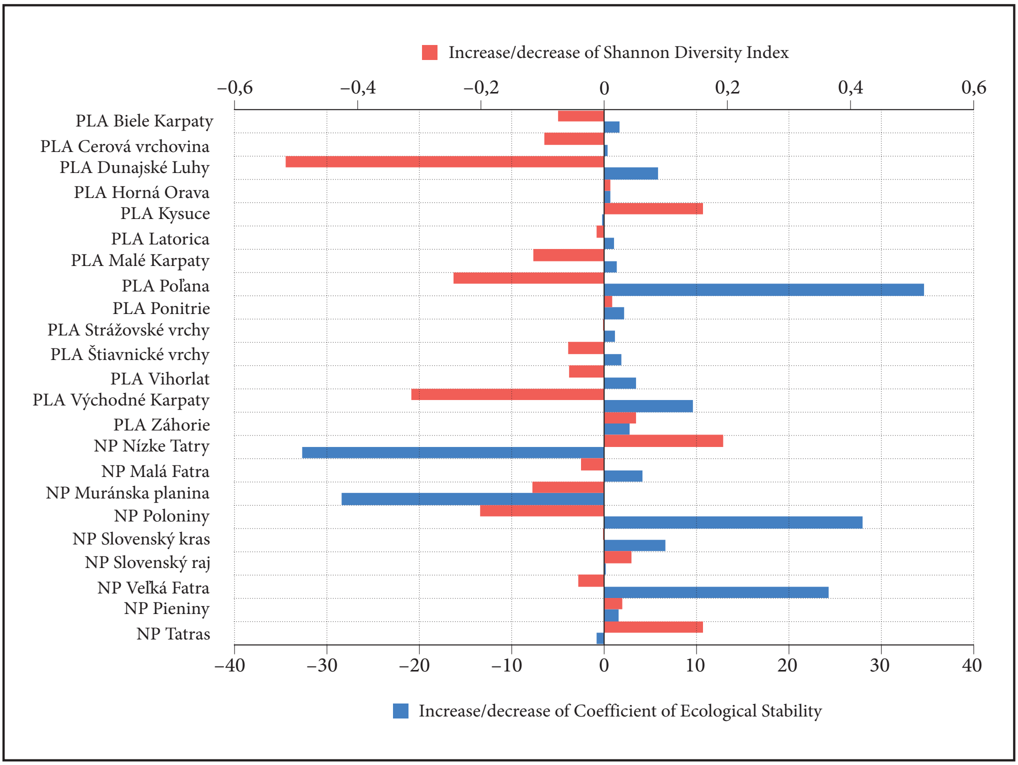


Figure 6: SDI and ESc change in the large protected areas of Slovakia between 1990 and 2018.

SDI value, i.e., a decrease in diversity of the landscape, occurred in the PLA Dunajské Luhy. A decline in human activity-related land cover classes (construction and agricultural activity), was observed and reflected in SDI values. A significant decrease in SDI values also occurred in the PLA Východné Karpaty, where the number of land cover classes did not change, but they were unequally distributed (represented) in the landscape. On the other hand, the highest increase of SDI index occurred in the NP Nízke Tatry, the Tatra NP, and the PLA Kysuce. The areas of coniferous forests have decreased, and the areas of transitional woodland-shrubs increased in the NP Nízke Tatry due to wind calamities and subsequent logging. The CLC classes are thus represented more evenly, but in this case, the increase in SDI values suggests a higher landscape diversity. However, it is questionable whether this radical increase has a positive effect on the stability of the landscape.

We have analyzed the stability of the landscape using the coefficient of ecological stability, according to Míchal (1982). All of the protected areas in both of the monitored years reached values of the ESc index higher than 1.0, which is a result of an almost well-balanced landscape, where the technical features are in relative balance with the preserved natural structures. The ecological stability coefficient of less than 1.0 was recorded only in the PLA Latorica for the year 1990. This value indicates that the area was used intensively mainly for large-scale agricultural production, while the self-regulation processes were weakened, which caused lower ecological instability in these areas. However, the value of ESc had increased above 1.0 in this area in 2018.

Ecological stability of the landscape had decreased in four protected areas, while it increased in the others. A small, almost negligible decline occurred in the PLA Kysuce and the NP Vysoké Tatry. However, a significant decrease occurred in the NP Nízke Tatry and the NP Muránska Planina. Although ESc values still reached high levels in these areas (higher than in the other protected areas), these changes are alarming as these are areas with habitats of protected species. In the NP Muránska Planina, the greatest threat is the loss of the natural habitats of the critically endangered capercaillie (Figúr, Malina and Urban 2016). On the contrary, the most significant increase in ESc values, i.e., a significant increase in the ecological stability of the landscape, occurred in the NP Poľana, the NP Poloniny, and the NP Veľká Fatra.

4 Discussion and conclusion

In the large-scale protected areas of Slovakia, the most substantial changes occurred between transitional woodland-shrubs (CLC 324) and mixed forests (CLC 313). Changes among these classes represent an ongoing process. On the one hand, it is **a process of succession**, and on the other, it is **a reduction of the forest area**. According to Vološčuk (2010), the assessment of the secondary succession of dendroflora in the abandoned former pasture sites with permanent grassland is perceived rather negatively from the landscapes' characteristic appearance point of view. However, this process is positive, considering the ecological stability of a landscape, where forest ecosystems represent the most stable elements. In this sense, it is essential to perceive landscape diversity and stability as two different concepts. A decline in the stability of the landscape despite the increase in the landscape diversity was a frequent phenomenon. Increased landscape diversity is often a result of radical interventions in the landscape, both natural and anthropogenic. The values of landscape-ecological indices have to be interpreted very sensitively for this reason. Although the values of the SDI index have increased over the period studied, irreversible and degrading changes for the landscape occurred. The share of CLC 324 (transitional woodland-shrub) increased, while the share of CLC 312 (coniferous forests) decreased, mainly due to wind calamities and subsequent logging in the NP Nízke Tatry. Therefore, land cover classes had a more even representation in the landscape, and the landscape diversity increased. Is the increase in the landscape diversity beneficial to the landscape in this way? According to Guerra, Rosa and Pereira (2019), monitoring of land cover changes is particularly crucial in protected areas where long-term ecosystem stability is a critical aspect of conservation. We agree with Ružičková, Moravčíková and Lehotská (2009), who states that the resulting values of the landscape's diversity index do not describe the ecological stability and quality of the assessed area and do not take the internal differentiation (disaggregation) of the landscape structure features into account. The penetration of dendroflora in secondary succession into the abandoned agrarian ecosystems can cause a decrease in the value of landscape character (patterns of elements in the landscape) and can be understood as a degradation process. Secondary succession of dendroflora in grassland ecosystems can also be understood as ecological damage because by disrupting internal links and processes, it weakens the natural functions of permanent grassland ecosystems (Vološčuk 2010). These conditions are suitable for the spreading of non-native and invasive plant species and plant species in the form of scattered groups of shrubs and trees (David, Mojses and Boltižiar 2013). According to Šebo and Kopecká (2014), small meadows in Slovakia will almost entirely disappear due to the difficulty of their maintenance. This problem has been also observed throughout other countries in Central Europe (Pruchniewicz 2017).

The second most dominant sub-process was the reduction of forest area when forest stands were converted to transitional woodland-shrubs. This class (CLC 324) can arise through an entirely different development and can thus take on completely different values of ecological stability or diversity. On the one hand, it may include areas artificially mined by heavy machinery with severely anthropogenically affected and degraded landscape. However, it may also include areas affected by wind disasters left to develop spontaneously and thus with slower but spontaneous forest regeneration. The issue of landscape management after wind disasters is still very up-to-date, and there is a constant debate about whether it is necessary to remove or leave calamity wood in the landscape. According to Urbanovičová, Miklisová and Kováč (2014), it is much more appropriate to leave the fallen wood after a wind calamity in the landscape to enable the survival of specific forest species and to preserve the diversity of forests. The wind is becoming one of the most important abiotic factors, which causes various disturbances in the landscape of Slovakia (Konôpka, Zach and Kulfan 2016). The importance of protected areas in Slovakia is also confirmed by the fact that deforestation is visible on a much smaller scale in the protected areas than in the surrounding unprotected areas (Butsic et al. 2017). For example, the difference can also be seen between the Polish and Slovak sides of the Tatra National Park, with radical differences in the opinions on logging in the national parks, on bark beetles, and large predators hunting (Janiga et al. 2012). A new law entered into force in Slovakia on 1 January 2020, strengthening the competence of the State Nature Conservancy of Slovak Republic. Logging will not be possible in the protected areas with the third and higher degree of protection without its consent, while so far, they have had such powers only in areas with the fifth degree of protection.

Based on the results obtained, we can conclude that the CLC database is a suitable data source to analyze main land cover changes in Slovakia in larger areas, but some classes may also include diametrically different types of landscapes (e.g., CLC 324) that perform different functions. However, the CLC database also has its negatives (Jovanović, Milanovic and Zorn 2018) and is not suitable for monitoring current changes (5–10 years) and for monitoring changes in small areas, as the Minimum Mapping Unit (MMU) is 25 ha. Also, the values of landscape ecological metrics should be sensitively interpreted because it does not take the internal differentiation of land cover classes into account. In the future, it is necessary to focus on the proper management of the landscape after wind calamities, as these are the primary triggers of the significant landscape changes in protected areas of Slovakia. Although the process associated with new construction activity did not predominate in any of the protected areas, purposeful innovations in line with the principles of sustainable development are still necessary for the development of these areas (Lencsésová, Gajdošík and Gúčik 2015).

Therefore, we agree with Paunović and Jovanović (2019), that it is necessary to put a special emphasis on exchange of best practices and improvement of the quality of all sustainable tourism elements from other countries.

ACKNOWLEDGMENT: This work was supported by the Slovak Research and Development Agency under Contract no. APVV-18-0185 Land-use changes of Slovak cultural landscape and prediction of its further development.

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Acta geographica Slovenica, 60-2, 2020, 91–105

PERIODICALLY INUNDATED UVALAS AND COLLAPSE DOLINES OF UPPER PIVKA, SLOVENIA

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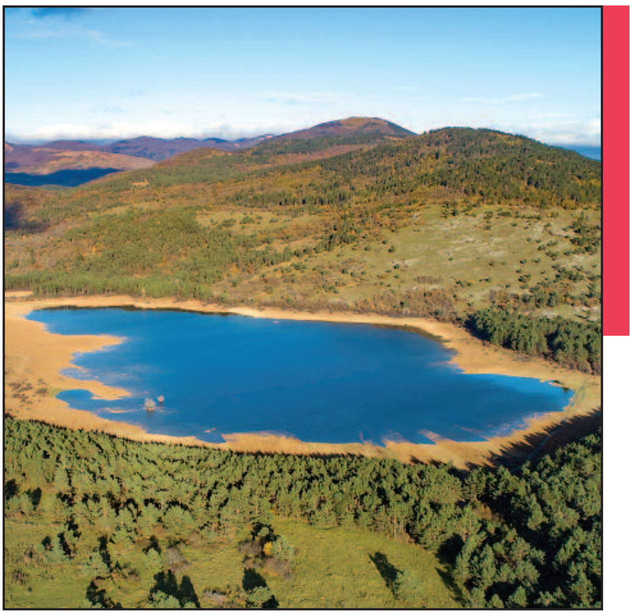

Palško Jezero is one of the largest intermittent lakes of Upper Pivka.

DOI: https://doi.org/10.3986/AGS.8051
UDC: 911.2:551.435.8(497.4)
COBISS: 1.01

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Periodically inundated uvalas and collapse dolines of Upper Pivka, Slovenia

ABSTRACT: Within the area of Upper Pivka there is a number of intermittent lakes because of oscillation of water table level close to the surface i.e. shallow karst. Our survey was focused on morphogenetic interpretation of depressions hosting intermittent lakes by means of classic morphographic mapping and sediment analyses that was supported by electrical resistivity tomography. We can interpret at least two different morphogenetic types of depressions. One type are depressions which are periodically inundated uvalas positioned in-between conical hills. The second type are circular depressions within karst plain that are collapse dolines filled with extensive flood deposits up to several metres thick.

KEY WORDS: geophysics, electrical resistivity tomography (ERT), geomorphology, collapse doline, uvala, shallow karst, karst, Slovenia

Periodično poplavljene uvale in udornice na območju Zgornje Pivke

IZVLEČEK: Na območju Zgornje Pivke so zaradi nihanja gladine podtalnice blizu površja (tj. plitvega krasa) številna presihajoča jezera. Raziskava se osredotoča na morfogenetsko razlago kotanj s presihajočimi jezeri na podlagi klasičnega morfografskega kartiranja in analiz sedimentov, podprtih z električno upornostno tomografijo. Na proučevanem območju lahko določimo vsaj dva morfogenetska tipa kotanj: periodično poplavljene uvale, umeščene med kopaste vzpetine, in okrogle udornice na kraških uravnavah, zasute z do več metrov debelo plastjo poplavnih sedimentov.

KLJUČNE BESEDE: geofizika, električna upornostna tomografija (ERT), geomorfologija, udornica, uvala, plitvi kras, kras, Slovenija

The paper was submitted for publication on March 3rd, 2020.
Uredništvo je prejelo prispevek 3. marca 2020.

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1 Introduction

The region of Upper Pivka is a part of the Karstic Ljubljanica River catchment, positioned within the Classical Karst of Slovenia (Gospodarič and Habič 1976; Šušteršič 1994; Gams 2003; Mihevc 2010; Stepišnik 2010). The highest sections of the catchment consist of high karst plateaus (Mihevc 2010) where surface drainage pattern is completely absent. In contrast, periodical surface drainage occurs on eight major poljes surrounded by high karst plateaus. The Karstic Ljubljanica River catchment drains towards the north-eastern boundary of the Classical Karst where it emerges in several karst springs. This complex hydrologic system is accompanied by a great variety of karst features, which makes the whole area an exceptional example of karst landscape (Ferk and Stepišnik 2011; Stepišnik and Repe 2015; Stepišnik and Trenchovska 2016). One of the most studied sections of the catchment is the Upper Pivka region that has particularly diverse hydrologic and hydrogeologic settings (Ravbar and Šebela 2004). This is a region of shallow karst where the water table level is positioned close to the relatively levelled surface (Habič 1985–1986; Habič 1989). During high water levels, several streams appear on the surface; their flow is directed northwards to the Postojna Cave. At these conditions, seventeen larger karst depressions within surrounding karst become inundated. The intermittent lakes are an important geoheritage of Slovenia. They were extensively studied and are considered as unique karst phenomena (Mulec, Mihevc and Pipan 2005; Stepišnik and Trenchovska 2016).

Previous literature is predominantly revising morphographic settings and hydrologic function of those lake depressions (Pleničar 1959; Habič 1975; Kranjc 1985; Habič 1985–1986; Habič 1989; Gams 2003; Ravbar and Šebela 2004; Habič 2005; Kovačič and Habič 2005; Kovačič 2006). They were simply described as periodically inundated karst depressions lacking systematical interpretation of their origin. Modern geomorphological research approach is concerned mainly by morphogenesis of surface features (Pavlopoulos, Evelpidou and Vassilopoulos 2009). The morphogenesis of the lake depressions has not yet been interpreted since interpretation would require more in-depth analysis than the simple morphographic, morphometric, and morphodynamic approaches that have been used so far.

Understanding the morphogenesis of relief features is actually an understanding of the formation, development and functioning of relief in a particular area. It enables the further interpretation of paleogeographic and paleoenvironmental conditions within the study area. Comprehensive understanding of geomorphological settings of the area enables possibilities of proper nature interpretation (Smrekar et al. 2014). This is important for enhancing geoturistical and geoeducational potential of protected areas, such as the Upper Pivka region. Furthermore, it enables more expedient and prudent management of geosites. Thus, morphogenetic assessment gives us possibilities for more appropriate measures for the nature protection and more efficient spatial management.

The aim of the study is to interpret morphogenesis of enclosed karst depressions hosting intermittent lakes of Upper Pivka. As a principal tool for interpretation we applied electrical resistivity tomography (ERT) that is a non-invasive geophysical analysis. We set the following goals: (1) general morphographic analysis and morphographic mapping of the wider area of the lakes, (2) detailed morphographic and morphometric analysis of lake depressions, (3) electrical resistivity tomography of selected section within the depressions, and (4) morphogenetic interpretation.

2 Regional settings

The Karstic Ljubljanica River catchment occupies an area of about 1,100 to 1,200 km^2 (Habič 1976). The highest sections of the area are high karst plateaus, the lower sections are mainly karst plains (or corrosion plains) and poljes. The total number of poljes within the area are eight, all of them have periodical streams, and they are inundated during high water levels (Habič 1976). The waters from poljes submerge to the underground through a number of ponors. The subsurface drainage system is diverted to a series of major springs of the Ljubljanica River at the edge of the Ljubljana Basin. This hydrologic system is accompanied by a great variety of surface and sub-surface karst features, which makes the whole area an exceptional example of karst diversity (Gams 1966; Gospodarič and Habič 1976; Zupan Hajna et al. 2008; Ferk et al. 2019).

The Pivka Basin represents the westernmost part of the Karstic Ljubljanica River catchment. The basin is enclosed by high karst plateaus. Waters are discharging in different directions towards the boundaries of the basin where they sink into the karst underground. The Upper Pivka is encompassing the southern part of the Pivka basin. The region is engulfed between high karst plateaus, while the northern part is merged with the rest of the Pivka Basin. The Upper Pivka is 15 km long and up to 5 km wide. The southernmost areas are located at an elevation of 640 m and gradually lower towards north to the elevation of 520 m. Within the area, bedded Cretaceous limestone prevail, with some Cretaceous dolomite breccia in the southern sections (Buser et al. 1967; Šikić, Pleničar and Šparica 1972). On the western edge of the area a buried fold of Eocene flysch that crops out at two separate tectonic windows is located (Pleničar 1959). The flysch fold is an active hydrogeologic barrier that is blocking westward drainage of susbsurface drainage diverting it towards east and north-east (Šikić and Pleničar 1975).

The topography of the northern part of the Upper Pivka comprises a karst plain dissected with numerous conical hills, dolines and other smaller karst features. The central part is almost a completely levelled karst plain dissected solely by dolines. The whole area of the Upper Pivka characterized by a number of large karst depressions which floors extend into the watertable oscillation level causing them to be periodically inundated. Within the western part of the karst plain the Pivka River and its short tributaries are positioned. The wide valley floor is covered by fine-grained alluvial deposits and at some stretches engulfed within narrow and up to 10-metre-deep canyon.

The wider area hosting intermittent lakes is proclaimed in 2014 as Pivka Lakes Nature Park due to its large biodiversity and habitat for many endangered species. The area is also included in the Natura 2000 network.

3 Materials and methods

Geomorphological analysis of karst depressions hosting intermittent lakes was accomplished through analytic geomorphological methods (Pavlopoulos, Evelpidou and Vassilopoulos 2009). Field morphographic analyses and mapping that included identification and spatial documentation of geomorphological features within the depressions and the surrounding slopes was supported by remote sensing data (Državna topografska karta … 2018; Lidar 2019;). Detailed field investigations were conducted after the remote sensing analyses. Field investigations were focused on karst depressions hosting intermittent lakes and their surroundings. Electronic surveying devices (GPS Garmin Oregon 600, laser distance meter Leica Disto, photo camera and drone) were used to support field morphographic and morphometric survey.

To establish subsurface structure of depressions the geophysical method of Electrical Resistivity Tomography (ERT) (also Electrical resistivity imaging (ERI)) was applied. The method is appropriate for subsurface tomography of karst terrains as the high contrast in resistivity values between carbonate rock and clayey material can easily be detected. It is particularly useful for determining the boundary between bedrock and overburden (Zhou, Beck and Stephenson 2000).

Five ERT measurements were conducted in five separate depressions. The data were collected using a SuperSting R1/IP resistivity meter developed by Advanced Geosciences Inc. A multi-core cable of 20 electrodes spaced at 5 m intervals was used. A dipole-dipole array, which is utilized in cases where vertical depth penetration and high resolution are paramount, was applied. The dipole-dipole array has been widely used in morphogenetic studies of dolines, collapse dolines and denuded caves (Zhou, Beck and Adams 2002; Stepišnik 2006; Stepišnik and Mihevc 2008; Kaufmann, Deceuster and Quinif 2012; Mihevc and Stepišnik 2012; Yeboah-Forson, Comas and Whitman 2014). The depth penetration of dipole-dipole array is approximately 15% of total spread length of profiles where the roll-along method has not been used (Herman 2001). The depth penetration in the measured profiles varies from 20.1 to 20.6 m in the profile centres.

The apparent resistivity data were inverted using AGI EarthImager 2D software. The root mean square error (RMS) quantifies the difference between the measured resistivity values and those calculated from the true resistivity model. A small RMS value indicates small differences (Zhou, Beck and Adams 2002; Zhou, Beck and Stephenson 2000). In the measurements, presented in this paper, 3–8 iterations were run to achieve the RMS errors from 2.05% to 7.70%. Contact resistance testing showed no outliers.

4 Results

Upper Pivka can be divided into two typical sections based on the relief features. The northern section is not a characteristic karst plain as it is dissected by numerous conical hills and in-between relief hollows. The floors of some hollows are within groundwater oscillation zone and accommodate intermittent lakes.

Detail investigation was conducted within two depressions within this area that are occasionally inundated. The first depression is of the northernmost intermittent lake named Jeredovce, and the second one is towards south named Krajnikov Dol.

Even though the Jeredovce depression is rarely inundated, it is referred by literature as an intermittent lake (Habič 2005; Kovačič and Habič 2005). The depression is elongated in the south-west – north-east direction. Its widest part is in the south-west, while it is gradually narrowing in the north-east direction. The floor is uneven and dissected by dolines. In some parts it is covered with flood loam. The length of the floor is ~1800 m, while the width on the southwest is ~600 m. The lowest altitude of the floor is in the south-western part at 538 m asl, while the north-western part is slightly higher at 540 m asl. The slopes of the depression are dissected by some dolines. The transition between the slopes and the surrounding karst

Figure 1: Locations of ERT profiles: A – Jeredovce, B – Krajnikov Dol, C – Veliko Zagorsko Jezero, D – Udor, E – Bačko Jezero.

surface is gradual. This depression is a part of a larger elongated lowland located in between the surrounding conical hills. The floor of the Jeredovce is flooded only in cases of the highest water levels. The highest recorded altitudes of flooding in this depression are 542 m (Habič 2005; Kovačič and Habič 2005).

ERT profile of Jeredovce was measured in the central part of the depression floor at an elevation of about 541 m throughout the entire profile. Five iterations were made to achieve RMS of 7.70%. The inverted resistivity for this profile show undulating carbonate bedrock with values from 500 to 1,500 ohm-m starting at depth from 4 to 14 m. At some parts, the carbonate bedrock reaches the surface, e.g. at electrode No. 13. The carbonate bedrock is covered by a sediment or regolith with resistivity about 200 ohm-m. Individual patches of sediments show lower resistivity values of about 100 ohm-m, probably owing to its loamy character.

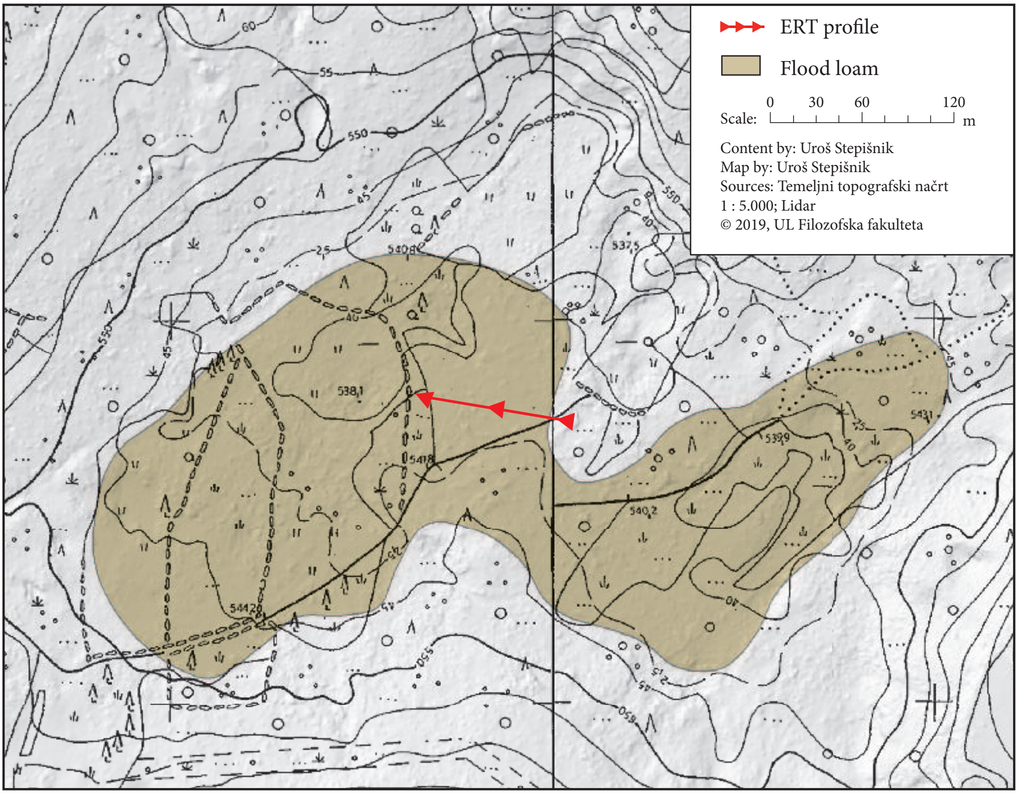

Figure 2: ERT profile location within Jeredovce depression.

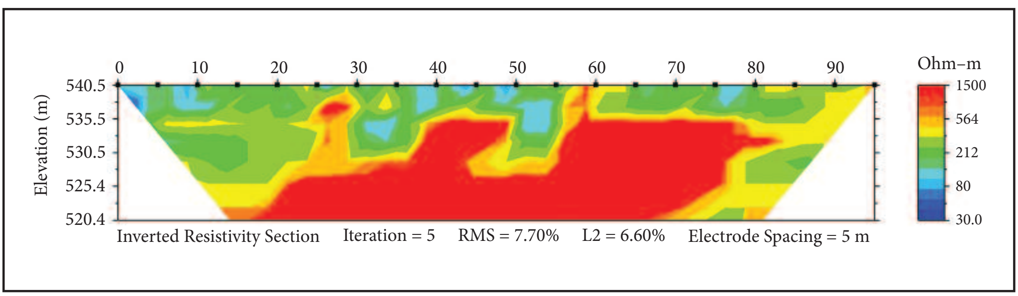

Figure 3: ERT profile of the Jeredovce depression.

Around one kilometre to the south of Jeredovce the depression Krajnikov Dol is located. The floor is flattened by flood loam at an altitude of 537 m. The levelled floor is elongated in south-west – north-west direction and has a length of 140 m and a width of 60 m. The elevation of the lake, which occasionally fills the depression floor, can be as high as 540 m (Habič 2005; Kovačič and Habič 2005). The slopes sourrounding the floor are gentle and dissected by shallow gullies. The rim of the depression is not distinct but it gradually transfers into sourrounding karst surface. The depression is not completely rounded but has an irregular shape in ground plan.

ERT profile of Krajnikov Dol was assessed from the east slope trough the floor with orientation 300 degrees. Elevation at the beginning and the end of profile was about 540 m. Seven iterations were made to achieve

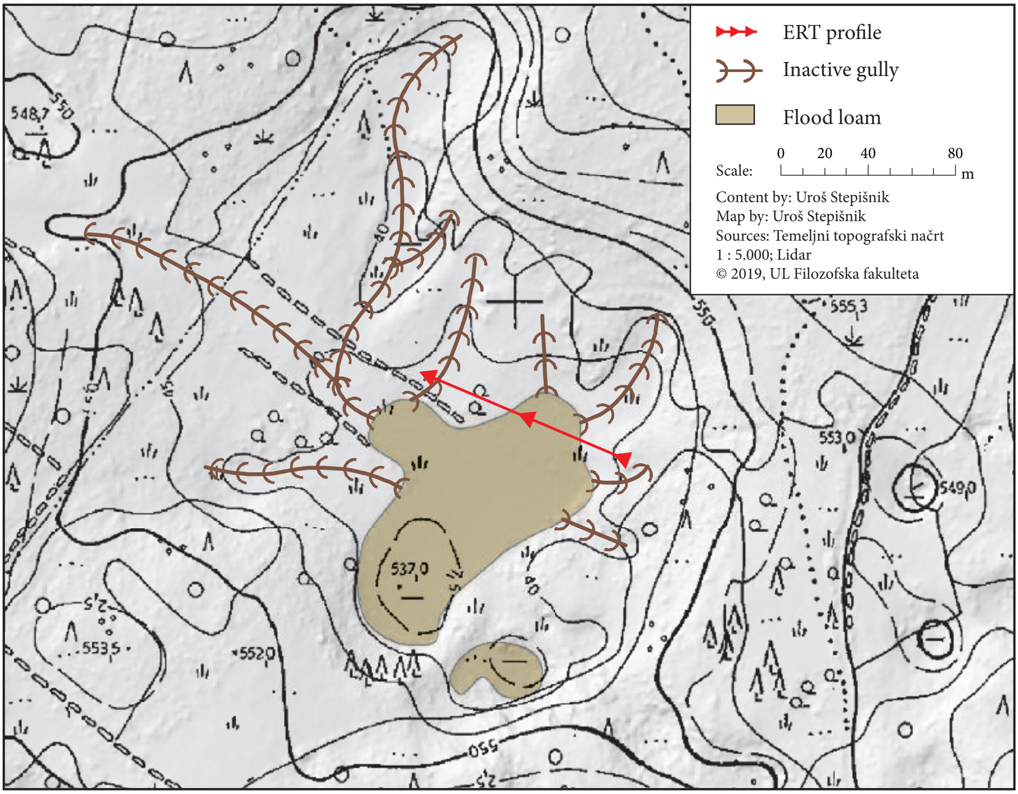

Figure 4: ERT profile location within Krajnikov Dol depression.

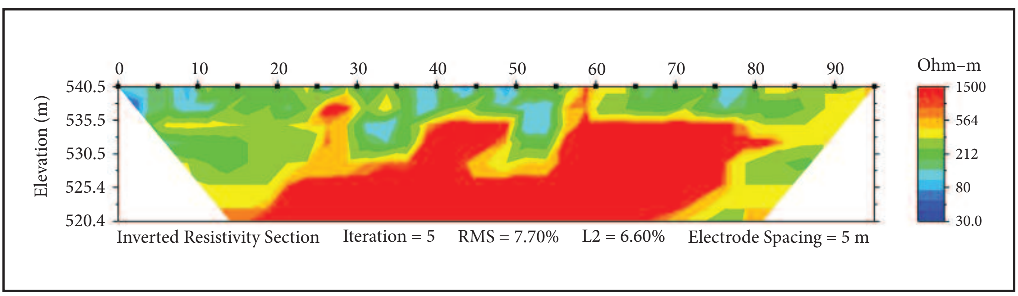

Figure 5: ERT profile of Krajnikov Dol.

RMS of 3.43%. Inverted resistivity of the east slopes exceed 500 ohm-m (electrodes 1–7), which means the slopes are built of carbonate bedrock. The resistivity at 5–8 m depth are lower – 200–400 ohm-m, which is probaby due to higher water content within the bedrock pores or due to regolith mantle. The middle part of the profile (electrodes 8–13) is located at approximately 538m asl. There, the resistivity values were below 100 ohm-m, which is due to the presence of loamy sediments with lower electrical resistivity. The depth of loamy fills does not exceed 5 m in the central part. Carbonate bedrock with resistivity values from 500 to 1,500 ohm-m is located below the loamy fills. On the western slopes (electrodes 14–20) the measured inverted resistivity exceed 500 ohm-m, which indicate the presence of carbonate bedrock. Resistivity at the final part of the profile (electrodes 18–20) are below 150 ohm-m at depths up to 10 m. This part of

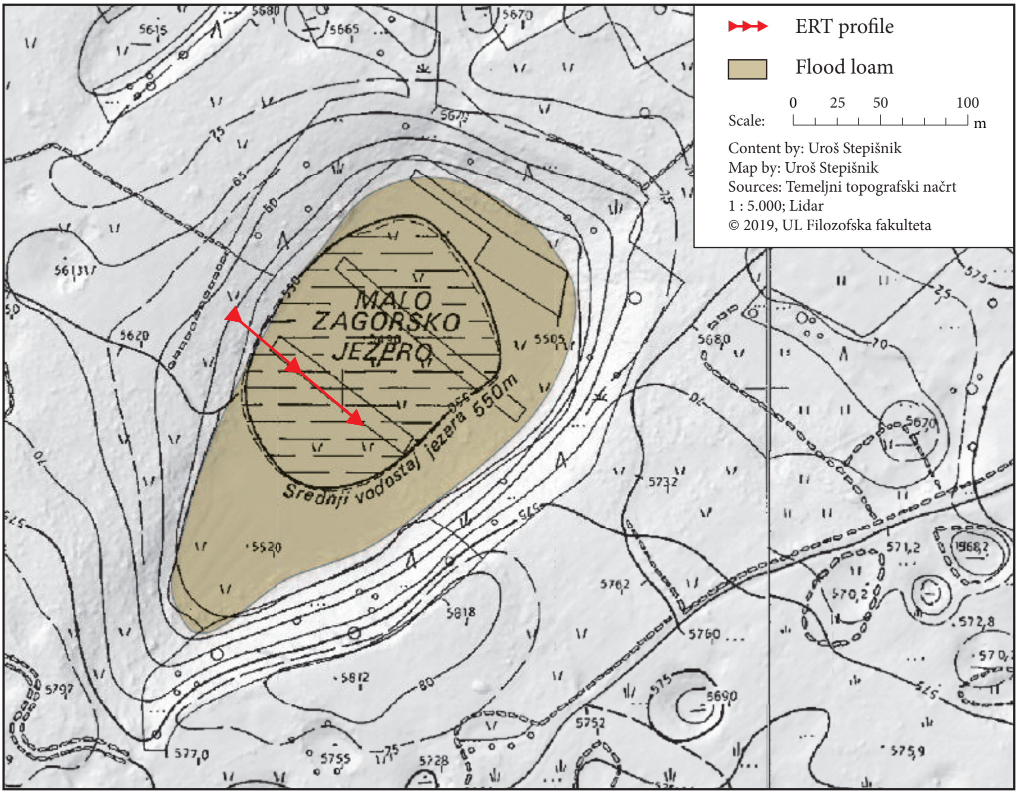

Figure 6: ERT profile location within Veliko Zagorsko Jezero depression.

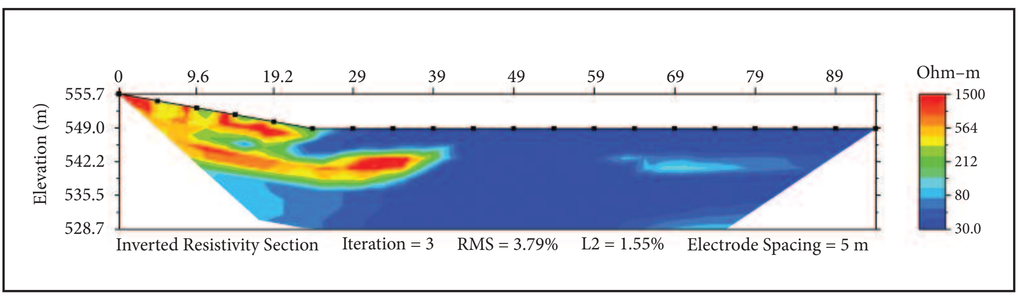

Figure 7: ERT profile of Veliko Zagorsko Jezero.

the profile crosses an inactive gully on the slope that is filled by weathered bedrock and sandy-loamy sediment located at its floor.

Towards the south the Upper Pivka karst plain is positioned. Within this section of the study area the largest number of depressions hosting intermittent lakes is located. Unlike the northern section, this area is completely levelled, dissected solely by dolines, while conical hills are completely absent. Unlike the northern part of the karst plain, the hollows of the intermittent lakes are in plan view of circular shape, contrary to the star-shaped depressions in the northern part. Moreover, the area of these circular depressions is smaller than the large depressions of the north. The largest group of circular depressions is located along the valley floor of the Pivka River. Detail investigation of thickness of flood loam

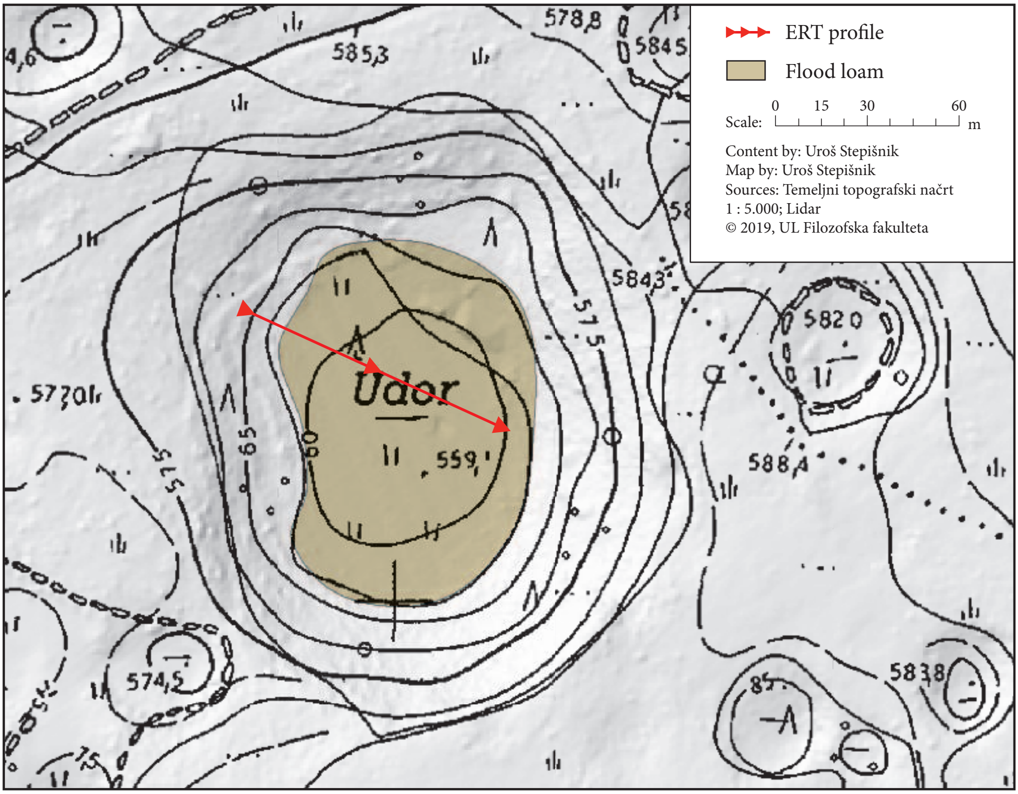

Figure 8: ERT profile location within Udor depression.

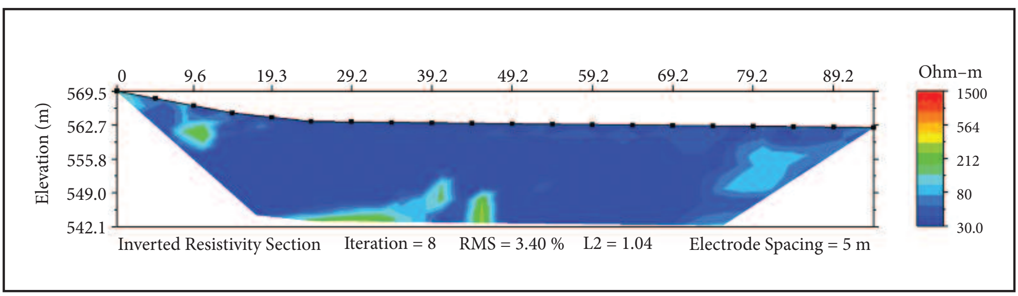

Figure 9: ERT profile of Udor.

deposits within floors was conducted within three depressions: Veliko Zagorsko Jezero, Udor and Bački Dol.

The depression of Veliko Zagorsko Jezero is positioned in the western part of the plain. It is oval in shape with a longer axis in the south-west-north-east direction. The length of the floor is ~300 m and the width is about ~150 m. Flood loam levels the floor at the altitude of 549 m. The floor of the depression passes sharply into the surrounding slopes. Almost all of the slopes are active, partly consist of steep rocky walls with collapse blocks below them. Only a part of the eastern slope is balanced (Stepišnik and Kosec 2011). Intermittent inundations within the Veliko Zagorsko Jezero depression reach elevations of 550 m, during extreme watertable levels even 551 m (Habič 2005; Kovačič and Habič 2005).

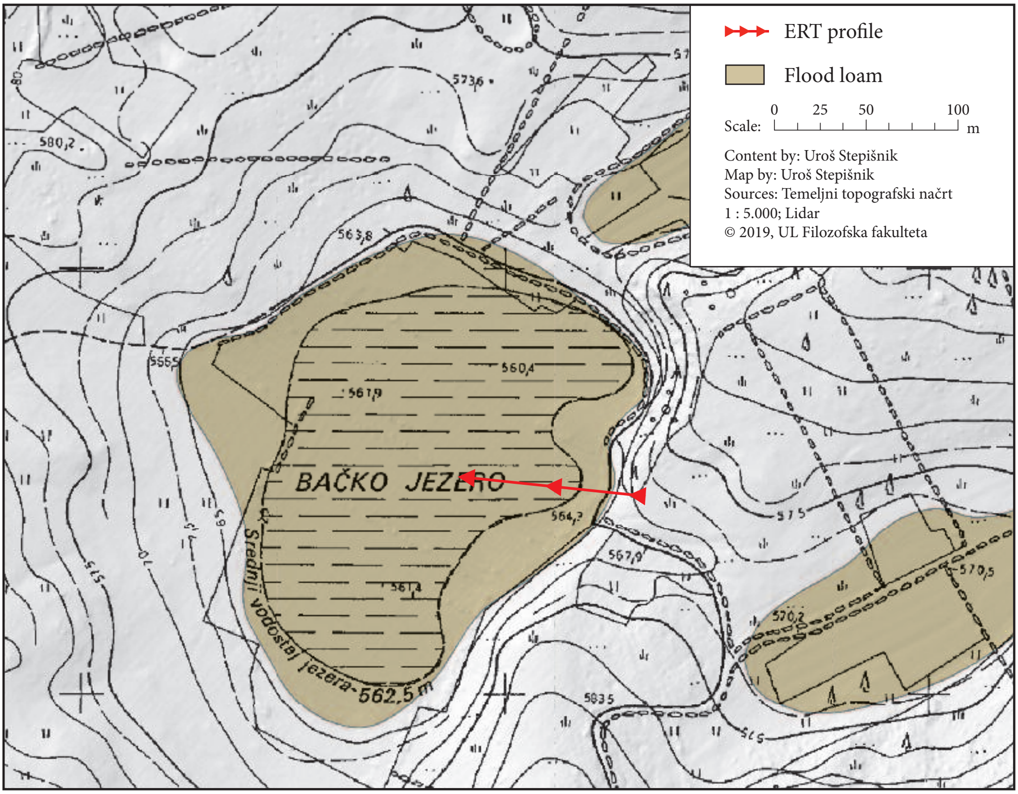

Figure 10: ERT profile location within Bačko Jezero depression.

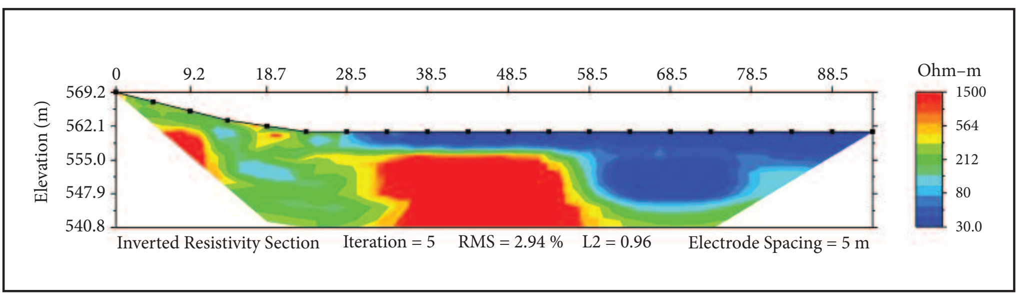

Figure 11: ERT profile of Bačko Jezero.

ERT profile of Veliko Zagorsko Jezero was measured from western slopes at an elevation of ~556 m towards the central part of the flattened floor (azimuth of profile: 115 degrees). Three iterations were made to achieve RMS of 3.79%. Inverted resistivity of the slope (electrodes 1–6) exceed 500 ohm-m, which means that the slope is built of carbonate bedrock. At the depth of around 10 m (elevation 545 m) is a zone with resistivity below 80 ohm-m, indicating cavernous spaces filled with loamy sediment. Below the possible sediment-filled cavity, the resistivity values reach up to 1,500 ohm-m, which means that the underlying layer consists of carbonate bedrock. The floor of the depression is filled with loamy sediment with resistivity between 30 and 80 ohm-m. The measured depth of the sediment exceeds 20 m in the central part of the profile.

The depression Udor is positioned ~500 m east of Veliko Zagorsko Jezero. It is almost circular in ground plan. Its floor is levelled by flood loam at an altitude of 559 m asl. The width of the floor is ~70 m and the length is ~100 m. Within the central part of the floor two suffusion dolines are formed. Levelled floor sharply transits into surrounding slopes that are active (Stepišnik and Kosec 2011). Parts of the north-eastern slopes are rocky walls with scree and collapse blocks below them. The intermittent lake within this depression is not mentioned in the literature, however the local inhabitants report occurrence of occasional inundations.

ERT profile of Udor was measured from the north-western slope, starting at 570 m asl crossing the entire floor with its final part at the foot of the south-east slope (azimuth of profile: 130 degrees). Eight iterations were made to achieve RMS of 3.40%. The north-west slopes show relatively low inverted resistivity values, which only exceed 200 ohm-m a few metres below the surface. Only the upper parts of the slopes are covered with carbonate rock debris, which is underlain by loamy sediments. The floor of Udor depression is filled with loamy sediments with resistivity below 50 ohm-m. The measured depth of the sediment exceeds 20 m in the south-east part of the floor.

Bačko Jezero is the most south-eastern depression of the Upper Pivka karst plain and is positioned about one kilometre south of Udor. Its ground plan is irregularly shaped, it is elongated in the south-west – north-east direction. Flood loam is levelling the floor at an elevation of about 560 m. The levelled floor is ~270 m long and ~160 m wide. The floor's transit to the western and northern slopes is very gradual. These slopes are fully balanced (Stepišnik and Kosec 2011). Regular inundation of this depression extends to an altitude of 562 m. At extremely high levels of karst waters, the elevation of the floods reaches up to ~568 m (Kovačič and Habič 2005).

ERT profile of depression Bačko Jezero was measured from its east slope (elevation of about 750 m) towards the central part of the flattened floor (azimuth of profile: 270 degrees). Five iterations were made to achieve RMS of 2.94%. The inverted resistivity of the east slope are between 200 and 500 ohm-m, with sections of higher resistivity values (500–1500 ohm-m) at a depth of 1 to 10 m. Resistivity values of the slopes may be interpreted as a result of weathered carbonate rock. The floor of the depression consists of two morphologically different sections. The first one (electordes 7–13) shows low resistivity values of the upper 5 m (30 to 50 ohm-m), underlain by a section that has resistivity values up to 1500 ohm-m. According to the measurements, this part of the floor consists of 5 m of loamy sediments, deposited over carbonate bedrock. The central part of the depression (electrodes 13–20) exhibits 16m of thick loamy sediments with low resistivity values ~50 ohm-m, underlain by sediments with resistivity up to 200 ohm-m reaching depth of over 20 m.

5 Discussion

The area of Karstic Ljubljanica River catchment is one of the most diverse areas of the Dinaric Karst (Gospodarič and Habič 1976; Gams 2003; Mihevc 2010; Ferk 2016). The uppermost of its drainage basin represents the region of Upper Pivka, which is well-known for its shallow karst and a number of intermittent lakes (Habič 1975; Habič 2005; Mulec, Mihevc and Pipan 2005). Our survey was focused on systematic geomorphologic analysis and morphogenetic interpretation of those depressions which have floors in water table oscillation levels by means of morphographic and sediment analyses and non-invasive geophysical examination.

Our analyses show that the region of Upper Pivka is hosting several different mophogenetic types of large karst depressions. Previously, the authors described them simply as depressions that are regularly inundated, (Pleničar 1959; Habič 1975; Kranjc 1985; Habič 1985–1986; Habič 1989; Gams 2003; Ravbar and Šebela 2004; Habič 2005; Kovačič and Habič 2005; Kovačič 2006) disregarding their morphogenesis. Although morphogenetic interpretation is of uttermost importance for the interpretation of nature, for understanding the functioning of the entire hydrological system and for the protection of nature, it has not been interpreted so far.

Throughout our systematic morphographic survey of selected features, we identified equifinality within all intermittent karst depressions of Upper Pivka. It means that even though they exhibit similar morphology they differ in their morphogenesis. We established that large karst depressions of Upper Pivka can be divided into two distinct morphogenetic types. The first type of depressions are areas of lowered relief in-between surrounding conical hills. The second type are closed depressions which are circular in a ground-plan and surrounded by levelled karst surface.

The first type of depressions is typical for the area where the corrosion plain is dissected by conical hills in the northern section of Upper Pivka. Those topographic hollows are not circular in ground-plan, but they are diverging in-between conical hills and are star-shaped. Topography and orientation of those depressions are largely affected by local geologic structure. Their slopes are covered by karren and balanced (Stepišnik and Kosec 2011; Godard et al. 2016) while floors are covered by thicker layer of regolith. Floors that are periodically inundated are partially levelled by fine grained loamy deposits. Thickness of deposits reaches up to 5 m, but generally it is shallower. From the morphographic perspective they are comparable to karst hollows of tropical karst that are termed cockpits (Brook and Hanson 1991; Gams 2003; Day and Chenoweth 2004; Ford and Williams 2007). Yet they differ from cockpits in much gentler inclination of encircling slopes (Brook and Hanson 1991; Day and Chenoweth 2004). Additionally, cockpits are characteristic for karst of tropical climates and not for the humid temperate climatic zone of the study area.

The most appropriate term used for the first type of depressions would be uvalas. Cviji(1893) introduced uvalas into karstological literature, as a term describing karst depressions smaller than poljes and larger than dolines (Gams, Kunaver and Radinja 1973). Primarily their formation was explained as a result of merging of adjoining dolines (Cvijić 1893). Contemporary interpretation of the karst processes rejects its traditional use of the term and its morphogenetic interpretation (Ćalić 2011). The term uvala should apply solely to relief depression in-between conical hills. In a ground plan, these are circular relief forms that slightly extend in-between the gaps of surrounding conical hills. Their margins are not clearly recognisable in the relief. In a cross section, they are bowl-shaped with a flat bottom that regularly hosts dolines. Their dimensions differ as they depend on spatial distribution of sourrounding conical hills. Uvalas are formed by accelerated vertical denudation along tectonically deformed zones (Čar 1982; Ćalić 2011). Therefore, we can define the first type of depressions as periodically inundated uvalas.

The second type of depressions is typical for the central part of the corrosion plain that is almost completely levelled and not dissected by conical hills. These depressions are circular in ground-plan; most of them are lengthened in various directions. Most of the hollows have well expressed boundaries between slopes and surrounding karst plain. Their slopes are regularly steep, rocky and active (Stepišnik and Kosec 2011; Godard et al. 2016). Scree and boulders regularly cover lower sections of these slopes. Floors of those depressions are completely filled and levelled by fine-grained deposits. The latter indicate inundation phases and consequent deposition of suspended material from stagnant water bodies. The measured depths of fine-deposit fills exceed10 metres. Therefore, these hollows cannot be perceived as bowl-shaped features like uvalas from the northern section of the Upper Pivka. Additionally, we can deduce, that they were not formed by a process of lateral corrosion at watertable level as indicated in previous literature (Mulec, Mihevc and Pipan 2005).

According to their morphographic and morphometric characteristics, and according to the sediment bodies within their floors we can conclude that they are collapse dolines in a morphogenetic perspective.

The term collapse doline is applied for all landforms whose genesis is related to the removal of material due to specific geological structures and hydrological processes in the subsurface. Due to the gradual material removal in the underground, a depression termed collapse doline is formed on the surface (Stepišnik 2010). The size of those depressions depends on the dynamics and duration of the subsurface material removal processes. The shape of the collapse dolines depends on many factors, especially on their age and on the dynamics of the removal processes. Their floors are filled with large collapse blocks and scree. Over time, the rocky walls disappear, and the proportion of scree increases. At the last stage of development, all slopes of the collapses are gentle and balanced (Stepišnik and Kosec 2011; Godard et al. 2016), and floors are concave and covered by sediment (Stepišnik 2010). Collapse dolines in the hinterland of major karst ponors or springs where occasional inundation at the local watertable level within their floors takes place, have the same topography and shape of sediment bodies as those hollows in the region of Upper Pivka (Waltham, Bell and Culshaw 2005; Stepišnik 2006; Stepišnik 2008; Stepišnik 2010; Stepišnik 2011; Lipar, Stepišnik and Ferk 2019).

6 Conclusion

The Upper Pivka is part of the Karst Ljubljanica River catchment. This is one of the northernmost parts of the Dinaric Karst. Complex hydrological system is accompanied by a series of various karst phenomena, making this area known as an outstanding example of geomorphological and hydrological diversity of karst.

The study area of Upper Pivka is built predominantly of carbonates with watertable level oscillating close to the surface. High watertable levels are controlled by a hydraulic barrier of flysch bedrock on the western outskirts of the area and by the elevation of surface runoff of the Pivka River towards the north. A number of depressions within the karst plain of the Upper Pivka are being inundated at high water levels. Our morphogenetic interpretations of the intermittent depressions of Upper Pivka reject the preliminary characterisingthat they were created as swallow holes in a former polje (Habič 1975), or that they were formed by lateral corrosion during temporary inundations (Habič 1985–1986; Mulec, Mihevc and Pipan 2005). We established trough morphographic mapping, sediment analysis and electrical resistivity tomography that there are at least two different morphogenetic types of depressions formed in the Upper Pivka. The first type are depressions positioned in-between conical hills within the northern section of the study area. They are irregular in shape, with gentle and balanced slopes and with thin sediment cover within their floors. We morphogenetically interpreted them as periodically inundated uvalas. The second type are depressions positioned within the karst plain in the southern section of the study area. They are circular to semi-circular in ground plan with steep and regularly rocky slopes. Flood loam deposits within their floors can reach thickness of several tens of metres. According to their morphographic and morphometric characteristics, and according to the sediment bodies within their floors we can conclude that they are collapse dolines in a morphogenetic perspective.

New insights into the geomorphological development of the Upper Pivka periodically inundated depressions will enable a better understanding of the past and present processes of the wider area. At the same time, the new morphogenetic interpretation may be taken into account in nature protection measures and in the interpretation of the abiotic natural heritage of the protected area, which has not been properly emphasised so far.

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ACTA GEOGRAPHICA
SLOVENICA
GEOGRAFSKI ZBORNIK
2020

SPECIAL ISSUE

The disappearing cryosphere in the southeastern Alps

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Acta geographica Slovenica, 60-2, 2020, 109–124

THE DISAPPEARING CRYOSPHERE IN THE SOUTHEASTERN ALPS: INTRODUCTION TO SPECIAL ISSUE

Matija Zorn, Blaž Komac, Anne Carey, Mauro Hrvatin, Rok Ciglič, Berry Lyons

The cryosphere in the southeastern Alps is melting away. Sampling meltwater from the Triglav Glacier in 2017.

DOI: https://doi.org/10.3986/AGS.9396
UDC: 911.2:551.32(234.3)
COBISS: 1.02

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The disappearing cryosphere in the southeastern Alps: Introduction to special issue

ABSTRACT: Various ice bodies are an important source of paleoenvironmental data, and their study improves the understanding of present and future environmental conditions. Their changes are an important indicator of climate change. This special issue of *Acta geographica Slovenica* draws attention to the changing and disappearing cryosphere across the globe, with an emphasis on the southeastern Alps, and the necessity to conduct research in this field before the ice disappears forever. This paper briefly summarizes the current body of knowledge on glaciers, permafrost, cave ice, lake and river ice, and snow in the southeastern Alps, and it presents the contribution of *Acta geographica Slovenica* to this research and the main highlights of all five papers included in this special issue.

KEY WORDS: cryosphere, glaciers, permafrost, cave ice, ice, climate change, Alps, Slovenia

Izginjajoča kriosfera v jugovzhodnih Alpah: uvodnik k posebni izdaji

POVZETEK: Različna ledena telesa so pomemben arhiv paleookoljskih podatkov in njihovo preučevanje pripomore k boljšemu razumevanju sedanjih in prihodnjih okoljskih razmer. Njihovo spreminjanje je pomemben kazalnik podnebnih sprememb. S to posebno izdajo revije *Acta geographica Slovenica* želimo opozoriti na spreminjanje in izginjanje kriosfere po svetu, še posebej pa na območju jugovzhodnih Alp, ter na nujnost raziskav na tem področju, preden led za vedno izgine. V članku je na kratko predstavljeno znanje o ledenikih, permafrostu, ledu v jamah, ledu na jezerih in rekah ter snegu v jugovzhodnih Alpah, poudarjen pa je tudi prispevek revije *Acta geographica Slovenica* k tem raziskavam, kot tudi glavni poudarki vseh petih člankov, ki tvorijo to posebno izdajo.

KLJUČNE BESEDE: kriosfera, ledeniki, permafrost, led v jamah, led, podnebne spremembe, Alpe, Slovenija

The paper was submitted for publication on December 14th, 2020.
Uredništvo je prejelo prispevek 14. decembra 2020.

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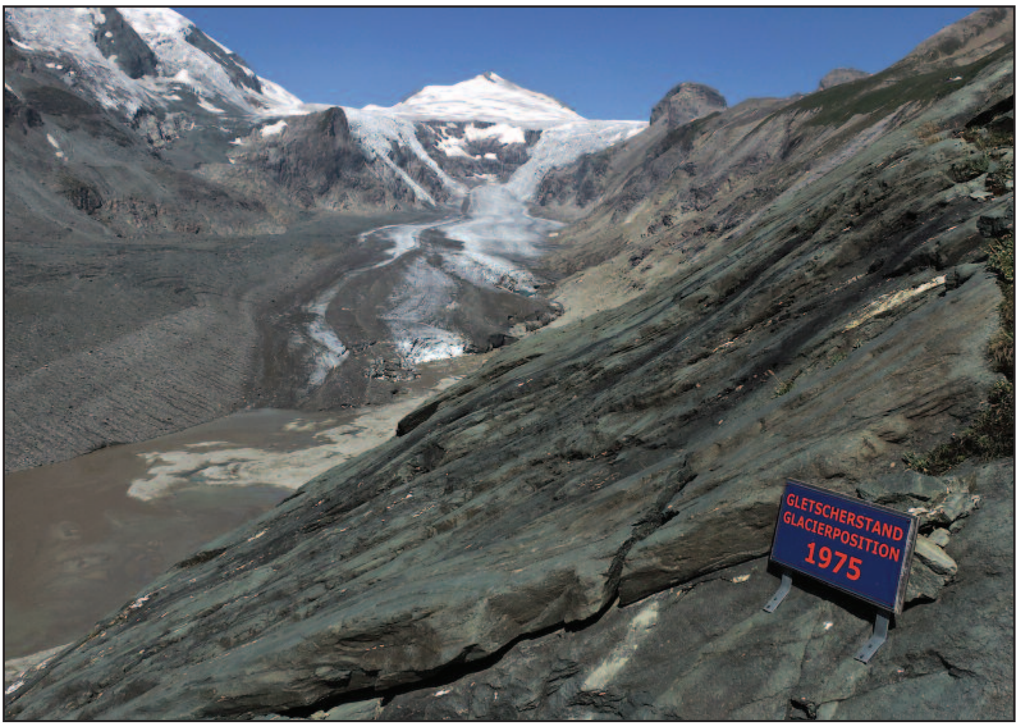
1 Introduction

Various ice bodies are an important source of paleoenvironmental data (e.g., Brook and Buizert 2018; Lipar, Zorn and Perko 2021). Their changes reflect climate change, and their study improves the understanding of present and future environmental conditions. The existence of ice bodies is under threat and, along with this, an important source of environmental data. Glaciers in the European Alps alone lost around 50% of their volume between the end of the Little Ice Age (from approximately 1850) and 1975, about 10% from 1975 to 2000, and an additional 10% from 2000 to 2009 (Kaufmann et al. 2015; Figure 1). Predictions that glaciers in the Alps will shrink to half their current size by 2050 (Zekollari, Huss and Farinotti 2019) and almost completely disappear by 2100 are alarming from the viewpoint of preserving the cryosphere and hence an important »archive« of data on the paleoenvironment. A very revealing piece of information for how fast the global ice is disappearing is that from 1994 to 2017 the volume of ice on the Earth's surface decreased by 28 trillion tons, and that the loss of over two-thirds of ice is connected with atmospheric melting (Slater et al. 2020).

This special issue of *Acta geographica Slovenica* draws attention to the changing and disappearing cryosphere in the southeastern Alps and elsewhere across the globe, and the necessity to conduct research in the areas that are under threat of soon being left without permanent ice and thus an important source of data on the past environment. In addition, the publication of the sixtieth volume of the journal (Zorn and Komac 2010; Ciglič et al. 2020) this year provides a good opportunity to highlight its importance in presenting material on the cryosphere in the southeastern Alps (Section 9).

To date, a total of forty-one papers related to the cryosphere have been published in *Acta geographica Slovenica*, which is a twelfth of all papers. Most were connected with both Slovenian glaciers (more than two-fifths of all papers on the cryosphere; see Section 9.1 for references), followed by papers examining past glaciations (just over a fourth; see Section 9.2 for references), snow and avalanches, and ice and geochemistry (just under a third; see Section 9.3 for references).



MATIJA ZORN

Figure 1: The Pasterze Glacier (Austria), the largest glacier in the eastern Alps, has shrunk by approximately a third since the end of the Little Ice Age (Kaufmann et al. 2015). The sign shows the edge of the glacier in 1975, and the photo shows its size in 2015.

2 Glaciers

Acta geographica Slovenica has been covering the developments on glaciers in the southeastern Alps for several decades. The first papers on this topic were already published in 1955, in the journal's third volume (Section 9.1), which means that already in the mid-twentieth century the journal became involved in what is currently a very topical scholarly discussion on the cryosphere. Most papers on this topic are connected with studies of the Triglav Glacier (e.g., Gabrovec et al. 2013) and the Skuta Glacier, which the ZRC SAZU Anton Melik Geographical Institute has been heading ever since 1946. Changes in both glaciers reflect climate change, which is one of the reasons that changes in the Triglav Glacier are included in the environmental indicators that the Slovenian Environment Agency uses to monitor climate change in Slovenia (Triglav … 2019).

Even up until recently it was assumed that the two glaciers in their present shape formed during the Little Ice Age (Gabrovec et al. 2014), but the latest research indicates that they may have persisted throughout the entire Holocene (Lipar et al. 2021).

Changes in glaciers in the southeastern Alps and elsewhere around the globe are connected with rising temperatures (Figure 2). In the area of the Triglav Glacier in the Julian Alps (southeastern Alps), at an elevation of approximately 2,500 m, the average annual temperature between 1961 and 2018 rose by a full 2.03 °C (Figure 3; Hrvatin and Zorn 2020).

3 Permafrost

Due to their geographical location and elevation, the southeastern Alps, including the Slovenian Alps, only have marginal permafrost areas. Because no research on permafrost in Slovenia has (yet) been conducted, its dimensions can only be inferred indirectly from the temperature and partly from geomorphological conditions. Based on the average annual temperature of 0 °C, which in the southeastern Alps is typical at an elevation between 2,400 and 2,500 m, it can be assumed that permafrost is possible at the highest elevations of the Julian Alps (northwest Slovenia) and the Kamnik–Savinja Alps (northern Slovenia). However, because the high mountains in the southeastern and Slovenian Alps are predominantly composed of carbonate rock and karstified, so that in the summer rainwater can percolate through the rock, it is also less likely that permafrost has remained frozen there since the last ice age (Vrhovec 2004).

According to Boeckli et al. (2012), who designed the Alpine Permafrost Index Map, the country with the most permafrost in the Alps is Switzerland, followed by Italy, Austria (Figure 4), France, and Germany. Slovenia and Liechtenstein only have negligible areas of permafrost. In the Alpine countries, areas of permafrost are believed to be larger than areas covered in glaciers; they are estimated to cover up to 3% of the entire Alps, but only from 0.1 km^2 to 25.7 km^2 in Slovenia.

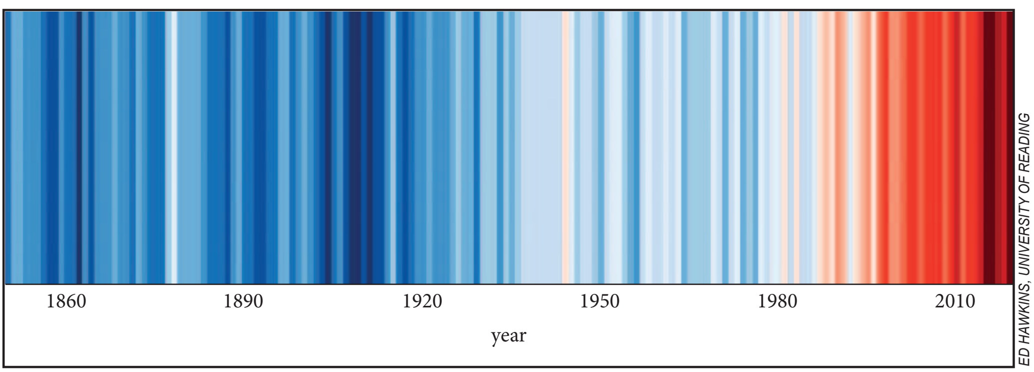


Figure 2: The warming stripes show global temperature change between 1850 and 2019 (Show … 2020). According to the World Meteorological Organization, 2015–2019 was the warmest five-year period on record, and 2010–2019 was the warmest decade on record. Since the 1980s, each successive decade has been warmer than any preceding decade since 1850 (Hawkins 2020; WMO Statement … 2020).

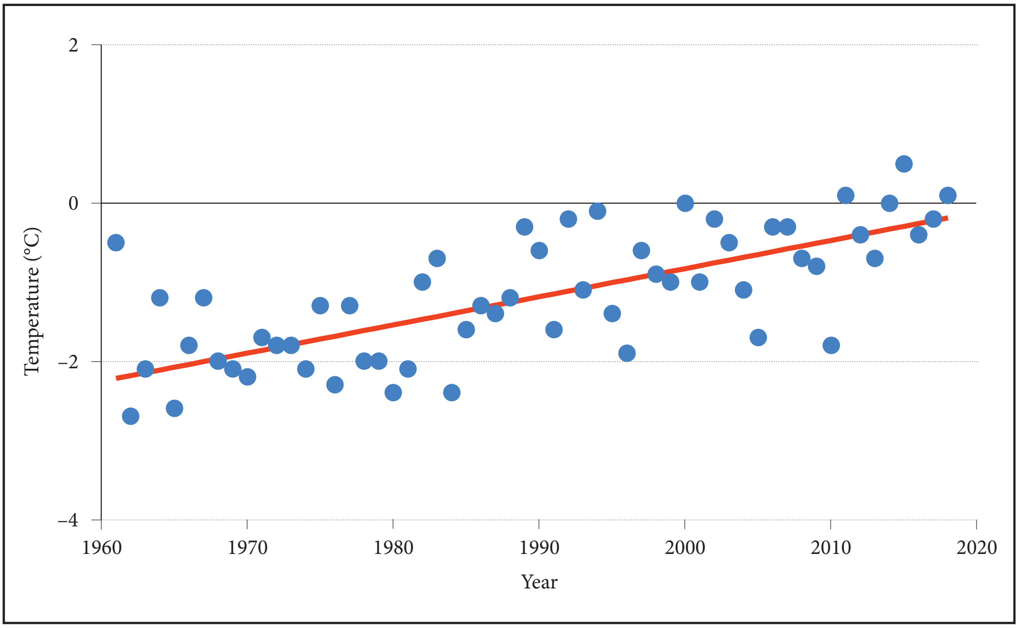


Figure 3: Average annual temperature trend at the Kredarica temperature station in the Julian Alps (southeastern Alps) at 2,513 m, 1961–2018. Between 1961 and 2018, the average annual temperature rose by 2.03 °C (Hrvatin and Zorn 2020).

MATIJA ZORN

Figure 4: The Dösen Rock Glacier in the High Tauern (Central Austria; Kellerer-Pirklbauer, Lieb and Kaufmann 2017) contains a permanent ice body.

However, many remnants of permafrost from previous environmental conditions can also be found in the southeastern Alps (Gabrovec et al. 2014; Colucci et al. 2016a; Triglav Čekada et al. 2016). Certain karst caves can feature active patterned ground likely related to seasonal frost heaving (Gams 1971; Obu et al. 2018; Oliva et al. 2018; Mihevc and Urbančič 2019), and on the surface, such as the western side of Mount Triglav, effects of permafrost on sediments can be seen (Šifrer 1963; Gabrovec et al. 2014).

In deep karst depressions, strong temperature inversion is related to the cave climate, which in turn influences surface landforms. Mihevc (2015, 2018) found patchy permafrost in these depressions due to subterranean air circulation through karst.

In the Alps, problems with permafrost disappearing due to climate change are primarily manifested in an increasing rockfall trend (Vrhovec 2003, 2004; Noetzli, Hoelzle and Haeberli 2003; Gruber, Hoelzle and Haeberli 2004; Bodin et al. 2015), but a great deal of high-mountain infrastructure (Haeberli et al. 2010; Hock et al. 2019) and hence tourism is also under threat (Urbanc and Pipan 2013; Ritter, Fiebig and Muhar 2012). It is estimated that due to global warming 10% of the infrastructure in the French Alps is characterized by a high risk of destabilization (Duvillard, Ravanel and Deline 2015).

4 Cave ice

Changes in the volume of ice in the southeastern Alps can be observed not only in the glaciers, but also in ice caves (Mihevc 2018; Carey et al. 2019). Permanent ice in caves is also a form of permafrost. In the cave register of Slovenia, permanent ice is reported in over 550 caves (Mihevc 2018), which are not limited only to the high mountains. Most of them have an entrance at an elevation between 1,000 and 2,400 m. With regard to the southeastern Alps, Colucci et al. (2016b) report that the climate thresholds for ice caves include a mean summer air temperature < 13 °C and a mean winter air temperature < −2 °C. In the southeastern Alps, some caves also exhibit relict permafrost and cryotic conditions in the rock (Colluci and Guglielmin 2019).


ANTON PODGORSKI

Figure 5: The main ice gallery in Snežna Cave.

Just like surface glaciers, »cave glaciers« are indicators of climate change. With regard to the Jura Mountains between Switzerland, France, and Germany, Luetscher, Jeannin and Haeberli (2005, 982) report that the »equilibrium line altitude of ice caves is believed to have increased several hundred metres« over approximately the past quarter of the twentieth century.

In Slovenia the most studied ice caves are Paradana Cave, Snežna Cave, and the Triglav Shaft. Paradana Cave (western Slovenia; entrance at 1,135 m) has an estimated ice volume of about 8,000 m^3. There have been documented gains and losses of ice since 1950, with an increased loss since 1986 (Mihevc 2018). Snežna Cave (northern Slovenia; entrance at 1,514 m) has about 4,000 m^3 of ice. Observations of the cave ice date back to 1980, when the ice and snow at the entrance melted and allowed entrance into the cave. Since then, the volume of snow and ice at the entrance has dropped, and the level of ice in the main ice gallery (Figure 5) dropped more than 1 m (Mihevc 2018). The discovery of the Triglav Shaft (northwest Slovenia; entrance at 2,377 m) is also connected to climate change because its entrances were covered by the Triglav Glacier until the early twentieth century (Gams 1961; Tičar et al. 2018). Very recently, the geochemistry of ice and stable isotopes from these ice caves were studied by Carey et al. (2019, 2020). The results show that the ice in the caves originates from local precipitation modified by the addition of Ca^{2+} and HCO_3 from the dissolution of the local bedrock, and that the isotopic profiles are similar to those of other ice caves in central and eastern Europe.

Ice caves represent the smallest portion of the terrestrial cryosphere because the largest cave ice bodies generally have a volume of up to 150,000 m^3 (Kern and Perşoiu 2013). The ice in caves preserves environmental archives because it contains proxies such as chemicals, pollen grains, and macrofossils (Perşoiu and Lauritzen 2018; Perşoiu and Onac 2019). However, the complexity of ice in caves is greater and less understood compared to surface ice (Lipar, Zorn and Perko 2021). Because ice caves occur at lower elevations and lower latitudes than glaciers generally do, they provide a unique paleoenvironmental source in those regions.

5 Lake and river ice

In addition to a reduction in permanent ice, global warming and the subsequent warming of standing and running inland waters also reduce the number of days in winter when lakes and rivers are covered in ice. From 1918/19 to 1929/30, ice appeared on Lake Bohinj (the Julian Alps, elevation: 526 m) 54.6 days a year on average, from 1961 to 1990 it appeared 50.6 days, and from 1991 to 2001 only 30.9 days (Frantar 2004; Frantar and Uhan 2005). According to the United States Environmental Protection Agency, which uses lake ice as a climate change indicator, the lakes are generally freezing later than they did in the past and show a trend toward earlier ice breakup in the spring (Climate … 2020). For the northern hemisphere, Magnuson et al. (2000, 1743) showed for ice on lakes and rivers (Figure 6) that in the period from 1846

BORIS FARIČ, REGIONAL MUSEUM PTUJ–ORMOŽ (INV. NO.: G 120 S)

Figure 6: Ice on the Drava at Ptuj (east Slovenia). The 1766 votive painting was commissioned by the residents of Ptuj as an act of gratitude to the town's patron saints for protecting the bridge against the ice jam. This threat is also reported in the sources later on, such as in the second half of the nineteenth century, when the blocks of ice were over a meter thick (Kolar 2019).

to 1995 »changes in freeze dates averaged 5.8 days per 100 years later, and changes in breakup dates averaged 6.5 days per 100 years earlier.« Somewhat downstream from Slovenia, where the Drava River forms the border between Hungary and Croatia, ice freezes approximately nine days later and breaks up approximately ten days earlier than in 1875. The duration of ice-cover on the Drava River decreased by fourteen days on a century average, and the number of total ice-affected days decreased by thirty-one days on a century average (Takács and Kern 2015).

6 Snow and river discharge

In addition to glaciers (Huss 2011) and cave ice, snow is also an important factor for freshwater storage in high-mountain karst areas of the southeastern Alps. In the spring and early summer, snow feeds many springs, but changes are also observed in the hydrological regime. In the Slovenian Alps, the annual number of days with snow cover from 1961 to 2018 saw a statistically significant decrease by 31 to 56 days, or by 22% to 67% at elevations between approximately 500 and 1,000 m (Figure 7). The exception is the high-mountain station on Mount Kredarica, where the decrease is less than 3%.

The consequences can be seen in the annual river discharges, in which, however, the afforestation of the mountainous (cultural) landscape (Gabrovec, Bičík and Komac 2019) and the resulting increased evapotranspiration must also be taken into account. The minimum annual discharge trends and the mean annual discharge trends in rivers in the southeastern Alps are decreasing; the latter are mostly between 10% and 25% (Figure 8). The maximum annual discharge trends are also decreasing for some rivers. Lower snow quantity and higher winter temperatures are changing the discharge regimes (Hrvatin and Zorn 2020).

From 1961 to 1990, Slovenian Alpine rivers were characterized by a distinctive snow-rain discharge regime (Hrvatin 1998). Because of snow retention, the discharge was the lowest in the winter and the main discharge maximum occurred in the spring due to melting snow. A secondary minimum followed in the summer, and after that a secondary maximum due to autumn rain.

From 1991 to 2018, the autumn discharge maximum exceeded the spring maximum for most mountain rivers, and the summer minimum has already become very close to the winter one. Because of the reduced volume and duration of snow cover and increasingly pronounced evapotranspiration, there has been a noticeable decrease in the discharge in late spring and early summer, and a discharge increase between October and December, implying that, because of the rising temperatures and thus less snowfall and more rainfall, winter in the mountains is »running late« (Table 1; Hrvatin and Zorn 2017, 2020).

In future climatic and hydrological conditions of the Alps, the glacierized basins might contribute 55 to 85% less water to streamflow runoff by the end of the twenty-first century (Huss 2011), and substantial reduction is especially expected for the summer (Weber et al. 2010). Water scarcity will affect not only the Alps, but also their densely populated surroundings (Nared, Razpotnik Visković and Komac 2015). The population in the Alps is approximately fourteen million (Price et al. 2011), but also taking into account their immediate surroundings this number increases to approximately seventy million (Which … 2020). Hydrological changes are already so pronounced (e.g., Gibson 2020) that Alpine countries are formulating common strategies against water scarcity (Water Management … 2011). In addition, the importance of Alpine rivers' discharge as a source of hydroelectric power must also not be overlooked (Razani et al. 2018).

With regard to snow in the Slovenian Alps, avalanches are by far the most studied phenomena (e.g., Gams 1955; Pavšek 2002; Volk Bahun 2020) and they were already presented in the third volume of *Acta geographica Slovenica* (see Section 9.3). In Slovenia, a few studies have examined snow cover in relation to water accumulation (Ogrin 2005; Ogrin and Ortar 2007), but research on the isotopic composition of snow is still in its infancy, as is also the case with ice (e.g., Vreča et al. 2013).

7 Papers in the special issue

This special issue adds a regional and global note to research on the cryosphere in the southeastern Alps. Thus, in addition to three papers examining the two Slovenian glaciers and ice (Carey et al. 2020; Triglav Čekada and Zorn 2020; Triglav Čekada et al. 2020), there is one paper discussing changes in glaciers in the southeastern Europe (Gachev 2020) and one paper on Antarctica, which provides a global dimension to the special issue (Lyons et al. 2020).

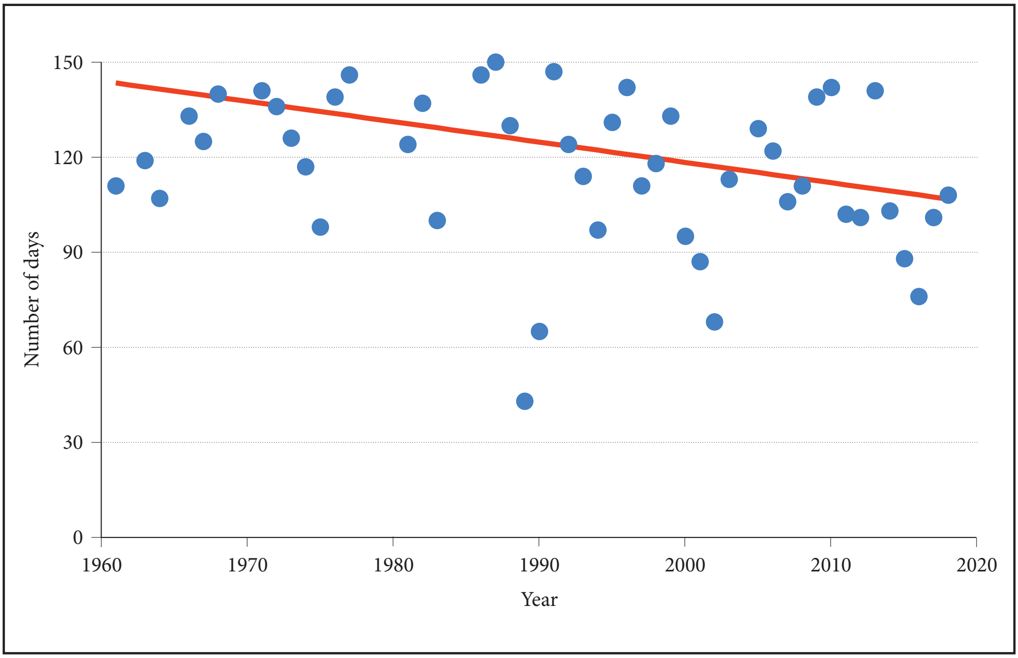


Figure 7: Trends in the annual days with snow cover at the Rateče precipitation station on the northern edge of the Julian Alps (southeastern Alps) at 864 m, 1961–2018. The number of days with snow cover decreased by a full thirty-six days or just over a quarter (Hrvatin and Zorn 2020).

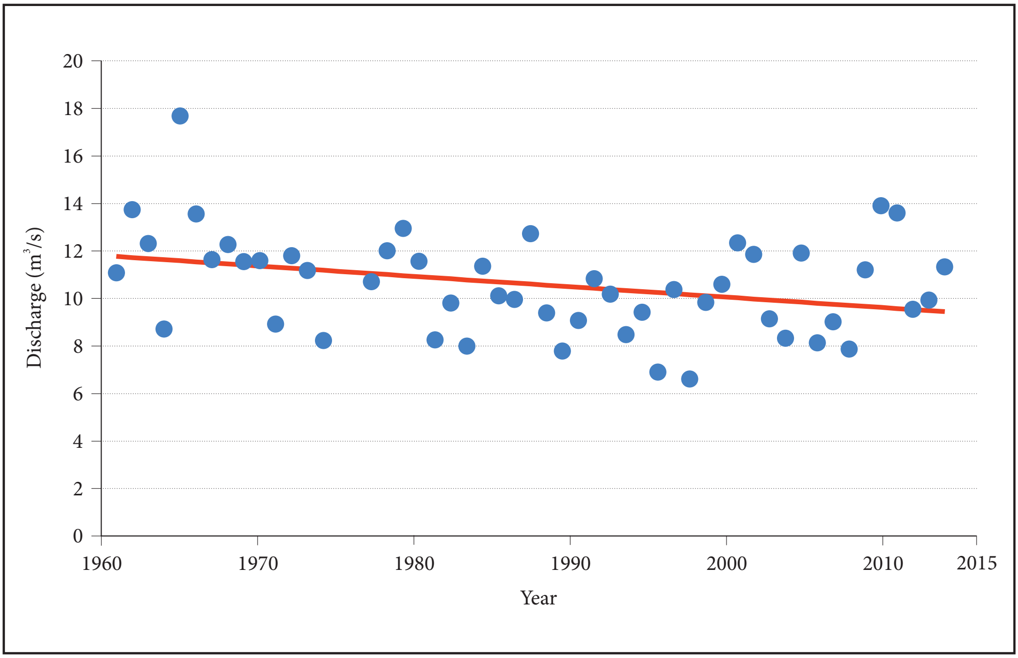


Figure 8: Mean annual discharge trend of the Sava Dolinka River at the Jesenice gauging station on the northeastern edge of the Julian Alps (southeastern Alps) with a drainage area of 257.56 km^2, 1961–2013. The mean annual discharge trend decreased by just over a fifth (Hrvatin and Zorn 2020).

Table 1: Changes in the monthly discharge coefficients between 1961–1990 and 1991–2018 for selected rivers in the Julian Alps (southeastern Alps; blue shading indicates decreasing ratios and red shading shows increasing ratios; Hrvatin and Zorn 2020).

River: Gauging station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Koritnica: Kal-Koritnica I	0.14	0.04	0.07	–0.15	–0.33	–0.35	–0.13	–0.07	0.04	0.31	0.30	0.13
Mostnica: Stara Fužina II	0.03	–0.11	0.09	–0.06	–0.54	–0.30	0.08	–0.14	0.06	0.61	0.17	0.11
Radovna: Podhom	0.10	0.03	0.13	0.00	–0.51	–0.37	–0.14	–0.12	–0.05	0.24	0.46	0.23
Sava Bohinjka: Sveti Janez	0.06	–0.01	0.13	0.09	–0.43	–0.54	–0.13	–0.18	0.02	0.43	0.39	0.17
Sava Dolinka: Jesenice	0.16	0.04	0.06	–0.08	–0.30	–0.32	–0.17	–0.10	–0.10	0.20	0.38	0.22
Soča: Kobarid I	0.12	0.02	0.06	–0.07	–0.33	–0.41	–0.15	–0.15	0.03	0.31	0.38	0.19
Tolminka: Tolmin	0.10	0.03	0.05	–0.06	–0.28	–0.45	–0.12	–0.04	0.10	0.19	0.34	0.15

The paper on Antarctica is featured first and is dedicated to isotopic geochemistry of calcium carbonate encrustations in soils in Antarctica's Taylor Valley. These encrustations are important because they preserve records of geochemical, hydrological, and atmosphere processes affecting these soils. The results suggest, among other things, that the $\delta^{13}C$ signature in the encrustations can be used to ascertain the difference between pedogenic and lacustrine carbonate in the soils studied. In addition, the $\delta^{18}O$ data indicate that evaporation/sublimation of water, perhaps in thin films, plays a major role in the production of these encrustations (Lyons et al. 2020). Interestingly, also in the southeastern Alps, carbonate deposits recently exposed due to glacier retreat were studied as possible paleoenvironmental indicators (Lipar et al. 2021).

The second paper deals with geochemical analyses of the glacier ice, cave ice, meltwater (paper cover figure), and spring water in the southeastern Alps (Carey et al. 2020). This paper is to some extent a continuation of a paper published a year earlier (Carey et al. 2019). Whereas the 2019 paper is focused on ice in caves at elevations between approximately 1,100 and 1,500 m, the paper in this special issue presents data from ice in caves at elevations between 2,350 and 2,450 m. Analyses of ice and meltwater from both Slovenian glaciers are also included.

The third and the fourth papers continue the journal's tradition of exploring glaciers in the southeastern Alps. The paper on the Triglav Glacier is already the tenth such paper published in the journal (see Section 9.1), but the first one to report in detail on changes in its thickness, volume, and mass balance. Previous papers primarily focused on changes in the glacier's area. The results show that the Triglav Glacier's mean thickness has thinned from approximately 40 m to less than 3 m since the mid-20th century, and that during this period the glacier's annual specific mass balance was –0.45 m w.e.a^{-1} (Triglav Čekada and Zorn 2020).

The Skuta Glacier is examined for the fifth time in the journal (see Section 9.1), but this is the first time that its thickness is studied in detail. Although the area of the Skuta Glacier has not changed significantly over the past half-century, the average elevation of its upper edge has decreased by approximately 40 m. The analyses show that the maximum seasonal snow cover depth at the end of the accumulation season is important for preservation of the glacier's thickness (Triglav Čekada et al. 2020).

The fifth (and last) paper in this special issue is also dedicated to very small glaciers and snowfields, but this time in southeastern Europe in general. Changes in the glaciers and snowfields in the Prokletije Mountains (Albania) and Durmitor Mountains (Montenegro) show high short-term variations over the past decade and a downward long-term trend (Gachev 2020), just like the two Slovenian glaciers in the southeastern Alps examined. Elsewhere across southern Europe, very small glaciers also survive at very low elevations (2,000–2,500 m), despite the unfavorable climate conditions. This is primarily the result of high levels of winter precipitation, which produces large snowfalls, and in some places this snow may last all year round, sustaining these glaciers even today (Hughes 2014; Hughes and Woodward 2017). On the other hand, the last three papers in the issue show that, because small glaciers are confined in karst depressions, topography and the karst surface also play a vital role in sustaining them. This also agrees with the findings of other researchers (e.g., Grunewald and Scheithauer 2010) that in the concluding stages of glacial degradation the impact of climate factors shows a relative decrease, whereas the impact of terrain increases.

In the southeastern Alps and elsewhere in southeastern Europe, permanent ice can still be found on the surface and in caves, which should be taken advantage of as soon as possible to secure the important paleoenvironmental data that this ice is storing before the data are lost forever.

The editors strives for the papers published in this special issue of *Acta geographica Slovenica* to not only serve as records of past research, but also stimulate further research and cooperation in this area.

ACKNOWLEDGEMENTS: The authors acknowledge financial support from The Ohio State University's Slovene Research Initiative and the Slovenian Research Agency research core funding Geography of Slovenia (P6-0101).

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9 Appendix: A chronological list of papers on the cryosphere published in *Acta geographica Slovenica / Geografski zbornik*

9.1 Contemporary glaciers

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Acta geographica Slovenica, 60-2, 2020, 125–139

THE ISOTOPIC GEOCHEMISTRY OF $CaCO_3$ ENCRUSTATIONS IN TAYLOR VALLEY, ANTARCTICA: IMPLICATIONS FOR THEIR ORIGIN

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Ground image of the Lake Hoare basin (Lake Hoare on far left) looking west up Taylor Valley, Antarctica.

DOI: https://doi.org/10.3986/AGS.7233
UDC: 550.42:552.54(292.3)
COBISS: 1.01

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The isotopic geochemistry of $CaCO_3$ encrustations in Taylor Valley, Antarctica: Implications for their origin

ABSTRACT: Calcium carbonate ($CaCO_3$) encrustations occur in most desert soils, including polar ones, and such encrustations preserve records of geochemical, hydrological, and atmosphere processes affecting these soils. We have collected a series of $CaCO_3$ encrustations found underneath surface rocks in the soils and tills of Taylor Valley, McMurdo Dry Valleys (~78°S lat.), Antarctica. These encrustations were analyzed for $^{87}Sr/^{86}S$ and $\delta^{18}O$ and $\delta^{13}C$ to determine what relation they have with the underlying soils, and the material in which they are in contact, and to identify the processes that control their formation. In all but one case, the isotopic data indicate that the source of Sr to these encrustations is not from the rock on which it is associated. The primary source of Sr (and by analogy Ca) is either from dust that has been deposited through aeolian processes or from the aggregate of till material within the soils. The $\delta^{13}C$ values for Taylor Valley encrustations ranged from 5.7 to 11.0‰, and are consistent with a carbon source from atmospheric CO_2. The $\delta^{18}O$ values range from –8.1 to –11.2‰ and are heavier than expected for equilibrium calcite precipitation from Taylor Valley meteoric water. Taken together these results indicate that the $CaCO_3$ was formed by rapid evaporation of films beneath clasts that had become supersaturated with respect to $CaCO_3$.

KEY WORDS: calcium carbonate, isotopic ratio, salt deposit, McMurdo Dry Valleys, Antarctica

Izotopska geokemija inkrustacij $CaCO_3$ v Taylorjevi dolini na Antarktiki: izsledki, ki nakazujejo njihov izvor

IZVLEČEK: Inkrustacije kalcijevega karbonata ($CaCO_3$) so značilne za večino puščavskih prsti, tudi polarnih, v njih pa so ohranjeni podatki o geokemičnih, hidroloških in atmosferskih procesih, ki so vplivali na te prsti. Zbrali smo niz inkrustacij $CaCO_3$, odkritih pod površinskimi kamninami v prsteh in tilih v Taylorjevi dolini – eni izmed McMurdovih suhih dolin na Antarktiki (~78° j. z. š.). Analizirali smo vsebnost $^{87}Sr/^{86}S$ ter $\delta^{18}O$ in $\delta^{13}C$ v teh inkrustacijah, da bi ugotovili, kako so povezane s spodaj ležečimi prstmi in materialom, s katerim so v stiku, ter določili procese, ki uravnavajo njihov nastanek. Razen v enem primeru izotopski podatki kažejo, da Sr v teh inkrustacijah ne izvira iz kamnine, s katero je inkrustacija povezana. Glavni viri Sr (in po analogiji tudi Ca) so bodisi prah, ki ga je nanesel veter, bodisi agregati ledeniških sedimentov (tilov) v prsteh. V inkrustacijah iz Taylorjeve doline je bilo od 5,7 do 11 ‰ $\delta^{13}C$, kar se ujema z vsebnostjo ogljika iz atmosferskega CO_2. Vrednosti $\delta^{18}O$ so od –8,1 do –11,2 ‰, to pa je več, kot bi pričakovali za uravnoteženo izločanje kalcita iz meteornih vod v Taylorjevi dolini. Skupni rezultati kažejo, da je $CaCO_3$ nastal s hitrim izhlapevanjem slojev pod klasti, prenasičenimi s $CaCO_3$.

KLJUČNE BESEDE: kalcijev karbonat, izotopsko razmerje, nanos soli, McMurdove suhe doline, Antarktika

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1 Introduction

Calcium carbonate layers within soils and as encrustations on the undersides of rocks and pebbles occur in many landscape types. It has been postulated that these layers and crusts, when moisture is drawn upwards evaporates, precipitating carbonate minerals from supersaturated films. Although pedogenic carbonate has been observed and analyzed from a variety of soils from different latitudes, most of the work has been done in warm desert and semi-arid environments. Several of investigations, however, have described pedogenic carbonates in polar locales where desert conditions exist. Authigenic carbonates in cold climates can take many forms and are formed by several different processes (Lacelle 2007). Pedogenic carbonates in cold environments, such as polar regions, have been defined as those that form on the inside of soil clasts (Lacelle 2007). This particular type of carbonate deposition has been observed in the Canadian High Arctic, the Antarctic Maritime and Svalbard (Bunting and Christensen 1978; Vogt and Corte 1996; Forman and Miller 1984; Courty et al. 1994). In all these various types of such carbonates, isotopic analysis has been used to elucidate the source of C and O and to discern the processes involved in the formation of these minerals (e.g., Lacelle 2007). In addition, $^{87}Sr/^{86}Sr$ analyses have served as a useful tool to define the source of Ca in several past investigations of pedogenic carbonates (e.g., Quade, Chivas and McCulloch 1995; Capo and Chadwick 1999; Naiman, Quade and Patchett 2000; Van der Hoven and Quade 2002).

In this paper we present $\delta^{13}C$, $\delta^{18}O$, and $^{87}Sr/^{86}Sr$ data from pedogenic carbonate encrustations from soils of Taylor Valley, Antarctica, one of the McMurdo Dry Valleys. Taylor Valley (TV) is a polar desert with low precipitation rates (~3 cm a-^{1}) and a mean annual temperature of approximately –20 °C (Doran et al. 2002; Fountain et al. 2010). In Taylor Valley low relative humidities generate rapid sublimation of snow and produce very low soil moisture concentrations thus limiting chemical weathering and dissolution/precipitation reactions.

The objectives of this work were to assess the sources of water, carbon and calcium in the formation of calcium carbonate and to ascertain the processes that produced these minerals. In addition, we compare the formation mechanisms of these Antarctic encrustations to encrustations formed in other desert environments.

2 Materials and methods

2.1 Study area

The McMurdo Dry Valleys (MCM) (77–78°S) are the most extensive ice-free region in Antarctica (Figure 1). The valleys are a mosaic of glaciers, soils, exposed bedrock, ephemeral streams and perennially ice-covered lakes. Since 1993 Taylor Valley (TV) has been the primary operational location of the McMurdo Dry Valleys Long-Term Ecological Research (MCM-LTER) site where meteorological, glaciological, hydrological, geochemical, and ecological research has been conducted regularly (Fountain et al. 1999).

The soils and tills in TV are derived from a number of rock types within the region. These include the Precambrian to Ordovician granitoid and metamorphic basement rocks, the Devonian aged Beacon Supergroup (sandstones, shales, conglomerates), and the Ferrar Dolerite (Jurassic age). The Ferrar intrudes the Beacon and basement rocks in the form of sills and dikes in numerous locations in the McMurdo Dry Valleys. In addition, the more recent McMurdo Volcanic rocks are present both *in-situ* as erupted cones, and also as debris transported within the tills. In Taylor Valley, the volcanics range in age from 1.50 to 3.89 Ma (Wilch et al. 1993). The TV soils are composed of unconsolidated material ranging from primarily sand to boulder size, although small grain sizes exist. Relatively flat areas are often covered by desert pavement and the active layer is only ~50 cm in depth.

Much work has been done in determining the glacial chronology and soil/till age of the MCM region. Several eastward advances and retreats of the Taylor Glacier (from the East Antarctic Ice Sheet) deposited till in the western parts of TV and northward advances of the West Antarctic Ice Sheet has deposited tills in eastern to central TV during glacial times (Denton et al. 1989; Hall et al. 2000). The lakes in TV have fluctuated dramatically in size, with valley-wide glacial Lake Washburn existing from approximately 23,000 to 8500 years ago (Hall, Denton and Hendy 2000) to low stands at ~1kyr ago (Lyons et al. 1998). There have been numerous fluctuations in lake levels between these times (Hall et al. 2010). As the lake level rises, soils are inundated and become lake sediments, and as the lakes decrease in size, the lacustrine sediments become part of the terrestrial environment. A portion of the organic C currently observed in the soils is ancient lacustrine organic matter, or what has been termed »legacy« organic C that had been deposited during earlier aged high stands of the lakes (Burkins et al. 2000). $CaCO_3$ that forms in the lakes and in ephemeral streams today is usually associated with algal mats, and it is clear that much of the present day $CaCO_3$ observed in the soils of MCM was actually produced within a lacustrine environment when lake levels were higher. In fact, lacustrine-derived $CaCO_3$ in soils has been observed throughout the TV (Doran et al. 1999; Hendy 2000). The stable isotope composition of current lacustrine carbonate has been previously measured (Lawrence and Hendy 1989) and can be compared to pedogenic forms of carbonate in order to ascertain the origin of carbonate minerals in these soils.

2.2 Sample collection, preparation, and protocol

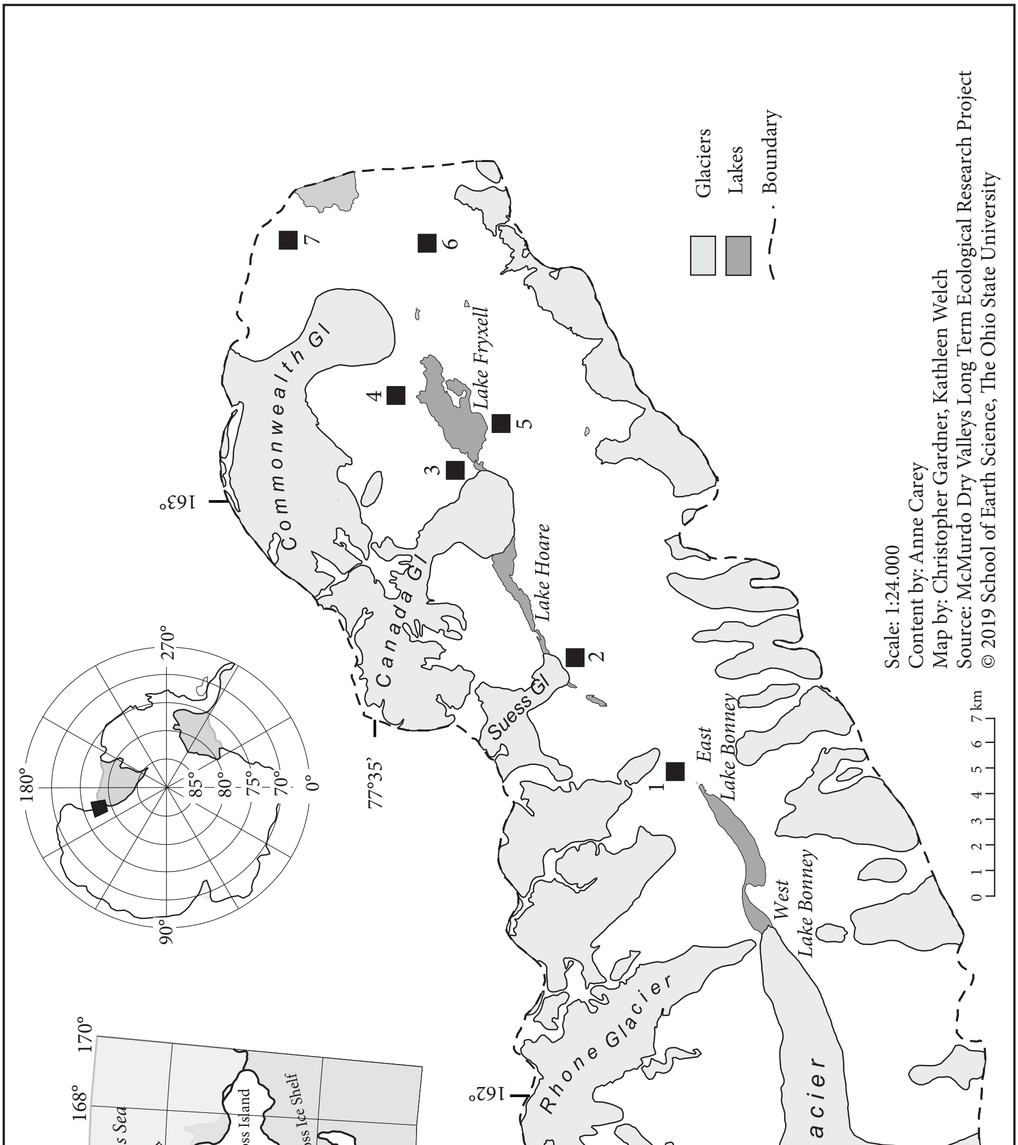
Thirteen groupings of surface »rocks« sitting at the soil surface were collected in locations throughout TV (Figure 1). Each rock was chosen for the noticeable amounts of carbonate encrustation on its underside (Figure 2).

Each group of rocks was collected within a one-meter radius area and the individual specimens ranged from about 1 cm to about 6 cm in diameter. GPS coordinates were taken at each of the 13 sampling locations and local geological and surrounding landscape features were also recorded. The rocks in each group were of different lithologies, including the major bedrock types in the area: marble, basement dike, granite, gneiss (all from the basement complex), dolerite and kenyite (McMurdo Volcanics). On return to the USA, these rocks were visually identified according to type. Rocks were kept separated throughout the sampling and analytical process. In the lab, pre-cleaned stainless steel dental tools were used to scrape off much of the encrusted calcite onto a clean piece of paper. Vinyl gloves were worn during this procedure, and each time a new rock was scraped, the dental tools and gloves were cleaned with distilled-deionized water and wiped dry between samples. About 10–100 mg of scraped material was collected and transferred into new plastic vials.

A portion of this material was analyzed for its strontium isotopic composition ($^{87}Sr/^{86}Sr$) and Sr concentration at the Radiogenic Isotopes Laboratory at The Ohio State University. Prior to dissolution, the aliquots were pre-washed using ultrapure ammonium acetate as described by Montañez et al. (1996). Roughly 10–100 mg of the carbonate scrapings were dissolved using high-purity acetic acid, and a spike of ^{84}Sr was added to analyze Sr by isotope dilution. The Sr in the samples was purified using cation exchange chromatography following procedures described by Foland and Allen (1991). The Sr isotopic measurements were made using a multi-collector MAT-261A thermal ionization mass spectrometer using dynamic multiple ion collection as described in Foland and Allen (1991). The accuracy of these measurements was determined by the analysis of reference standard, SRM987, for which the value has been determined to be 0.710242 ± 0.000010 (one sigma external reproducibility). The analytical precision of the total Sr analysis was ± 1%.

Another fraction of the carbonate from each sample was analyzed for its $\delta^{13}C$ and $\delta^{18}O$ compositions. Scrapings were first washed with deionized water using a vacuum filtration assembly and at least 100 μg was packaged in clear plastic vials in Columbus and sent to University of Utah, where they were analyzed as CO_2 on a Finnigan MAT 252 mass spectrometer following reaction with orthophosphoric acid and cryogenic purification using an automated Isocarb system (see Swart, Burns and Leder 1991). All data (including values from the literature) are reported using delta notation relative to the Pee Dee belemnite (PDB) standard for carbonates and the standard mean ocean water (SMOW) standard for waters. Analytical precision for both the $\delta^{13}C$ and $\delta^{18}O$ was ~0.1‰.

Figure 1: Map of Taylor Valley, McMurdo Dry Valleys, Antarctica with locations of samples. Samples included 1) NE shore of Lake Bonney, basement dike at elevation 82 m asl; 2) Defile, dolerite, gneiss, granite and marble at elevation 193 m; 3) North shore of Lake Freyxell, kenyite at elevation 37 m; 4) NE shore of Lake Fryxell, dolerite, and granite at elevation 46 m; 5) SW shore of Lake Fryxell, basement dike and dolerite at elevation 57 m; 6) Lake Fryxell to Explorer's Cove, dolerite and granite at elevation 83 m; 7) N shore of explorer's Cove, dolerite at elevation 26 m. Not show on this map is 8) Marble Point, basement rock at elevation 108 m located approximately 19 km north of location 7. ➤



Glaciers
Lakes
Boundary
Commonwealth Gl
Canada Gl
Suess Gl
Rhone Glacier
Taylor Glacier
Lake Fryxell
Lake Hoare
East Lake Bonney
West Lake Bonney
1
2
3
4
5
6
7
163°
162°
77°35'
77°45'
0 1 2 3 4 5 6 7 km
Scale: 1:24.000
Content by: Anne Carey
Map by: Christopher Gardner, Kathleen Welch
Source: McMurdo Dry Valleys Long Term Ecological Research Project
© 2019 School of Earth Science, The Ohio State University
180°
270°
90°
0°
85°
80°
75°
70°
160°
162°
164°
166°
168°
170°
77°
78°
Ross Sea
McMurdo Sound
Ross Island
Ross Ice Shelf
Study area

Figure 2: Example of rocks with carbonate encrustation at Mount Speed along the Shackleton Glacier at -84.46567, -177.1357167.

3 Results

$^{87}Sr/^{86}Sr$ data for $CaCO_3$ encrustations (calcite) from TV are presented in Table 1. Previously published lake and stream $^{87}Sr/^{86}Sr$ values within each of the three lake basins are similar in their geographic distributions as the encrustation data (Lyons et al. 2002; Dowling, Lyons and Welch 2013). In general, the $^{87}Sr/^{86}Sr$ values for all TV soils and waters increase (i.e., become more radiogenic) with increasing distance from the Ross Sea coast (Jones and Faure 1968; Lyons et al. 2002; Dowling, Lyons and Welch 2013). There also is an increase in $^{87}Sr/^{86}Sr$ with increasing distance from the coast for all rock types except for the marble (Lyons et al. 2002). The range of $^{87}Sr/^{86}Sr$ values for lakes and streams is on the lower end of $^{87}Sr/^{86}Sr$ values of the various rock sources within the entire MCM regime, perhaps suggesting the relative importance of both seawater and McMurdo Volcanic sources of Sr to the lakes (Lyons et al. 2002; Dowling, Lyons and Welch 2013). The range of $^{87}Sr/^{86}Sr$ ratios for carbonate encrustations in TV is smaller and is slightly less radiogenic than the lakes and streams (Table 1). There is no relation between the $^{87}Sr/^{86}Sr$ ratios in carbonate encrustations and the rock type from which they were taken nor between the $^{87}Sr/^{86}Sr$ ratios of the encrustations and elevation.

The $\delta^{13}C$ and $\delta^{18}O$ data from the $CaCO_3$ encrustations and other materials in TV are presented in Table 2. The $\delta^{13}C$ and $\delta^{18}O$ values range from –5.70 to –11.02, and –8.13 to –11.18 (PDB), respectively. In general, the $\delta^{13}C$ values are much more enriched than the soil organic matter (Burkins et al. 2000) and the $\delta^{18}O$ values are more enriched than the lacustrine carbonate in TV (Hendy et al. 1977; 1979).

4 Discussion

4.1 Source of Ca to the $CaCO_3$ encrustations based on Sr isotopic analysis

Naiman, Quade and Patchett (2000) and Van der Hoven and Quade (2002) have demonstrated in Arizona soil, in the desert southwest of the USA, that there are two primary sources of Ca that form pedogenic

Table 1: $^{87}Sr/^{86}Sr$ ratios for calcite encrustations and soils in TV (*Jones and Faure 1968).

Rock type coated with the $CaCO_3$ crust	$^{87}Sr/^{86}Sr$	Mean	Standard Deviation	Sr (ppm)
Marble Point (basement dike)	0.7081			890
Northern shore of Explorers Cove (dolerite)	0.7081			584
Between coast and Lake Fryxell		0.7083	0.00000	
Granite	0.7083			431
Basement dolerite	0.7083			827
North east of Lake Fryxell		0.7089	0.00000	
Dolerite	0.7089			504
Granite	0.7089			443
North central of Lake Fryxell (kenyite)	0.7090			202
South east of Lake Fryxell		0.7087	0.00010	
Basement dike	0.7088			268
Basement dike	0.7087			470
Dolerite	0.7086			429
Defile		0.7101	0.00148	
Gneiss	0.7109			1030
Granite	0.7109			497
Marble	0.7079			1740
Dolerite	0.7108			625
Northeast of Lake Bonney (basement dike)	0.7118			327
Soils				
Basin of Lake Bonney*	0.7136			
Near Lake Fryxell*	0.7089			
Near LaCroix Glacier*	0.7125			
Near Canada Glacier*	0.7101			

Table 2: $\delta^{13}C$ and $\delta^{18}O$ for Taylor Valley soil $CaCO_3$ encrustations. The far-right column reflects the $\delta^{18}O$ of water in equilibrium with the $\delta^{18}O$ of the carbonate. Values are in ‰.

	Pee Dee Belemnite		$\delta^{18}O$ Standard Mean Ocean Water	
Sample no.	$\delta^{13}C$	$\delta^{18}O$	Coplen et al. 1983	Water
12BD	7.47	−8.56	22.09	−12.3
25A*	5.70	−10.30	20.29	−14.1
25B	8.39	−8.23	22.43	−12.0
25D	9.14	−9.33	21.29	−13.1
46D	8.49	−10.82	19.76	−14.6
46G	8.18	−11.18	19.38	−15.0
59D	7.95	−8.13	22.53	−11.9
59Gn	8.42	−9.37	21.25	−13.2
59Gr	11.02	−10.37	20.22	−14.2
59M	7.24	−9.64	20.97	−13.4
69DB1	7.15	−10.50	20.09	−14.3
69G	7.33	−10.33	20.26	−14.1
75D*1	7.04	−8.54	22.11	−12.3
88B1	6.73	−10.39	20.20	−14.2
99K	7.20	−10.74	19.84	−14.6

carbonates: the local parent geologic material and aeolian dust. Much of the Ca in $CaCO_3$ in TV has been hypothesized to have originated from either the *in-situ* weathering of marble, mafic volcanic rock debris within the tills, and/or dust containing carbonates (Campbell and Claridge 1977; Keys and Williams 1981; Green, Angle and Chave 1988). The McMurdo Volcanics source of dissolved Sr is important to Lake Fryxell as it is found only in tills in the Lake Fryxell basin (Lyons et al. 2002). Measurements from the surface of nearby Canada Glacier yielded a value of 0.70991 (Dowling, Lyons and Welch 2013).

As noted above, there is little relationship between the $^{87}Sr/^{86}Sr$ of the rock types and the encrustations taken from them. The $^{87}Sr/^{86}Sr$ values from the $CaCO_3$ encrustations on the dike samples were less radiogenic than the dikes themselves. The $CaCO_3$ encrustations from the dolerites have much lower $^{87}Sr/^{86}Sr$ values than the Ferrar Encrustations on the granites and the dolerite samples were much less radiogenic than the granites (e.g., Lyons et al. 2002). Similarly, the one $^{87}Sr/^{86}Sr$ value from an encrustation on a gneiss sample was 0.7109, which is also much less radiogenic than the Olympus Granite-Gneiss, which ranges between 0.7150 and 0.7210. The authigenic carbonate from the kenyite (McMurdo Volcanics) sample had an $^{87}Sr/^{86}Sr$ value more radiogenic than the McMurdo Volcanics themselves (~0.7030 to 0.7045).

Clearly Sr within the encrustations has different Sr isotopic compositions than their »carrier« rocks. These data strongly suggest that the source of Sr, and by inference Ca, is not from the direct chemical weathering of the *in-situ* parent rocks but is also at least in part from another source. There is one encrustation that did not fit this pattern – the one in association with a piece of marble from ~22 km inland (Figure 1) had an $^{87}Sr/^{86}Sr$ ratio of 0.7079. The only reported $^{87}Sr/^{86}Sr$ value from the Asgard Marble is 0.7088, but that sample came from Wright Valley just to the northwest of Marble Point, far from our sample location (Faure, Jones and Owen 1973). Since the $^{87}Sr/^{86}Sr$ value for the marble encrustation (0.7079) is only slightly less radiogenic than the Asgard Marble, it is probable that the Ca in the $CaCO_3$ encrustation was derived from the marble itself, thereby overwhelming any contribution from the aerosol.

Extensive chemical weathering occurs within the TV environment, but that weathering has only been documented in the austral summer where there is abundant liquid water in the fixed stream channels that drain glacier melt water (Nezat, Lyons and Welch 2001; Gooseff et al. 2002). Because there is no overland flow and only a few locations where subsurface melt affects the surficial soils (Levy et al. 2012), most of the soil in TV has little contact with liquid water during the year (Fountain et al. 1999). Snow provides this water, but snow is rapidly sublimated instead of going through prolonged melting and any accumulated snow remaining from the previous winter disappears by the end of the austral summer (Fountain et al. 1999).

4.2 Dust flux to MCM and its chemical signature

Aeolian transport significantly redistributes particulate material in the MCM and it has been suggested that the geometry of TV dictates the direction of net dust flux with transport from higher elevations to lower elevations down-valley (Lancaster 2002; Šabacká et al. 2012; MacDonell, Fitzsimons, and Moelg 2013). Mean daily wind speeds are higher up-valley to the west nearer to the Taylor Glacier and East Antarctic Ice Sheet and decrease near the coast (Fountain et al. 1999; Doran et al. 2002). This results in higher aeolian sediment flux up-valley (Lancaster 2002). Strong katabatic winds (especially in the austral winter) can transport dust from higher elevations to the lower elevations down valley (i.e., to the east). The aeolian dust flux in the MCM region has been measured ~1 m above the landscape surface and the values generally decrease from west to east as described above, ranging from 1.10 to 0.24 $g\,m^{-2}\,yr^{-1}$ for Lake Bonney and Explorers Cove/New Harbor (eastern most portion of TV), respectively (Lancaster 2002). The dust fluxes in the Lakes Fryxell and Hoare basins are dominated by fine grained (<50 μm) material, while Lake Bonney basin is primarily sand size particles (>90% by weight). The general up-valley increase in particle flux and grain size may suggest that the Lake Bonney basin and the Lakes Fryxell-Hoare basin dust inputs have different chemical compositions. Recent work from collectors placed close to the ground indicates that the aeolian material being blown in TV is of local origin, different size fractions have different major element geochemistries, and the finer grained fraction has higher Ca concentrations (Deuerling et al. 2014). More recent work on aeolian samples collected at higher elevations off the ground (1 m) suggest a more homogeneous geochemistry (Diaz et al. 2018).

The geologic materials up-wind (i.e., west) of TV are primarily Ferrar Dolerite and the Beacon Supergroup rocks. The dolerite has $^{87}Sr/^{86}Sr$ values of 0.712–0.714, while to our knowledge only the carbonates in the Beacon rocks have been analyzed, and they are very radiogenic (i.e. >0.725) (see data and references in Lyons et al. 2002). Samples collected in aeolian collectors on Taylor Glacier in the Bonney basin (west) and in Explorers Cove (east) yielded $^{87}Sr/^{86}Sr$ ratios of 0.71575 and 0.70864, supporting the notion that the dust is from very local (i.e., individual basin) sources (Diaz 2017) and are generally within the range of the values for our carbonate encrustations (Table 1).

4.3 Local soil as a source of Sr

As noted above, the Sr isotope ratios of the encrustations are geographically similar to what has been previously reported for TV stream waters (Lyons et al. 2002; Dowling, Lyons and Welch 2013). The most recent values for the Fryxell and Hoare basins range 0.70837–0.71084 and 0.70837–0.71091, respectively, while the Bonney Basin samples are more radiogenic, ranging between 0.71255 and 0.71418 (Dowling, Lyons and Welch 2013). As previously noted, the few measurements on TV dust yield similar values. The stream values have a narrower range than the encrustations, but the geographic trends are similar. Dowling, Lyons and Welch (2013) concluded that in the Fryxell and Hoare basins the dissolution of $CaCO_3$ must play an important role in contributing dissolved Sr and Ca to these streams, and that the primary source may be from pieces of Asgard Marble within the stream beds. They also suggested that the initial Sr^{2+} that occurs in the authigenic carbonate minerals within the soils probably originates from the weathering of a wide range of sources, including previously existing secondary carbonates and Ca-rich dust.

Much research has clearly demonstrated that calcite within crystalline rocks, even at very low abundances, is the major contributor of dissolved Ca to aquatic systems (e.g., Lyons et al. 2005; Andrews and Jacobson 2017). As a polar example, it has been shown that the dissolution of fracture-filling calcite from moraines on Baffin Island is a major source of Sr, and hence Ca, to pedogenic crusts (Lacelle, Lauriol and Clark 2007). The $^{87}Sr/^{86}Sr$ values available for the lithologies in TV are whole rock values. Unfortunately, we are unable to evaluate whether calcite in the crystalline rocks in the soils and tills of TV is a potential source of Sr. It should be noted that calcite fillings in volcaniclastic rocks from Minna Bluff, ~150 km south of our study area, had $^{87}Sr/^{86}Sr$ values of 0.70327 (Antibus et al. 2014), suggesting that calcite within at least the McMurdo Volcanics could be a source of Ca and Sr to these soils.

The MCM soils are primarily glacier deposited tills and lacustrine sediments and, as mentioned above, consist of materials from all the regional bedrock groupings; they are not derived from one lithology. There are differences in the amounts of various types of material (e.g. the Ross tills having abundant kenyite) and their ages, so the soils are a heterogeneous mix of geologic materials (Foley et al. 2006). These differences in both lithology and age lead to important differences in the geochemistry of the soils from basin to basin in TV. These geographical differences superimpose important ecological and biogeochemical differences such as landscape-scale differences in N:P ratios (Barrett et al. 2007). Soils also demonstrate an increase in radiogenic Sr moving inland, with a value of 0.7089 in the Fryxell Basin, increasing to 0.7101 along the transition from the Fryxell to the Hoare Basin, 0.7125 as the eastern reaches of the Bonney Basin, to 0.7136 within the more western portions of the Bonney Basin (Jones and Faure 1968) which is reflected in both stream waters and local dusts.

The general pattern of increasing radiogenic ratios of these carbonate encrustations from east to west in TV fits with all the available stream, lake, dust and soil data. In general, the carbonate samples are slightly less-radiogenic than their corresponding soils, suggesting that in the Fryxell and Hoare basins the McMurdo Volcanics may be preferentially weathered within the soils. This idea of selective weathering of the till materials is not a new one as it has been mentioned as a mechanism to explain the variation of major ion stream chemistry and the Sr isotopic compositions for the stream waters of the Fryxell Basin (Lyons et al. 2002; Dowling, Lyons and Welch 2013). In the Bonney basin, the less radiogenic (than the soil) carbonate values might reflect input from marine aerosol or more intensive weathering of the Ferrar Dolerite. The process of dissolution and reprecipitation of $CaCO_3$ within the soil profile may play an important role in maintaining the Sr isotopic variation constrained to some overall local basin-wide value. All these data support the idea that this trend of less to more radiogenic values from east to west in TV reflects local, rather than far-afield, input of Sr.

4.4 Sources of Carbon and Oxygen to the $CaCO_3$ encrustations

The stable isotopic geochemistry of C and O in modern soil carbonate is primarily determined by the local climate. Other work has clearly demonstrated that $\delta^{18}O$ values are well correlated with the isotopic composition of the local meteoric water and $\delta^{13}C$ values are related to vegetation type and soil respiration rates (Cerling 1984; Lipar et al. 2017). At low biological respiration rates in the soil, the influence of atmospheric CO_2 on the $\delta^{13}C$ signal is more pronounced. In cold climates several types of carbonate precipitates exist that are produced through different processes which lead to different isotopic compositions (Lacelle 2007). The evaporation and transpiration of water and sublimation of snow and ice can lead to loss of pCO_2 that can also greatly affect both the $\delta^{13}C$ and $\delta^{18}O$ signatures of pedogenic carbonates (Marion, Introne, Van Cleve 1991; Clark and Lauriol 1992). The freezing of liquid water causes supersaturation with respect to $CaCO_3$ and the non-equilibrium conditions produced by this process can affect the stable isotopic composition of the $CaCO_3$ produced (Clark and Lauriol 1992; Courty et al. 1994; Lacelle, Lauriol and Clark 2007). Such kinetic fractionation usually leads to enrichment of the isotopes in the carbonate minerals. The difference in thermal conductivity between the larger clasts, where precipitation occurs, and the finer grained soil influences this process, as the freezing front moves more rapidly in the larger material. This type of pedogenic carbonate, formed in the active layer of high latitude soil, is common (Lacelle 2007).

The $\delta^{13}C$ signature of soil respiratory CO_2 depends in part on the nature and amount of organic matter present in the soil. In modeling the $\delta^{13}C$ values of pedogenic carbonates, Cerling (1984) used values of −13‰ and −27‰ for pure C_4 and pure C_3 plant biomass, but CO_2 from this organic matter source can mix with atmospheric CO_2 ($\delta^{13}C = -6.5‰$) to produce an intermediate value of $\delta^{13}C$ of soil CO_2. Measurements of materials in the sub-Arctic boreal region of Saskatchewan, Canada show a positive correlation between $\delta^{13}C$ values of pedogenic carbonates and organic carbon in the soils (Landi, Mermut and Anderson 2003). Even pedogenic carbonates from interior Alaskan floodplain sediments fall in the range of those of Cerling (1984), having values as depleted as −7.9‰, clearly demonstrating a biologically influenced signal (Marion Introne, Van Cleve 1991).

Soil organic matter in TV is extremely low, resulting in great part from past climate and glacial histories, and has accumulated in soils in a distinct low elevation pattern (<250m above sea level) corresponding to the spatial distribution of ancient lacustrine systems. The mean $\delta^{13}C$ values for various organic matter sources in MCM soils range between −20.8 and −24.3‰ (Burkins, Virginia and Chamberlain 2000). Because the organic matter concentrations in soil are so low, the CO_2 flux from Antarctic soils is also extremely low. The CO_2 present in Antarctic soils may originate from atmospheric sources or via the *in-situ* respiration of organic C (Parsons et al. 2004). CO_2 fluxes in TV soils fluctuate throughout the day and show very low concentrations of CO_2 escaping from the soil. In the Lake Fryxell and Hoare basins, CO_2 is actually taken up by soils during rapid decreases in soil temperature (Parsons et al. 2004). Recent work in hot desert soils clearly shows that similar diel variations driven by inorganic processes play a significant role in CO_2 dynamics (Ma et al. 2013). It is unknown if these diel variations have influence on $CaCO_3$ dynamics within the active layer of Antarctic soils.

The $\delta^{13}C$ values for the TV carbonate encrustations are very enriched with values ranging from +5.7 to +11.0‰ (Table 2). These values contrast greatly with the modern lacustrine carbonates in Lake Fryxell which range from +3 to −18% depending on water depth (Lawrence and Hendy 1989). Using a CO_2-$CaCO_3$ fractionation factor of −14.4 ($10^3 \ln\alpha$) at 0°C (Friedman and O'Neil 1977), the $\delta^{13}C$ values for a TV pedogenic carbonate with a 100% atmospheric CO_2 source would be +7.4‰. Ten out of fifteen of the TV encrustations are within ±1‰ of this value, suggesting that the primary source of C to these carbonates is atmospheric CO_2. Only one sample is more than 1‰ greater than this value. That one sample (from a basement dike specimen from SW Lake Fryxell) may have some carbon derived from CO_2 respired organic matter or, perhaps, it was formed at a warmer temperature. Ancient lacustrine carbonates obtained in what are now TV soils show a more depleted, but still positive, set of $\delta^{13}C$ values (2.4–6.8‰), suggesting a larger percentage of biologically respired CO_2 (Hendy et al. 1979). The lack of a biological source or influence on the C in these TV $CaCO_3$ soil encrustations is not a surprise given the low organic carbon present in the soils and the very low CO_2 fluxes from the soils, as noted above (Burkins et al. 2000; Parsons et al. 2004). The $\delta^{13}C$ of the TV encrustations are very similar to what has been previously reported for pedogenic carbonates (1.5–9.0‰) in Wright Valley just north of TV (Nakai et al. 1975).

Previous work on authigenic carbonates in Antarctica reflects the influence of the $\delta^{18}O$ of the water present. Aragonite that was deposited subglacially on gneissic bedrock in the Vestfold Hills, Antarctica (68°30' S) has very depleted $\delta^{18}O$ values ranging from −17.3 to −14.1‰ (Aharon 1988). Lacustrine carbonates deposited at higher lake stands in TV are also depleted with $\delta^{18}O$ values of −32 to −46‰ (Hendy et al. 1977; 1979). In both cases, these $\delta^{18}O$ values reflect the extremely depleted values associated with the local meteoric waters derived from glacier melt (Gooseff et al. 2006).

These TV encrustations have $\delta^{18}O$ values (Table 2) more similar to the Type 3 evaporite calcite crusts for other polar regions reviewed by Lacelle (2007) than the subglacial and lacustrine-derived carbonates from the Antarctic. There is no reflection in the TV carbonates of the very depleted $\delta^{18}O$ values for the snow/ice melt waters observed in the TV region, which range from −27 to −40.4‰ (Gooseff et al. 2006). Our $\delta^{18}O$ values from the encrustations when converted to water at 0°C in equilibrium with the carbonate produce values of −11.9 to −15.0‰ (Table 2). Given this enrichment with respect to the TV meteoric waters, the data suggest strong evaporative loss of ^{16}O prior to carbonate precipitate. Evaporation of thin films and water droplets has also been used to explain enriched $\delta^{18}O$ in carbonate encrustations in warm deserts (Knauth, Brilli and Klonowski 2002; Quade et al. 2007). These high $\delta^{18}O$ values in the TV encrustations are undoubtedly due to precipitation during extensive evaporation and light isotope loss.

4.5 Formation of Taylor Valley pedogenic carbonate

We envision the following scenario for carbonate mineral encrustation formation in polar desert systems like the McMurdo Dry Valleys. During snowfall events small amounts of Ca are solubilized from the Ca-containing minerals and rocks (probably $CaCO_3$) in the soils, and/or mineral dusts and/or desiccated marine aerosols. Given that snowfall deposition is minimal (≤ 3 cm a^{-1}), and relative humidity is extremely low, sublimation and evaporation rates are high. During the evaporative process calcite becomes supersaturated in the remaining water film and is precipitated with CO_2 as the primary carbonate source as indicated by the $\delta^{13}C$ values. These Taylor Valley carbonate encrustations form in an extremely arid setting and demonstrate that carbonate mineral formation in soils can occur with little to no biological processes being involved. This lack of biological process affecting $\delta^{13}C$ compositions of ΣCO_2 is also observed in TV streams (Lyons et al. 2013). These Antarctic carbonate encrustations form an extreme position in $\delta^{13}C$ and $\delta^{18}O$ when compared to other cold environment authigenic carbonates and a rapid rate of precipitation leading to non-equilibrium conditions due to a rapid loss of CO_2 as outlined in Lacelle (2007).

5 Conclusions

Except for the carbonate crust on a marble sample, which obtained its Sr (Ca) from weathering of the parent marble, it is hypothesized that the carbonate encrustations on all the other TV rock samples receive their Sr (and by inference their Ca) from surface soil sources including potential locally derived aeolian debris. The encrustations are less radiogenic than the soils from their respective lake basins indicating that selective dissolution of volcanic materials and/or marine aerosol may play an important role in their formation. The $\delta^{13}C$ values of the rock encrustations indicate they are produced in place with atmospheric CO_2 as the primary carbon source. Our results suggest that the $\delta^{13}C$ signature can be used to ascertain the difference between pedogenic and lacustrine carbonate in MCM soils. The $\delta^{18}O$ values of the $CaCO_3$ encrustations do not directly reflect the very depleted values of the local melt water source. The $\delta^{18}O$ values for the $CaCO_3$ encrustations suggest extensive evaporation has led to their formation, similar to deposits from warm deserts, as well as other active layer and polar soil environments. The $\delta^{18}O$ data indicate that evaporation/sublimation of water, perhaps in thin films, plays a major role in the production of these encrustations.

ACKNOWLEDGEMENT: The fieldwork was supported through NSF Grants OPP-9813061 and ANT-0423595. We thank Kate Harris, Nevada Hanners, and A. J. (Rabbit) Kaltenback for their help in sample collection. We are extremely grateful to Ken Foland and Jeff Linder for the Sr isotope analyses. We thank Kathy Welch, Chris Gardner, Sarah Fortner and Michele Cook for their editing of the initial draft of the manuscript. We also thank Chris Gardner for creating Figure 1 for this paper. The first draft of this paper was completed while the senior author was supported by a Royal Society Travel Grant; he thanks Prof. J. Laybourn-Parry and the School of Physical Sciences and Geography at Keele University for their hospitality during that time. Finally, the senior author greatly appreciates being asked to contribute to and to co-edit this special addition of *Acta geographica Slovenica*. Thanks to Matija Zorn and Blaž Komac!

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Acta geographica Slovenica, 60-2, 2020, 141–153

THE GEOCHEMISTRY OF ICE IN THE SOUTHEASTERN ALPS, SLOVENIA

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Cave ice in the Ivačičeva Cave in the Julian Alps (southeastern Alps, Slovenia).

DOI: https://doi.org/10.3986/AGS.7420
UDC: 911.2:551.324(234.323.6)
551.324:550.4(234.323.6)
COBISS: 1.01

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The geochemistry of ice in the southeastern Alps, Slovenia

ABSTRACT: The Triglav Glacier in the Julian Alps and the Skuta Glacier in the Kamnik-Savinja Alps are among the south-easternmost glaciers in the Alps. Historical data show that ice masses are undergoing mass loss as the overall climate warms. Glacier ice and cave ice contain a wealth of paleoclimatic information, and rapid sampling is needed if any such information is to be saved before the ice is completely melted. We present the first comprehensive geochemical and water isotope data from glacier ice, meltwater, spring water, and cave ice in the Mount Triglav area and glacier ice from the Skuta Glacier. The samples primarily reflect the initial precipitation signal that has been greatly modified by the input of local $CaCO_3$-rich dust with lesser amounts of marine aerosol and vegetation debris.

KEY WORDS: glaciochemistry, glaciokarst, ice caves, cave ice, water isotope, Triglav Glacier, Skuta Glacier, Alps

Geokemija ledu v jugovzhodnih Alpah, Slovenija

POVZETEK: Triglavski ledenik v Julijskih Alpah in Ledenik pod Skuto v Kamniško-Savinjskih Alpah sta med najbolj jugovzhodnimi ledeniki v Alpah. Njuno dolgoletno opazovanje kaže, da se ledenika zaradi segrevanja ozračja krčita. Ker ledeniški in jamski led hranita številne podatke o preteklem podnebju, je njuno vzorčenje nujno, dokler so podatki (led) še na razpolago. V članku predstavljamo prve obsežnejše podatke o geokemiji in vodnih izotopih iz ledeniškega ledu, talilne vode, izvirske vode in jamskega ledu na območju Triglava ter ledeniškega ledu iz Ledenika pod Skuto. Vzorci v prvi vrsti odražajo začetni signal padavin, ki je bil močno spremenjen z vnosom aerosola, obogatenega s karbonatom ter v manjši meri z delci morskega in rastlinskega izvora.

KLJUČNE BESEDE: geokemija, glaciokras, ledene jame, jamski led, vodni izotopi, Triglavski ledenik, Ledenik pod Skuto, Alpe

The paper was submitted for publication on January 17th, 2019.
Uredništvo je prejelo prispevek 17. januarja 2019.

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1 Introduction

The Triglav Glacier in the Julian Alps (NW Slovenia) at app. 2450–2550 m and the Skuta Glacier in the Kamnik-Savinja Alps (N Slovenia) at app. 2000–2200 m are the only glacier remains in Slovenia (Gabrovec et al. 2013; 2014; Triglav Čekada et al. 2020; Triglav Čekada and Zorn 2020; Figure 1) and among the south-easternmost glaciers in the Alps (Grunewald and Scheithauer 2010). Due to their small size and the relief-dependent lack of movement, they are defined as glacierets (Kumar 2011). As such, from the environmental perspective they represent important mountain geomorphosites (Reynard and Coratza 2016).

The beginning of the research of the Slovenian Alps dates back to the 17th and 18th century (Mikša and Zorn 2016), and the size of the Triglav Glacier has been estimated as far back in time as 1897 (Triglav Čekada, Zorn and Colucci 2014; Del Gobbo et al. 2016). Excellent historical data on the Triglav and Skuta glaciers are available due to continuous detailed measurements of both glaciers by the ZRC SAZU Anton Melik Geographical Institute since 1946 and 1948, respectively (Pavšek 2004; 2007; Gabrovec et al. 2013; 2014). Between the years 2000 and 2013 the ice volume of the Triglav Glacier has decreased from 35,000 m^3 to app. 7,400 m^3 (Del Gobbo et al. 2016) and has probably reached the smallest size since the Last Glacial Maximum (Lipar et al. 2021). The Skuta Glacier has also experienced mass loss during the past six to seven decades (Pavšek 2007; Triglav Čekada et al. 2020).

Glacier ice and cave ice represent a wealth of paleoclimatic information (Yao et al. 2011), but work in Slovenia (Mihevc 2018) and in other parts of the Julian Alps (Colucci et al. 2016) indicates that, like the Triglav and Skuta glaciers, these ice masses continue to undergo mass loss as the overall climate warms. Rapid sampling of these deposits is needed if any such information is to be preserved. In this paper we present the first comprehensive geochemical and water isotope data, collected in 2017 and 2018, from both ice and meltwater from Triglav and Skuta glaciers' areas. These data also include measurements of cave ice from the Ivačičeva Cave (IC; Figures 2 and 4) and the Triglav Shaft (TS; Figures 3 and 4) located very close to the Triglav Glacier, and water from the spring of the Triglavska Bistrica Creek (TBC) in the Vrata Valley below the Triglav Glacier (TG) at 1175 m (Figure 1). The purpose of this work was to describe the chemistry of the ice and its meltwater and to provide new information on the isotopic composition at this elevation in the Julian Alps and the Kamnik-Savinja Alps. We also continue to evaluate the potential for use of cave ice in paleoclimatological studies (Carey et al. 2019). In addition, we discuss the hydrological connectivity among precipitation (i.e., glacier ice), meltwater, cave ice and karst spring water in glaciokarst landscape (Zorn, Hrvatin and Perko 2020).

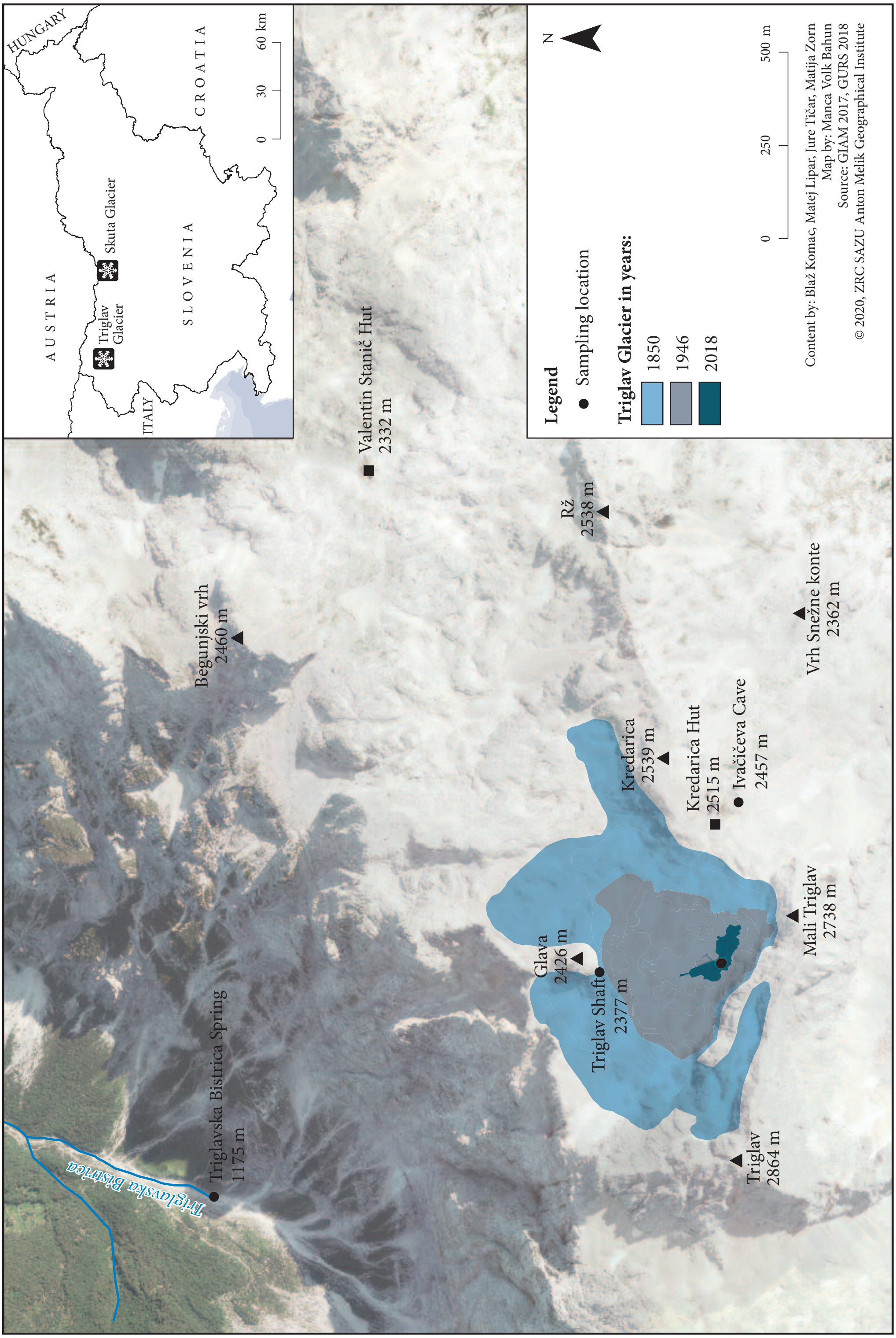
2 Study area and methods

2.1 Study area

The Mount Triglav (2864 m; Julian Alps) regional landscape has been termed glaciokarst (Kunaver 1983; Žebre and Stepišnik 2015) with the flatter depressions in the landscape providing locations for the collection and accumulation of winter snow (Del Gobbo et al. 2016). The ice samples from the Triglav Glacier (TG) area come from the glacier, the Triglav Shaft (TS; *Triglavsko brezno*) and Ivačičeva Cave (IC; *Ivačičeva jama*). The Triglav Shaft is a vertical ice cave 274 m deep. Entrance to the cave occurs at 2377 m and was covered by the glacier until the early 20th century. The Ivačičeva Cave is situated next to the Kredarica mountain hut at 2457 m (Tičar et al. 2018). The spring water sample is from spring of the Triglavska Bistrica Creek (TBC) in the Vrata Valley which is app. 1200 m directly below the Triglav Glacier and Triglav Shaft (Figure 1).

The Julian Alps bedrock is dominated by Triassic-Jurassic shallow water carbonate rocks (Šmuc and Rožič 2009). There is a weather observatory at 2514 m that is less than 0.5 km from the glacier. The mean annual temperature during 1981–2010 was –1.0 ± 0.6 °C and the mean annual precipitation was 2070 mm (water equivalent), with mean winter snow accumulation of 5.14 m (Del Gobbo et al. 2016). The wind

Figure 1: Map showing location of sampling location and the extent of the Triglav Glacier since 1850. Inset map shows location of larger, detailed figure. ➤ p. 144


HUNGARY
AUSTRIA
CROATIA
ITALY
SLOVENIA
Triglav Glacier
Skuta Glacier
0
30
60 km
N
Legend
Sampling location
Triglav Glacier in years:
1850
1946
2018
0
250
500 m
Content by: Blaž Komac, Matej Lipar, Jure Tičar, Matija Zorn
Map by: Manca Volk Bahun
Source: GIAM 2017, GURS 2018
© 2020, ZRC SAZU Anton Melik Geographical Institute
Valentin Stanič Hut
2332 m
Rž
2538 m
Begunjski vrh
2460 m
Vrh Snežne konte
2362 m
Kredarica
2539 m
Kredarica Hut
2515 m
Ivačičeva Cave
2457 m
Mali Triglav
2738 m
Glava
2426 m
Triglav Shaft
2377 m
Triglav
2864 m
Triglavska Bistrica Spring
1175 m
Triglavska Bistrica

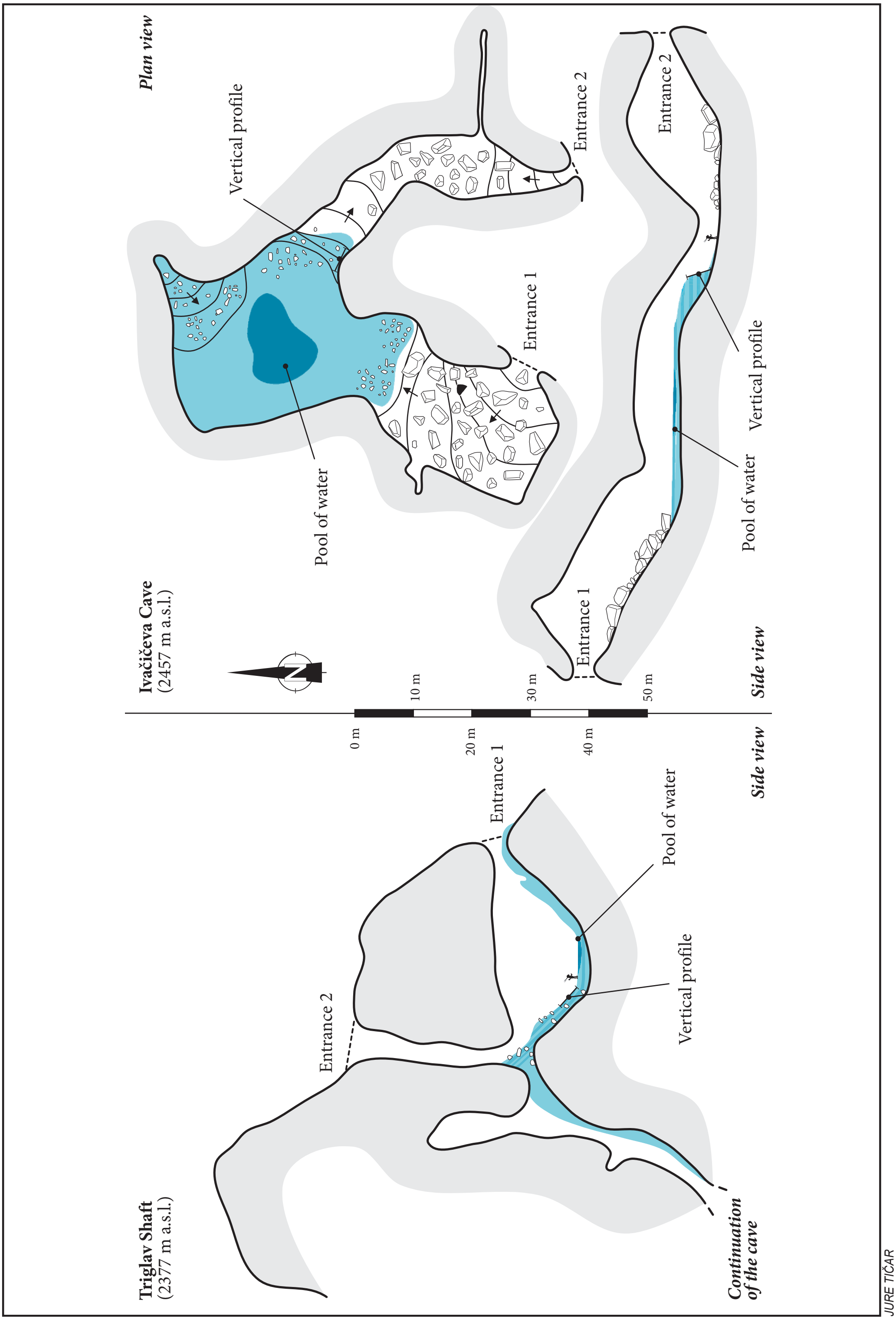

JURE TIČAR

Figure 2: Ice sampling in the Ivačičeva Cave.


MATIJA ZORN

Figure 3: Entrance chamber of the Triglav Shaft where ice samples were taken.

Figure 4: Sketch of the entrance part of the Triglav Shaft and the Ivačičeva Cave with the location of sampling (black dot). ➤ p. 146


Plan view
Ivačičeva Cave
(2457 m a.s.l.)
Vertical profile
Entrance 2
Entrance 1
Pool of water
N
0 m
10 m
20 m
30 m
40 m
50 m
Side view
Entrance 2
Entrance 1
Vertical profile
Pool of water
Side view
Triglav Shaft
(2377 m a.s.l.)
Entrance 2
Entrance 1
Pool of water
Vertical profile
Continuation
of the cave
JURE TIČAR

direction is influenced by the top of Mt. Triglav just west from the station, thus the prevailing winds come from northwest or southeast with speeds up to 190 km/h (Nadbath 2014).

Ice was also sampled from the Skuta Glacier (SG; Figure 1). The Skuta Glacier (Kamnik-Savinja Alps) is located in a cirque oriented toward the northwest, which preserves it from the Sun for most of the year and also influences the wind direction. The glacier lies at an average elevation of app. 2070 m. The broader Mt. Skuta (2532 m) area is dominated by Triassic carbonate rocks (Mioč 1983), so the setting of the glacier is also in a karstic environment. Both glaciers are fed with snow also through avalanches.

2.2 Methods

Ice samples were collected using a clean ice axe, placed into plastic bags and allowed to melt. Samples for ion analysis were filtered in the laboratory through 0.45 μm pore size *Millipore* filters using clean plastic syringes into precleaned low density polyethylene bottles, as discussed in Carey et al. (2019). Samples for water isotope analyses were not filtered but immediately upon complete melting of the ice, the resultant water was decanted into scintillation vials, minimizing any headspace. Water samples were collected directly into precleaned polyethylene bottles and filtered (except the isotope samples) using the same technique as the melted ice.

The samples were kept in the dark in a refrigerator until shipped to the laboratory at *The Ohio State University*. Major ions were analyzed by ICP-OES (Inductively Coupled Plasma Optical Emission Spectrometry) and ion chromatographic techniques (Welch et al. 2010). Nutrients (NO_2^- + NO_3^-, NH_4^+, PO_4^{3-} and H_4SiO_4) were determined with a *Skalar SAN*++ nutrient analyzer using methods supplied by the manufacturer. The $\delta^{18}O$ and δD of water were analyzed using a *Picarro* liquid water isotope analyzer. Samples were compared to VSMOW ($\delta^{18}O$ = 0‰; δ^2H = 0‰) and to internal laboratory standards as a means of correcting raw data. Some of the ice collection bags were filled with our cleanest deionized water and analyzed as samples to provide any evidence of contamination from the bags and these were used as blanks. Chloride, sulfate, sodium and potassium in these blanks were below our levels of detection while magnesium and calcium concentrations had mean values of 0.9 μM and 3.5 μM, respectively. Details on accuracy and precision can be found in Welch et al. (2010) and Carey et al. (2019). Bicarbonate concentrations were determined by the difference in charge balance as HCO_3^- = Σcations – Σanions as discussed in Welch et al. (2010).

3 Results

The major ion and nutrient data are presented in Table 1. Several general statements can be made about the data. They include, in general, Ca>>Mg=Na>K; HCO_3>SO_4>Cl; ΣDIN (sum of NO_2^- + NO_3^- + NH_4^+)>>PO_4^{3-}; except for the Triglavska Bistrica Spring (TBC) in the Vrata Valley, H_4SiO_4 concentrations are very low. The $\delta^{18}O$ and δD range between –8.1‰ and –12.7‰ and between –56.3‰ and –96.4‰, respectively (Table 2). We have plotted our isotopic analyses of the ice with a regional meteoric water line which we developed from published data (Figure 5). The isotope values all fall on or very close to the regional meteoric water line. The very high Ca and HCO_3 values strongly indicate that all the ice and snow are greatly influenced by local $CaCO_3$-rich dust.

4 Discussion

4.1 Geochemical data

The mean values for both the glacier and cave ice in the Triglav Glacier area (Table 2) are compared to a high elevation snow pit and ice core data from Mt. Ortles, Italy (Gabrielli et al. 2010) and the closest ice core to the Triglav Glacier as the Mt. Ortles core is the only core taken from the Eastern Alps, near the border of Italy, Switzerland and Austria. These samples from Italy were collected at an elevation of 3860 m and is the nearest high-elevation ice data adjacent to ice-free areas. These ice data represent a regional picture of high elevation precipitation chemistry in this area of the Alps and it is the nearest ice core analyzed

Table 1: Major ion and nutrient chemistry of ice and water samples.

Sample number	Sample	Cl^- µM	SO_4^{2-} µM	HCO_3^- µM	Na^+ µM	K^+ µM	Mg^{2+} µM	Ca^{2+} µM	SDIN µM	PO_4^{3-} µM	Si µM	N:P
TS 1	Cave Ice	3.9	9.3	248.3	3.9	3.1	4.5	127	12.0	0.50	1.1	24.1
TS 2	Cave Ice	1.7	6.8	234	2.6	0.5	2.1	121	0.4	0.24	0.7	1.7
TS 3	Cave Ice	2.0	15.8	406.5	5.7	2.0	4.9	212	1.7	0.15	2.6	11.3
TS 4	Cave Ice	3.4	9.1	243.5	5.7	1.3	4.5	127	5.1	0.09	0.9	56.7
TS 5	Cave Ice	3.4	14.2	337.5	7.0	1.5	6.2	179	10.0	0.02	1.0	333
TS 6	Cave Ice	1.7	11.1	828.5	2.2	<0.3	4.1	171	10.5	0.03	1.2	16.7
TG 1	Glacier Ice	9.3	9.0	281.2	8.3	8.9	4.1	143	23.9	0.12	1.1	199
TG 2	Melt water	1.1	7.2	182.3	0.9	<0.3	4.1	96	3.6	0.05	0.6	72.0
TG 3	Melt water	0.8	10.1	315.5	0.9	<0.3	6.6	163	3.7	0.04	0.9	92.5
TBC	Spring Water	4.5	3.9	1223	0.4	<0.3	134	496	24.9	0.04	6.2	622
SG 1	Glacier Ice	11.2	16.8	315	3.5	1.8	<4	179	3.9	<0.01	0.5	>390
SG 2	Glacier Ice	1.8	16.7	92.6	10.9	1.5	6.2	52	1.6	<0.01	0.3	>160
IC 1	Cave Ice	2.1	8.4		4.52	1.81	22.4	200	5.9	0.07	0.3	84.3
IC 2	Cave Ice	1.4	9.8		2.25	0.83	2.98	121	1.4	0.04	0.1	35.0
IC 3	Cave Ice	2.0	7.4		2.71	0.94	5.48	109	2.9	0.03	0.1	96.7
IC 4	Cave Ice	0.9	3.4		3.28	0.47	1.86	77	1.7	0.03	<0.1	56.7
IC 4 - test	Cave Ice	1.5	5.8		1.84	0.63	3.74	124	3.3	0.03	<0.1	110
IC 5	Cave Ice	1.8	7.4		2.37	5.13	26.3	134	16.4	0.03	0.1	547

Table 2: Stable isotope analyses of ice and water samples compared to VSMOW ($\delta^{18}O = 0‰$; $\delta^2H = 0‰$).

Sample number	Sample	Values		Accuracy	
		$\delta^{18}O$, ‰	δD, ‰	$\delta^{18}O$, ‰	δD, ‰
TS 1	Cave Ice	–12.10	–87.44	0.08	1.51
TS 2	Cave Ice	–11.38	–77.05	0.08	1.51
TS 3	Cave Ice	–9.64	–65.40	0.08	1.51
TS 4	Cave Ice	–10.53	–72.54	0.08	1.51
TS 5	Cave Ice	–11.96	–82.15	0.08	1.51
TS 6	Cave Ice	–10.67	–79.79	0.08	1.51
TG 1	Glacier Ice	–10.08	–68.63	0.08	1.51
TG 2	Melt water	–8.06	–52.72	0.08	1.51
TG 3	Melt water	–8.15	–52.37	0.08	1.51
TBC	Spring Water	–9.84	–64.94	0.08	1.51
SG 1	Glacier Ice	–8.69	–58.06	0.08	1.22
SG 2	Glacier Ice	–8.90	–58.72	0.08	1.22
IC 1	Cave Ice	–8.82	–57.46	0.05	0.59
IC 2	Cave Ice	–8.63	–57.04	0.05	0.59
IC 3	Cave Ice	–8.40	–54.16	0.05	0.59
IC 4	Cave Ice	–8.54	–56.14	0.05	0.59
IC 4 - test	Cave Ice	–9.01	–59.90	0.05	0.59
IC 5	Cave Ice	–8.12	–53.75	0.05	0.59

for some of the same analyzed in our samples. We assume that the precipitation regime in the Triglav region is generally similar to that in the Mt. Ortles area and it is then modified, either by the input of chemicals as the precipitation falls or after it is deposited on the glacier surface. Enrichment factors (Triglav ice/Mt. Ortles snow) can then be computed for elements under investigation (Table 1). These enrichment factors range from as little as 1.1 for Mg and as high as 19.1 for Ca (Table 3). Calcium in the Mt. Ortles snow has been shown to be a proxy for »dust« (Gabrielli et al. 2010). Because the surrounding bedrock in the Triglav area is carbonate, we assume that these very large enrichments of Ca in the Triglav ice and in the meltwater are both due to the local input of $CaCO_3$-rich dust. The dust either dissolves as the ice melts or is solubilized when acid is added to the cation samples prior to ICP-OES analysis, or both. The lesser enrichments in Cl, SO_4, Na, and K are probably also related to increased particle input from marine aerosol, pollution, and/or organic matter debris deposited as primary precipitation or blown onto the glacier surface as aeolian deposition through time. The very low H_4SiO_4 values suggest, however, that the deposited dust either is extremely low in silicate minerals or that these minerals are filtered out of the sample during processing. We have observed debris on the filter paper after filtration so the latter is more likely. This phenomenon of local dust deposition onto glacier surfaces has been observed on many glaciers all over the world, including on glaciers in the ice-free regions of Antarctica where local soils can be suspended and re-deposited by winds (Lyons et al. 2002; 2020). In addition, local dust deposition and erosion commonly occur in Slovenia, even in lower-lying regions (e.g., Zorn 2009; Miler 2014; Miler and Gosar 2015; Zupančič, Horvat and Skobe 2015).

The cave ice has a geochemistry similar to the meltwater, which may suggest that the cave ice is formed from the refreezing of summer glacier melt (Table 1).

DIN concentrations have mean value of 6.3 μM and median of only 3.3 μM. All but two of the samples have DIN < 1 μM. The DIN values observed in the Ivačičeva Cave ice are lower than the average DIN in ice of 15 μM and 24 μM observed respectively in Paradana Cave and Snežna Cave, two other ice caves in Slovenia studied (Carey et al. 2019). The similar values observed in the Triglav area glacier ice of 6.5 μM and the cave ice of 6.3 μM suggest that the DIN mass flux behaves conservatively in the glaciokarst flow systems in the Triglav area. The dissolved PO_4^{3-} concentrations were at or below 0.50 μM in all the samples with the majority of samples measuring < 0.1 μM, with very low values in the Skuta Glacier ice and in the cave ice (Table 1).

The DIN:P molar ratios varied widely, from app. 2 to 390 in the ice to a ratio of 622 in the spring water (Table 1). The glacier melt yielded DIN:P of 72 and 92.5, higher than those of aquatic vegetation (app. 16) but lower than DIN:P for trees of app. 165 (Sterner and Elser 2002). It is not clear what these large variations of dissolved N:P ratios mean or if they truly reflect any biogeochemical significance. The low PO_4^{3-}concentrations reflect its particle reactivity (and removal during the filtration step), and the presence of oxidizing conditions in all of these milieux.

4.2 Isotopic data

As noted above, the δ^{18}O and δD values fall close to the regional meteoric water line, suggesting little to no evaporation, sublimation, nor transpiration has occurred (Figure 5). The two glacier ice δ^{18}O samples had values of –8.9‰ and –8.7‰, while the glacier melt water was lighter, at –10.08‰. The Triglav Shaft ice had a greater range of δ^{18}O, –12.10‰ to –9.64‰ which may suggest a seasonal variation of snow and water input. This pattern may also represent even longer time variations than seasonal ones, as we do not know the true age of this material. However, the melt and spring waters are generally more enriched than the glacier ice values. Whether this enrichment is due to some evaporitic loss or melt actually being generated from ice (or more recent snow) with a heavier isotopic signature cannot be determined.

The cave ice samples show little variation in δ^{18}O, similar to what has been observed in the Snežna Cave ice app. 70 km to the east of the Triglav Glacier (Carey et al. 2019). This observation suggests that the ice from which we obtained samples may have originated from one water mass or from a constant or nearly constant isotopic source, as has been suggested previously for the Snežna Cave (Carey et al. 2019).

The unusual environmental setting of high elevation karst has allowed these ice caves to exist in a colder climate but continued warming (Hrvatin and Zorn 2017; 2018) will drive the loss of this part of the terrestrial cryosphere and perhaps the loss of the paleoclimate information contained therein. In addition, the terrestrial cryosphere will continue to transform in underground karst cryosphere, so the monitoring of the process is of essential.

5 Conclusion

We have sampled glacier ice, meltwater, spring water, and cave ice in the Triglav Glacier area and on the Skuta Glacier in the southeastern Alps (Slovenia) and analyzed these materials for major cations and anions, nutrients, and water stable isotopes. The samples primarily reflect the initial precipitation signal that has been greatly modified by the input of local $CaCO_3$-rich dust with lesser amounts of marine aerosol and vegetation debris. There is surprisingly little variation between the glacier ice and meltwater in their major elemental composition. The H_4SiO_4 also varies little, indicating the lack of silicate mineral weathering in those environments. The dissolved PO_4^{3-} concentrations are very low while the DIN concentrations vary by more than an order of magnitude. This produces DIN:P ratios that also vary greatly and thus limit our

Table 3: Comparison of mean chemistry from Triglav Glacier samples with Mt. Ortles snow pit chemistry (Gabrielli et al. 2010). Enrichment factors are calculated as Triglav Glacier chemistry divided by that of the Mt. Ortles snow pit.

Mean values	Cl μM	SO_4 μM	Na μM	K μM	Mg μM	Ca μM
Mt. Ortles snow pit at 3860 m	2.4	2.1	1.9	0.4	4.2	7.7
Mean Triglav Glacier	4.3	12.0	5.5	2.3	4.5	145
Mean Ivačičeva Cave ice	1.6	7.0				
Triglav Glacier enrichment factor	1.8	5.7	2.9	5.7	1.1	19.1

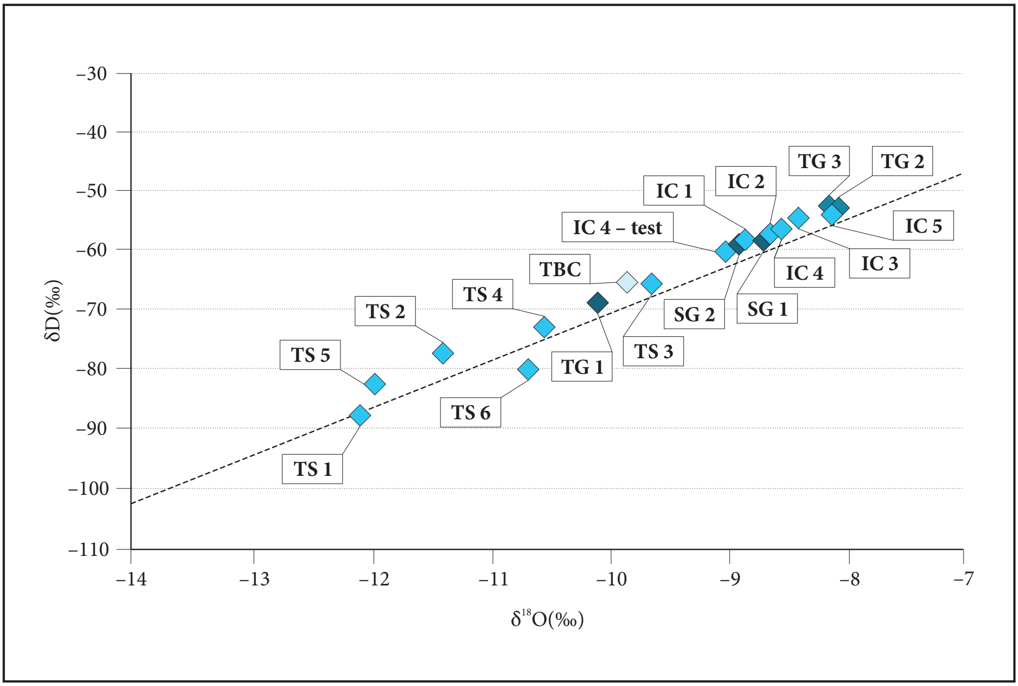


Figure 5: Triglav glacier area samples collected during 2017–2018. Also plotted is the regional meteoric water line for Slovenia of $\delta D=7.94*\delta^{18}O+9.029$ (regional line developed by Carey et al. 2019). Samples used to calculate the regional meteoric water line were collected at Global Network for Isotopes in Precipitation (GNIP) sites: Ljubljana (336 samples from 1981–2010), Portorož (84 samples from 2000–2006), and Kozina (39 samples from 2000–2003) (from data of Vreča et al. 2006; 2014). All GNIP data are available at the website of the International Atomic Energy Agency (Internet 1).

ability to evaluate the sources of and the ecological impacts of these nutrients within this environment. The $\delta^{18}O$ and δD values of the sample fall very close to the regional meteoric water line indicating very little modification of the primary precipitation by other processes, such as evaporation. The rapid loss of glacier ice, as documented by the on-going work of personnel from the ZRC SAZU Anton Melik Geographic Institute (e.g., Gabrovec 2013; 2014), and also the loss of cave ice, as documented by Mihevc (2018) and others (Colucci et al. 2016), suggest strongly that in this region of the southeastern Alps the cryosphere is rapidly being lost due to climate warming and the increasing summer temperatures will undoubtedly hasten the loss.

ACKNOWLEDGEMENTS: We are very grateful for the support from The Ohio State University's Slovene Research Initiative that supported the collaboration of Anne E. Carey and W. Berry Lyons with Matija Zorn, Blaž Komac, Jure Tičar, and Matej Lipar. Partial support came from research program no. P6-0101 and infrastructure programme no. I0-0031 of the Slovenian Research Agency.

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Acta geographica Slovenica, 60-2, 2020, 155–173

THICKNESS AND GEODETIC MASS BALANCE CHANGES FOR THE TRIGLAV GLACIER (SOUTHEASTERN ALPS) FROM 1952 TO 2016

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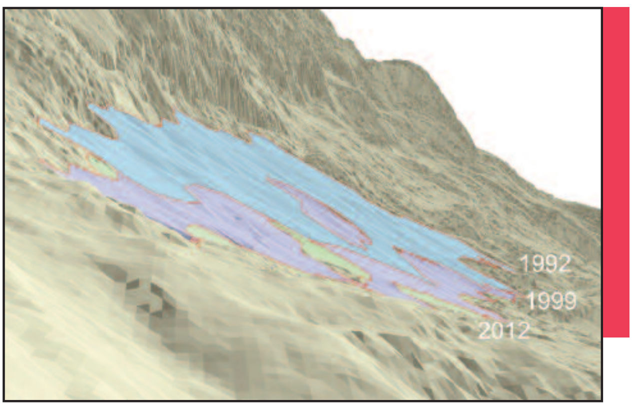

Side view of the extent of the Triglav Glacier in 1992, 1999, and 2012, covering approximately 1 hectare.

DOI: https://doi.org/10.3986/AGS.7673
UDC: 911.2:551.324.3(234.323.6) »1952/2016«
COBISS: 1.01

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Thickness and geodetic mass balance changes for the Triglav Glacier (southeastern Alps) from 1952 to 2016

ABSTRACT: Various geodetic and lidar measurements performed on the Triglav Glacier (Julian Alps, Slovenia) make it possible to study not only the extent of the glacier but also changes in its thickness and volume. These measurements also make it possible to calculate the geodetic mass balance of the glacier. Thickness and volume changes were calculated using glacier area measurements from 1952, 1975, and 1992, and annually between 1999 and 2016. The mean thickness decreased from 39.2 m in 1952 to 2.45 m in 2012. The maximum thickness decreased from 48.3 m in 1952 to 5.2 m in 2007. The mean specific mass balance was calculated for the area of 1 hectare that the glacier covered in 2016. From 1952 to 2016, the annual specific mass balance was -0.45 m w.e.a^{-1}.

KEY WORDS: climate change, glacier thickness, glacier volume, geodetic mass balance, Triglav Glacier, Slovenia

Spremembe debeline in geodetske masne bilance Triglavskega ledenika (jugovzhodne Alpe) v obdobju 1952–2016

POVZETEK: Različne geodetske in lidarske izmere velikosti Triglavskega ledenika omogočajo, poleg preučevanja sprememb njegove površine, tudi preučevanje sprememb debeline in prostornine. Poznavanje teh sprememb omogoča tudi izračun geodetske masne bilance ledenika. Za ugotavljanje sprememb debeline in prostornine, smo uporabili meritve površine ledenika v letih 1952, 1975, 1992 ter meritve med letoma 1999 in 2016. Povprečna debelina ledenika se je zmanjšala iz 39,2 m leta 1952 na 2,45 m leta 2012. Največja debelina pa se je zmanjšala iz 48,3 m leta 1952 na 5,2 m leta 2007. Letno specifično masno bilanco smo ugotavljali za območje velikosti 1,0 ha, ki ga je ledenik pokrival leta 2016. Povprečna specifična masna bilanca v celotnem obdobju 1952–2016 je bila $-0,45$ m w.e.a^{-1} (metri vodnega ekvivalenta na leto).

KLJUČNE BESEDE: podnebne spremembe, debelina ledenika, prostornina ledenika, geodetska masna bilanca, Triglavski ledenik, Slovenija

This article was submitted for publication on November 2nd, 2019.
Uredništvo je prejelo prispevek 2. novembra 2019.

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1 Introduction

Glacier area and volume changes are among the more visible consequences of climate change (Zängl and Hamberger 2004). Due to climate change, glaciers are disappearing worldwide (Zemp et al. 2015; Slater et al. 2020). In this regard, very small glaciers, or glacierets (Kumar 2011), such as the Triglav Glacier (Gabrovec et al. 2013, 2014), are especially threatened. Although small, these glaciers are still an important indicator of climate change (Lipar et al. 2021) because they respond to it more rapidly than larger glaciers (Brown, Harper, and Humphrey 2010; Colucci and Guglielmin 2015; Hughes 2018). In addition, small glaciers represent a numerically significant group, accounting for up to 80% of all glaciers located in mid- to low-latitude mountain ranges (Huss and Fischer 2016).

Changes in the area of the Triglav Glacier have been studied with direct measurements since 1946 (see Gabrovec et al. 2013, 2014 and references therein) and based on historical photographs and maps since 1829 (e.g., Triglav Čekada and Gabrovec 2013; Triglav Čekada, Zorn, and Colucci 2014; Triglav Čekada 2018). During the period studied, the glacier area decreased significantly (Figure 1), as did its thickness. Compared to area changes, which were studied in detail in the past (see Gabrovec et al. 2014), much less is known about thickness and volume changes. Based on geodetic measurements of the glacier in 1952 and 1999 and in 1952 and 2001, Gabrovec (2002a, 2002b) calculated the thickness and volume change. Verbič and Gabrovec (2002) calculated the volume of the Triglav Glacier based on ground-penetrating radar survey (GPRS) thickness measurements in 2000. Gabrovec (2008) later calculated the volumes of the Triglav Glacier for 1937, 1952, 1975, 1992, 1999, and 2005 based on photogrammetrically derived areas. Triglav Čekada and Gabrovec (2013) calculated the volumes of the glacier from 1976 to 2011 based on area measurements derived from non-metric photography, as well as using an empirical equation. The thickness of the glacier was also measured with GPRS in 2013. The GPRS thickness measurements were conducted at the same measuring points as in 2000 (Del Gobbo et al. 2016).

This article presents new calculations of thickness and volume changes as well as the first estimates of geodetic mass balance changes of the Triglav Glacier from 1952 to 2016. The calculations are based on digital terrain models (DTMs) developed based on geodetic tachymetric and photogrammetric area measurements of the glacier.

2 Data and methods

2.1 Geodetic, photogrammetric, and lidar measurements

Geodetic measurements on the Triglav Glacier have been performed regularly since 1999 (Triglav Čekada and Gabrovec 2008; Gabrovec et al. 2013, 2014), but the first tachymetric measurement was already made in 1952. Geodetic measurements made it possible to develop the DTMs that were used for thickness and volume calculations (Section 2.2.). The DTMs were derived from tachymetric or photogrammetrically acquired contour lines, and individual points on the surface of the glacier and glacier's perimeter.

Photogrammetric measurements were carried out with a calibrated medium-format Rolleimetric 6006 photogrammetric camera. Stereo photogrammetric measurements were conducted based on measured reference points by tachymetry and terrestrial or aerial photogrammetrically derived images. The results are presented on a map with a scale of 1:1,000 and a 5 m contour interval. The points on the surface of the glacier were measured at a density that depended on the annual area of the glacier, mostly at points where the terrain varied significantly, and so their number varies from year to year. The horizontal accuracy of these maps can be analytically estimated to be better than 20 cm (Triglav Čekada, Crosilla and Kosmatin Fras 2010), and vertical accuracy to be better than 0.5 m (taking into account, for example, the accuracy of control points used).

In addition to the detailed measurements of the glacier's area, the broader area around the glacier was measured three times between 1999 and 2016. In 2005, a special aerial stereo photogrammetric survey was performed with a large-format Leica RC 30 camera (Gabrovec et al. 2014) with an imaging scale of 1:4,000. A stereophotogrammetric acquisition of the area covering the approximate extent of the glacier in 1952 was performed. The results were mapped at a scale of 1:1,000.

In 2012 two aerial laser scanning surveys (lidar) were performed. The first lidar survey of the broader area around the Triglav Glacier was performed at the end of the accumulation period, on May 18th, 2012, and the second almost at the end of the ablation period, on September 18th, 2012 (Triglav Čekada et al. 2013). The latter was used in this study because it represents the local minimum of the glacier's area and depth. In both cases, a Riegl LM5600 laser scanner was used with a wavelength of 1550 nm, an average density of all points at 8 points/m^2, and an average flying height 700 m above the ground. Within the framework of the national aerial laser scanning of Slovenia, the broader area was again surveyed by lidar on August 8th, 2014 with a Riegl LMS-Q780 laser scanner with a wavelength of 1064 nm, an average density of 5 points/m^2, and a flying height 1000 m above the ground. The analytically determined vertical accuracy of all three lidar surveys is better than 30 cm, derived from equipment specifications and applied flying height above the ground (Triglav Čekada, Crosilla and Kosmatin Fras 2009). In 2014, a tachymetric survey of the glacier was also performed, and it was used to calculate the volume differences for 2014 (Figure 4) because lidar shows the glacier still very much under the snow. In all three lidar cases, a DTM with a cell size of 1 × 1 m was created from the laser point clouds.

The glacier measurements for 1975 and 1992 were based on stereo photogrammetric acquisition from the large-format Cyclical Aerial Surveying of Slovenia (CAS) aerial photographs. The results were mapped at a scale of 1:5,000, and the contour interval is 5 m. For 1992, a DTM with a cell size of 10 × 10 m was also created. CAS aerial photographs for 1975 were oriented in the D48/GK national coordinate system based on five identical reference points, which were clearly visible on the stereo images of special aerial photography from 2005. CAS aerial photographs for 1992 were oriented based on nine reference points from the 2005 stereo images. Due to the shadow cast by the peak of Mount Triglav on the central part of a snow-covered area of the glacier, the orientation and stereo acquisition of data from the 1975 imagery was more challenging. Thus, the resulting lower contrast inside the shadow area may have resulted in higher vertical errors.

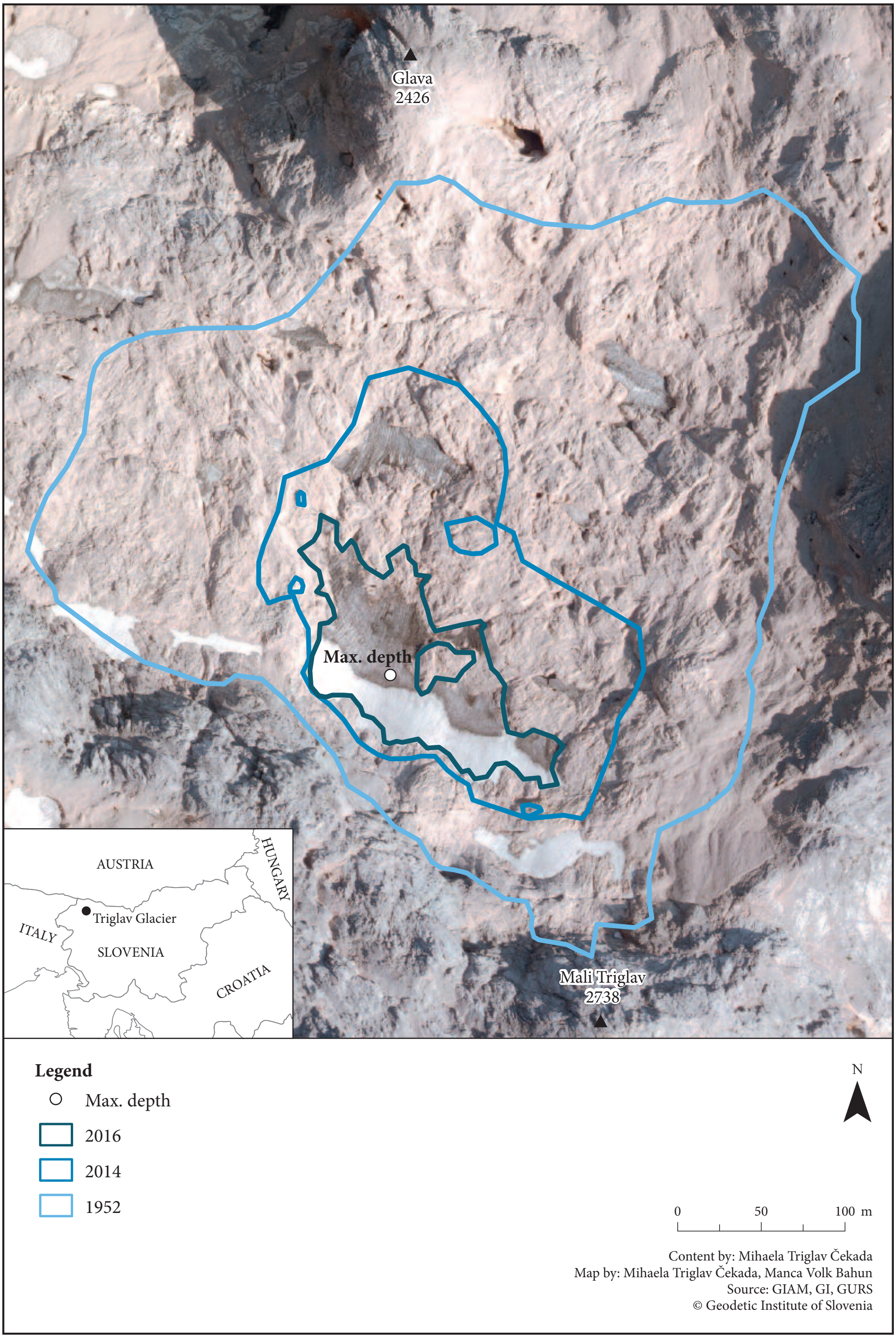
The area of the glacier was geodetically measured on September 8th, 2013, two weeks before the GPRS survey (September 22nd–24th, 2013; Del Gobbo et al. 2016). The 2013 DTM was created using both measurements: the glacier perimeter and points on the glacier's surface from the first measurement, and additional geodetic points from the glacier surface from the second one.

The measuring techniques used in the study years for area measurements are shown in Table 1. For 1975 and 2001, no areas are given because in these years the glacier was completely snow-covered. In these years the CAS photos were made in mid- and late October and the glacier was already covered with snow

Table 1: Measuring techniques applied for the Triglav Glacier area measurements (*snow-covered glacier).

Year	Survey/source date	Measuring techniques	Scale	Glacier area (hectares)
1952	October 4	Tachymetry	1:2,500	14.0
1975	October 29	Cyclical Aerial Surveying of Slovenia	1:5,000	*–
1992	September 8	Cyclical Aerial Surveying of Slovenia	1:5,000	4.3
1999	September 13–15	Medium-format aerial photogrammetric survey and tachymetry	1:1,000	1.1*
2001	October 16–17	Medium-format aerial photogrammetric survey and tachymetry	1:1,000	*–
2003	August 26–27	Medium-format aerial photogrammetric survey and tachymetry	1:1,000	0.6
2005	August 24–25	Special large-format aerial photogrammetric survey	1:1,000	1.2*
2007	September 13	Tachymetry and medium-format terrestrial photogrammetric survey	1:1,000	0.6
2008	August 27–28	Tachymetry and medium-format terrestrial photogrammetric survey	1:1,000	1.1*
2009	September 22–23	Tachymetry and medium-format terrestrial photogrammetric survey	1:1,000	0.6
2010	September 14–15	Tachymetry and medium-format terrestrial photogrammetric survey	1:1,000	2.5*
2011	September 13–14	Tachymetry and medium-format terrestrial photogrammetric survey	1:1,000	2.4*
2012	September 18	Special aerial laser scanning (lidar)		0.6
2013	September 8	Tachymetry and medium-format terrestrial photogrammetric survey	1:1,000	2.5*
2014	August 25	Tachymetry and medium-format terrestrial photogrammetric survey	1:1,000	3.6
2015	September 9–10	Tachymetry and medium-format terrestrial photogrammetric survey	1:1,000	1.7*
2016	September 24	Tachymetry and medium-format terrestrial photogrammetric survey	1:1,000	1.0*

Figure 1: The Triglav Glacier area in 1952, 2014, and 2016 presented on an orthophoto from August 26th, 2017. The location of the measured maximum thickness by GPRS from 2013 is marked »Max. depth.« ➤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Triglav Glacier
ITALY
SLOVENIA
CROATIA
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1952
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100 m
Content by: Mihaela Triglav Čekada
Map by: Mihaela Triglav Čekada, Manca Volk Bahun
Source: GIAM, GI, GURS
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(less than a meter thick) of a new accumulation season (Gabrovec et al. 2014), which has to be taken into account when interpreting the results. For the 1992 CAS photos, only the area of exposed ice is given, not including surrounding snow fields. Between 1999 and 2016, the area studied was mostly snow-covered. The glacier's actual snow-free area was only measured in 2003, 2007, 2009, and 2012.

Using area measurements, DTMs for all the study years were created and used for further thickness and volume calculations.

2.2 Thickness and volume

The relative thickness of the glacier, which is the vertical height difference between two years studied (Figure 2; Table 2), was calculated as the height difference between the two cells at the same location in the two DTMs applied (Figures 3, 4, and 6). During the glacier area measurements, glacier ice was not always exposed because at the end of the ablation period it was still covered with firn or snow (Table 1). For these years the calculated thickness and volume refer to the entire (i.e., combined) thickness of ice, firn, and snow, and not only the thickness of the ice.

The mean relative thickness of the glacier was calculated as the change in relative thickness in an area for which the volume change was studied; that is, for 14 hectares that the glacier covered in 1952 and for 1 hectare that the glacier covered in 2016. Because 2012 represents the glacier minimum in the period studied, sometimes (e.g., Table 3) the changes in relative thickness refer to the thickness change between the year studied and 2012.

The mean absolute thickness of the glacier (i.e., the mean difference between the surface of the glacier and the bedrock) was obtained taking into the account the mean relative thickness along with the GPRS measurements from 2013 (Del Gobbo et al. 2016). The 2013 GPRS measurements showed an ice layer averaging 1.95 m thick and a firn layer averaging 3 m thick (a total of 4.95 m).

To obtain the mean absolute thickness for 2012 as the glacier minimum in the period studied, 2.5 m (a mean relative thickness between 2013 and 2012) was subtracted from the 2013 GPRS-measured mean absolute thickness of 4.95 m (Del Gobbo et al. 2016) to obtain 2.45 m as the mean absolute thickness for 2012 (Figure 5).

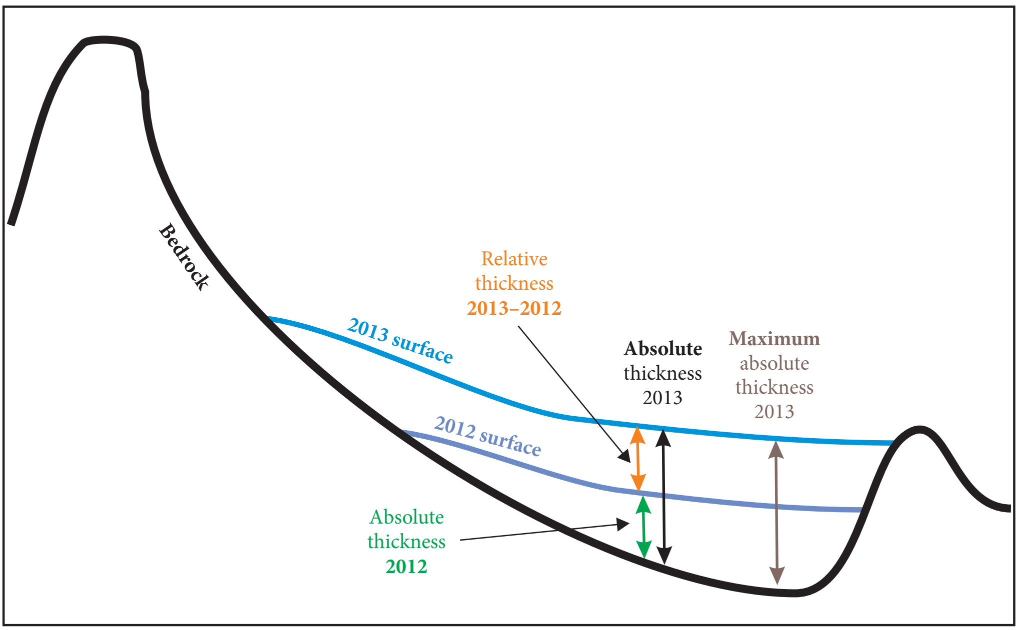


Figure 2: Sketch of relative and absolute thicknesses. The calculations refer to vertical thickness.

The maximum absolute thickness of the glacier was obtained for the location (cell) where the GPRS measurements in 2013 gave the maximum thickness of the glacier (Figure 1). For this cell, first the relative thickness between the year studied and 2013 was calculated. If the glacier was thicker in the year studied, then a layer of ice 5 m thick and layer of firn 3 m thick (8 m in total) from 2013 GPRS measurements (Del Gobbo et al. 2016) were added to the relative thickness, resulting in the maximum absolute thickness. If, in the year studied, the glacier was thinner than in 2013, the mean relative thickness was subtracted from the GPRS measurements from 2013 to obtain the maximum absolute thickness (Figure 5).

The volumetric changes of the glacier for 1952, 1975, 1992, 2001, 2005, 2012, and 2014 were calculated for an area of 14 hectares covered by the glacier in 1952 (Figure 3). Because the area of the glacier from 1999 to 2016 varied between 2.5 and 1 hectares, the volumetric changes in this period were also calculated for the area of 1 hectare that the glacier covered in 2016 (Figures 1 and 6). To allow better comparison through the entire period studied, the 1-hectare area from 2016 was also used for the volumetric change calculations for 1952, 1975, and 1992 (Tables 3 and 4).

The volumes were calculated using ArcGIS software, which allows calculation of volumes by producing a closed TIN (triangulated irregular network) by combining contour lines and individual points on the surface of the glacier and perimeter of the glacier. The TIN was then interpolated to a DTM raster with a grid size of 5 × 5 m.

2.3 Geodetic mass balance

Mass balance was introduced to compare changes in the mass of different glaciers. It describes the decrease or increase in the glacier's mass in the period studied. The mass balance is a product of volume change and the density of material in that volume. The mass balance can be measured directly (e.g., the glaciological mass balance) or indirectly (e.g., the geodetic mass balance, measured by geodetic methods; Tihbert et al. 2008; Zemp et al. 2010; Fischer 2011). Thus the geodetic mass balance can be calculated for all glaciers on which volumetric changes can be calculated and for which information is available on the density of snow, firn, and ice that has melted or newly accumulated (Fischer 2011; Huss 2013).

The mass balance measured for a specific location on the glacier is known as a specific mass balance and is described by the meters of water equivalent [m w.e.], or for the annual (net) specific mass balance in meters of water equivalent per year [m w.e. a^{-1}] (Benn and Evans 2010; Fischer 2011).

In the case of the Triglav Glacier, one glacial year was used as the base unit because geodetic measurements were mainly conducted at the end of the ablation period. For calculating the mass balance, an area of 1 hectare was used, which the glacier covered in 2016.

The use of adequate snow and ice densities is essential when calculating the mass balance. For example, newly fallen snow has a density between 50 and 200 kg/m^3, firn (snow that has survived at least one ablation period) between 400 and 830 kg/m^3, and glacial ice 830 to 917 kg/m^3 (Benn and Evans 2010). However, in geodetic mass balance calculation, a uniform density for the entire volume change is often applied. For larger alpine-type glaciers, an average value of 850 kg/m^3 is often used (Zemp et al. 2010; Fischer 2011). Thibert et al. (2008) give a density of 600 kg/m^3 for firn measured in the summer and autumn months. According to another source, this density is characteristic for firn at a depth of about 15 m, whereas it is 500 kg/m^3 at a depth of about 5 m (Schwerzmann et al. 2006). Huss (2013) gives two values, 600 kg/m^3 and 700 kg/m^3, for firn in the Alps for average depths up to 10 m.

On the Triglav Glacier, different layer densities were measured during the 2013 GPRS survey. A cross-section 1.75 m deep was dug into the firn. The first 20 cm represented a layer of new snow, which was deposited in early September, shortly before the measurements were conducted, and it had a density of 375 kg/m^3, whereas a density of 600 kg/m^3 was measured from 30 cm to the bottom of the cross-section (Del Gobbo et al. 2016).

In our calculations we used a uniform density of 600 kg/m^3 for the whole period studied (Section 3.2). In the period 1952 to 1999 most of the lost thickness was due to the loss of glacier ice and in the period after 1999 most of the lost thickness was due to the loss firn and snow. In Figure 8 a comparison of mass balance is given for the period 1952 to 1999 taking into account a density of 860 kg/m^3 (e.g., Zemp et al. 2010, 2015; Shahgedanova et al. 2012; Fischer, Huss, and Hoelzle 2015; Huss, Dhulst and Bauder 2015) and a density of 600 kg/m^3.

3 Results and discussion

3.1 Thickness and volume

For the years for which the broader area of the Triglav Glacier was surveyed (1952, 1975, 1992, 2001, 2005, 2012, and 2014; i.e., 14 hectares that the glacier covered in 1952), the raster of relative thicknesses was calculated between the DTM for a selected year and the September 2012 DTM because the latter represents one of the glaciers' minimums in the period studied.

Figure 3 shows some reddish parts, which is the result of orientation errors contained in the DTMs from 1952, 1975, and 2001. These three years were transformed or oriented into the national coordinate system using a smaller number of reference points, all of which were inside the 14-hectare area; they were specifically located only around the narrow area representing the current glacier and Mount Glava. This results in the reddish parts mainly appearing in the east in the 1952 raster, in the east and west in 1975, and mainly in the west in 2001. In comparison, the model from 1992 is much better oriented because its orientation is based on nine points and not only five, as in the case of 1975. For these years, the vertical accuracy is mostly ± 2 m or better, but poorer vertical accuracy may be expected for 1975 due to the problems with stereo photogrammetric acquisition mentioned in Section 2.1 (more details are provided in Gabrovec 2008 and Gabrovec et al. 2009). Gabrovec (2008) argues that due to this the volume for 1975 is most probably underestimated.

In Figure 3, relative thickness up to 2 m is shown in white and light gray. Especially for the DTMs for 1952, 1975, and 1992, it must be taken into account that this may be in the domain of vertical errors. The relative thicknesses up to 10 m are shown in yellowish-green shades, and higher relative thicknesses are in shades of blue.

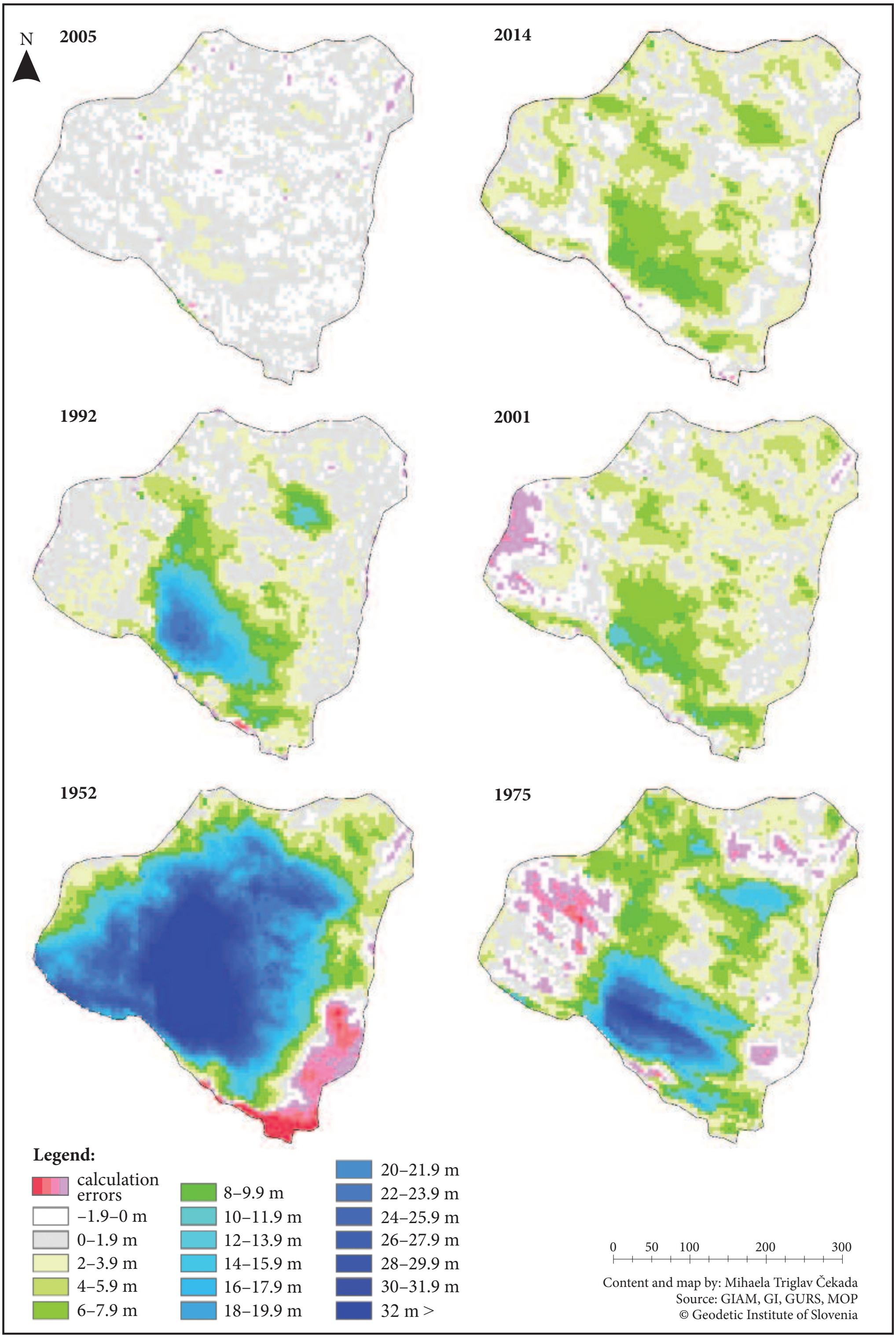
The 2001 and 2014 calculations show almost the same amount of snow and firn because in these glacial years the weather conditions were favorable (e.g., Vrhovec and Velkavrh 2001) for glacier preservation and the glacier ice remained hidden under the firn through the entire ablation period. The highest relative thicknesses can be found along Mount Triglav's rock wall (the southern side on the images in Figure 3); that is, in the area where the glacier has persisted for the last two decades. Similar relative thicknesses as in 2001 and 2014 can also be seen in Figure 4, where the relative thicknesses between the end of the accumulation period and the end of the ablation period in 2012 are presented (May–September). The snow accumulates in certain karst depression regardless of the year observed as a result of favorable microrelief conditions. There was on average 4.2 m more snow and firn in May compared to September 2012 (Figure 4).

Table 2: Changes in mean relative thickness and relative volume of the Triglav Glacier for the 14-hectare area covered by the glacier in 1952 and between two measurements in 2012 (*vertical accuracy for calculating mean relative thickness is ± 2 m or better, except for 1975, for which it may be poorer; **vertical accuracy is ± 0.6 m or better).

Period studied	Changes in mean relative thickness* (m)	Changes in annual mean relative thickness (m/year)	Changes in relative volume ('000 m^3)
1975–1952	−10.0	−0.44	−1,407
1992–1975	−1.5	−0.09	−207
2001–1992	−1.3	−0.14	−181
2005–2001	−2.6	−0.64	−360
2012–2005	−0.4	−0.05	−51
2014–2012	2.9	1.46	411
September–May 2012	−4.2**		−591

Table 2 presents changes in relative thickness and relative volume between the years studied and the two measurements in 2012. The thickness and volume decrease is especially noticeable in the first two and

Figure 3: Relative thicknesses of the Triglav Glacier in 1952, 1975, 1992, 2001, 2005, and 2014 relative to the 2012 DTM. The maps present the area of 14 hectares covered by the glacier in 1952. The grid cell size is 5 × 5 m. The vertical accuracy for calculating mean relative thickness is ± 2 m or better (except for 1975, for which it may be poorer). In reddish areas, the thickness calculation is not correct due to the errors within DTMs. ➤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Content and map by: Mihaela Triglav Čekada
Source: GIAM, GI, GURS, MOP
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a half decades and at the beginning of the twenty-first century. The change in the first two and a half decades was also noticed by Gabrovec (2008) and Triglav Čekada and Gabrovec (2013; Table 3). Due to favorable years for snow accumulation on the glacier from 2012 to 2014, glacier thickness increased, but as shown in Table 4 the decreasing trend continued in the following years (Figure 6).

Table 3 presents the mean relative thickness and relative volumes relative to 2012 compared to volume calculations previously published in the literature. To be able to directly compare our relative volumes with absolute volumes in the literature, one has to add to the relative volumes a volume of 14,700 m^3 (ice and firn) that the glacier amounted to in 2012. The 2012 volume was calculated from the area in 2012 (0.6 hectares; Table 1) and the mean glacier thickness in 2012 (2.45 m; see Section 2.2).These study's volume calculations are to some extent comparable with the volumes given by Gabrovec (2008) based on photogrammetrically derived areas and using the same data sources, although higher. Similar is true compared with values in Triglav Čekada and Gabrovec (2013) except for 1975, where our calculation is much lower, which may be connected to vertical errors for the 1975 calculation (see Section 2.1). The difference may also be attributed to the calculation errors of the source cited because the calculations are based on terrestrial non-metric photography and on an empirical equation. On the other hand, our calculations are much higher compared to the values in Gabrovec (2002b), which were acquired from DTMs based on the topographical maps of the glacier.

Some differences between our calculations and those from the literature may also partly be attributed to large thickness variability on very small glaciers, which cannot be satisfactorily summarized in empirical models. For the same reason, our glacier's mean relative thickness in 1975 is smaller than in 1992 because the former was calculated for a much larger area than the latter. This is not the case if the calculations are

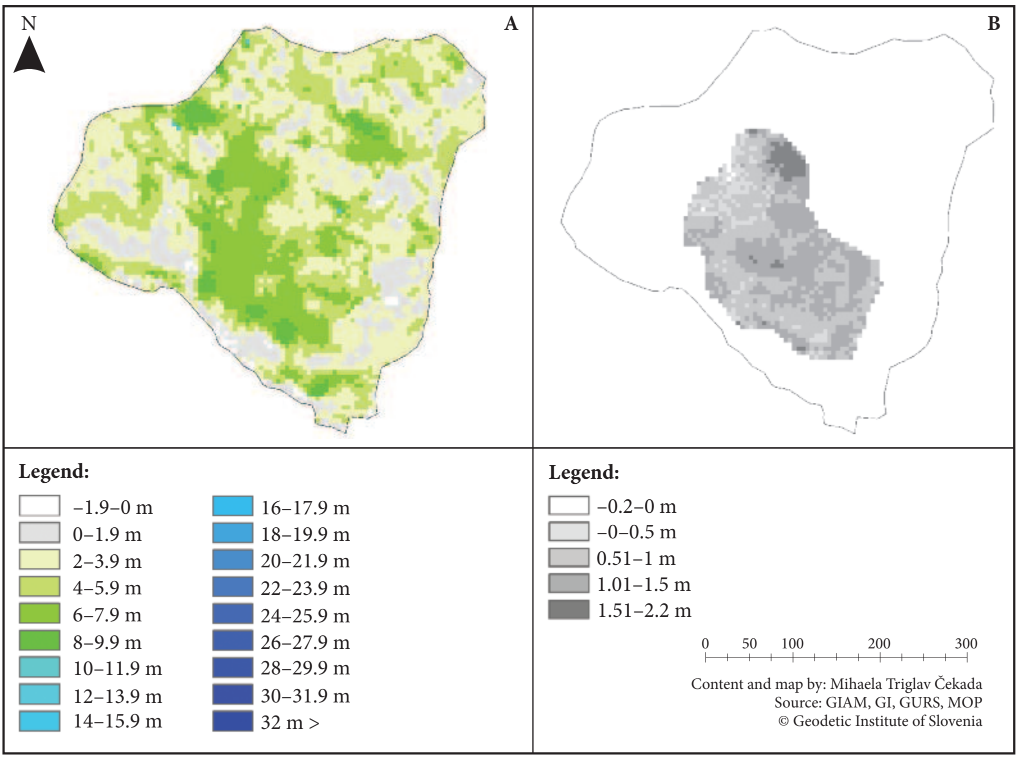


Figure 4: Relative thicknesses of the Triglav Glacier: a) between May and September 2012 and b) between August 8th and 25th, 2014 (the former is based on lidar data and the latter on the tachymetric survey). The grid cell size is 5 × 5 m. The vertical accuracy for calculating mean relative thickness is ± 0.6 m or better.

made only for the area of 1 hectare that the glacier covered in 2016 (Table 3). Calculations for the area of 1 hectare that the glacier covered in 2016 were primarily made from 1999 to 2016 (Figure 6) because during this period the area of the glacier mainly did not exceed 1 to 2.5 hectares (Table 1).

Table 3: Mean relative thickness (*vertical accuracy for calculating mean relative thickness is ± 2 m or better; except for 1975, for which it may be poorer), relative volume of the Triglav Glacier relative to 2012, and absolute volume. Columns 4, 7, 8, and 9 are summarized from the literature (for area, see Table 1): Gabrovec (2002b), Gabrovec (2008), and Triglav Čekada and Gabrovec (2013; two calculations) (**glacier area in 2016).

Survey/ source date	Study area (hectares)	Mean relative thickness* relative to glacier height in 2012 (m)	Mean thickness by Triglav Čekada and Gabrovec (2013) (m)	Relative volume relative to glacier height 2012 ('000 m^3)	Absolute volume ('000 m^3)	Volume by Gabrovec (2002b) ('000 m^3)	Volume by Gabrovec (2008) ('000 m^3)	Volume by Triglav Čekada and Gabrovec (2013) ('000 m^3)
October 4, 1952	14.0/1.0**	15.7/36.8**	–	2,206	2,221	1,500	2,000	–
October 29, 1975	14.0/1.0**	5.7/22.3**	14.5 (1976)	799	814	–	700	1,408/ 2,171.7 (1976)
September 8, 1992	14.0/1.0**	9.4/17.6**	9.3	406	421	>135	400	356/398.5
September 15, 1999	1.0**	5.4**	5.7	56	71	35 (2001)	60	60/70.5
August 25, 2005	1.0**	1.7**	5.7	17	32	–	20	5.8/27.5
September 15, 2010	1.0**	4.3**	4.6	43	58	–	–	27.5
September 24, 2016	1.0**	1.0**	–	10	25	–	–	–

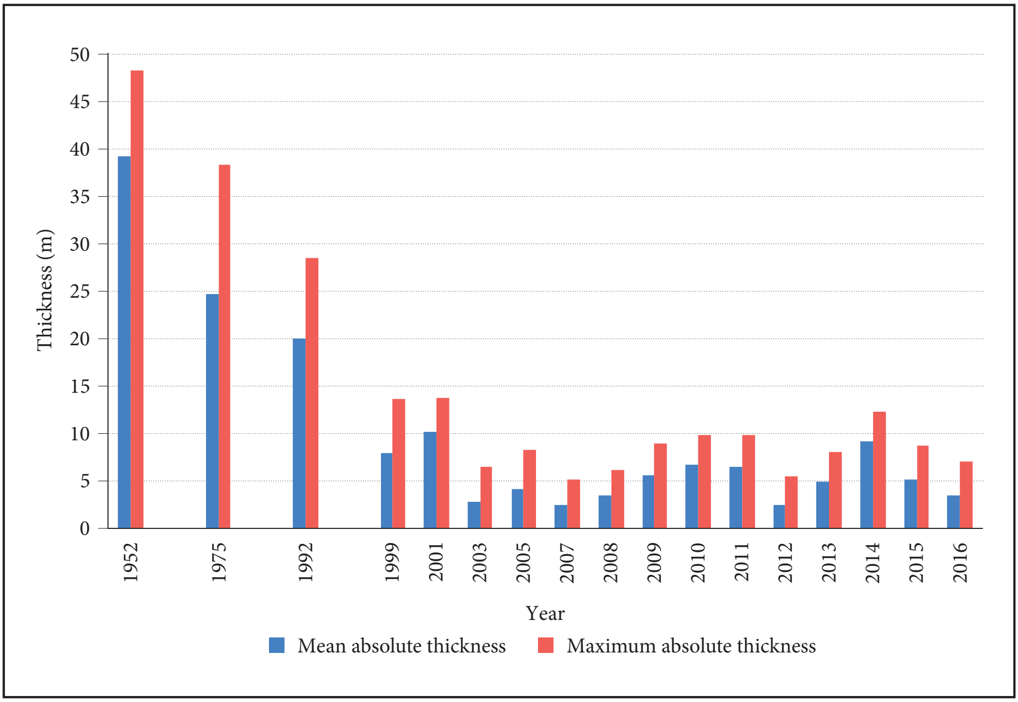


Figure 5: Mean absolute thickness and maximum absolute thickness (including ice, firn, and snow) of the Triglav Glacier from 1952 to 2016. Mean absolute thickness is calculated from relative thickness between the selected year and 2012 for an area of 1 hectare and taking into the account GPRS 2013 mean absolute thickness. Maximum absolute thickness was calculated for the location of maximum GPRS thickness in 2013.

Our volumes are also much higher compared to the volumes calculated from GPRS measurements. According to the GPRS measurements, in 2000 the glacier volume was about 35,000 m³ (Verbič and Gabrovec 2002) and in 2013 about 7,400 m³ (Del Gobbo et al. 2016). The differences may partly be attributed to the errors connected with our modeling, but also with the fact that our glacier volumes contain a combined volume of ice, firn, and snow, and not only ice volumes, as is the case with the GPRS measurements.

Figure 5 shows that during the period studied the glacier's maximum absolute thickness decreased from 48.3 m (in 1952) to 5.2 m (in 2007), and its mean absolute thickness from 39.2 m (in 1952) to 2.45 m (in 2012). Similar thinning was reported by Gabrovec (2002a, 2000b), who calculated a thickness decrease up to 35 m for a shorter period (1952–1999/2001).

The lowest mean absolute thicknesses of the glacier were calculated for 2003, 2007, 2008, 2012, and 2016. In these years, the mean absolute thickness did not exceed 3.5 m. Even in these years, the glacial ice was still preserved under a layer of firn because the mean thickness of ice does not exceed 1.95 m, as mentioned above in the description of the 2013 GPRS measurement. In addition, the maximum absolute thicknesses in these years, measured for the same location where the maximum thickness was measured by GPRS in 2013, did not exceed 6.5 m.

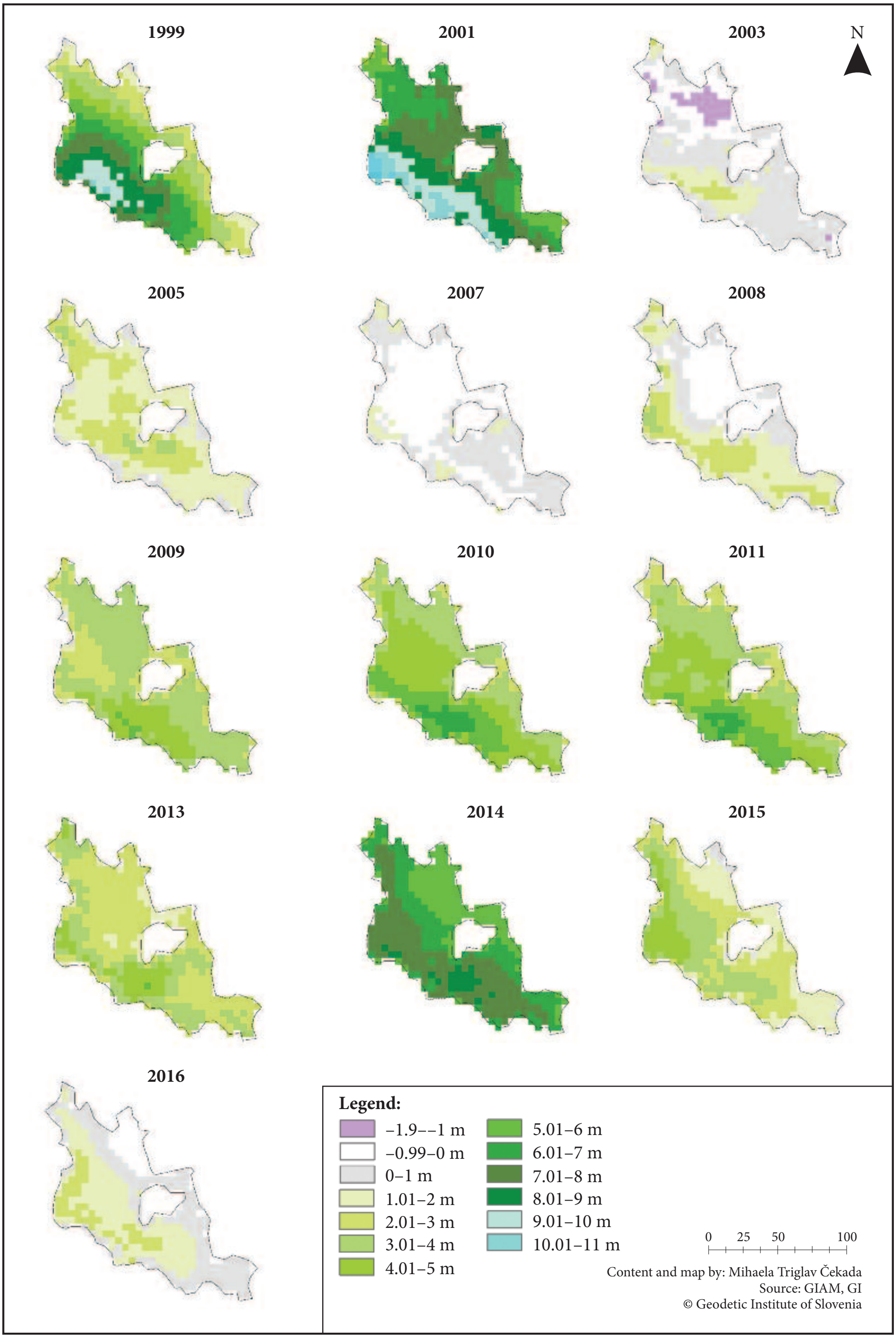
Table 3 compares our mean relative thicknesses to the glacier mean thicknesses in Triglav Čekada and Gabrovec (2013). To be able to directly compare our relative thicknesses with those from the literature, it is necessary to add a mean glacier thickness from 2012 (2.45 m; see Section 2.2) to the relative thicknesses. For 1975 and 2005, our calculations of the mean glacier thickness are lower, and for 1992, 1999, and 2010 they are higher than in Triglav Čekada and Gabrovec (2013). Here the differences can also be attributed to the different methods and errors connected with the sources used.

Figure 6 shows the differences in the relative glacier thickness (together for ice, firn, and snow) from 1999 to 2016 relative to 2012. In the favorable years for the glacier (1999, 2001, 2010, 2011, and 2014), surplus masses accumulated at the southern (i.e., the upper, highest, and steepest) part of the glacier alongside Mount Triglav's rock wall. In 2003, 2007, and 2008, the thickness of the glacier was almost the same as in 2012. The mass deficit is seen in the northern (i.e., the lower) part of the glacier. During six years between 2009 and 2014, excluding 2012, the glacier thickness increased. In 2015 and 2016 the glacier thinned again (Table 4).

Table 4: Changes in mean relative thickness (*vertical accuracy for calculating mean relative thickness is ± 2 m or better; except for 1975, for which it may be poorer) and annual mean relative thickness as well as changes in relative volume for the area of 1 hectare that the Triglav Glacier covered in 2016.

Time difference	Changes in mean relative thickness* (m)	Changes in annual mean relative thickness (m/year)	Changes in relative volume ('000 m³)
1975–1952	−14.5	−0.6	−149
1992–1975	−4.7	−0.3	−49
1999–1992	−12.1	−1.7	−124
2001–1999	2.3	1.2	23
2003–2001	−7.4	−3.7	−76
2005–2003	1.4	0.7	15
2007–2005	−1.7	−0.9	−17
2008–2007	1.0	1.0	10
2009–2008	2.1	2.1	21
2010–2009	1.2	1.2	12
2011–2010	−0.3	−0.3	−3
2012–2011	−4.0	−4.0	−41
2013–2012	2.6	2.6	27
2014–2013	4.1	4.1	42
2015–2014	−5.0	−5.0	−51
2016–2015	−1.8	−1.8	−17

Figure 6: Relative thicknesses of the Triglav Glacier relative to 2012 in the area of 1 hectare covered by the glacier in 2016. The grid cell size is 5 × 5 m. Vertical accuracy for calculating mean relative thickness is ± 2 m or better. ➤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Content and map by: Mihaela Triglav Čekada
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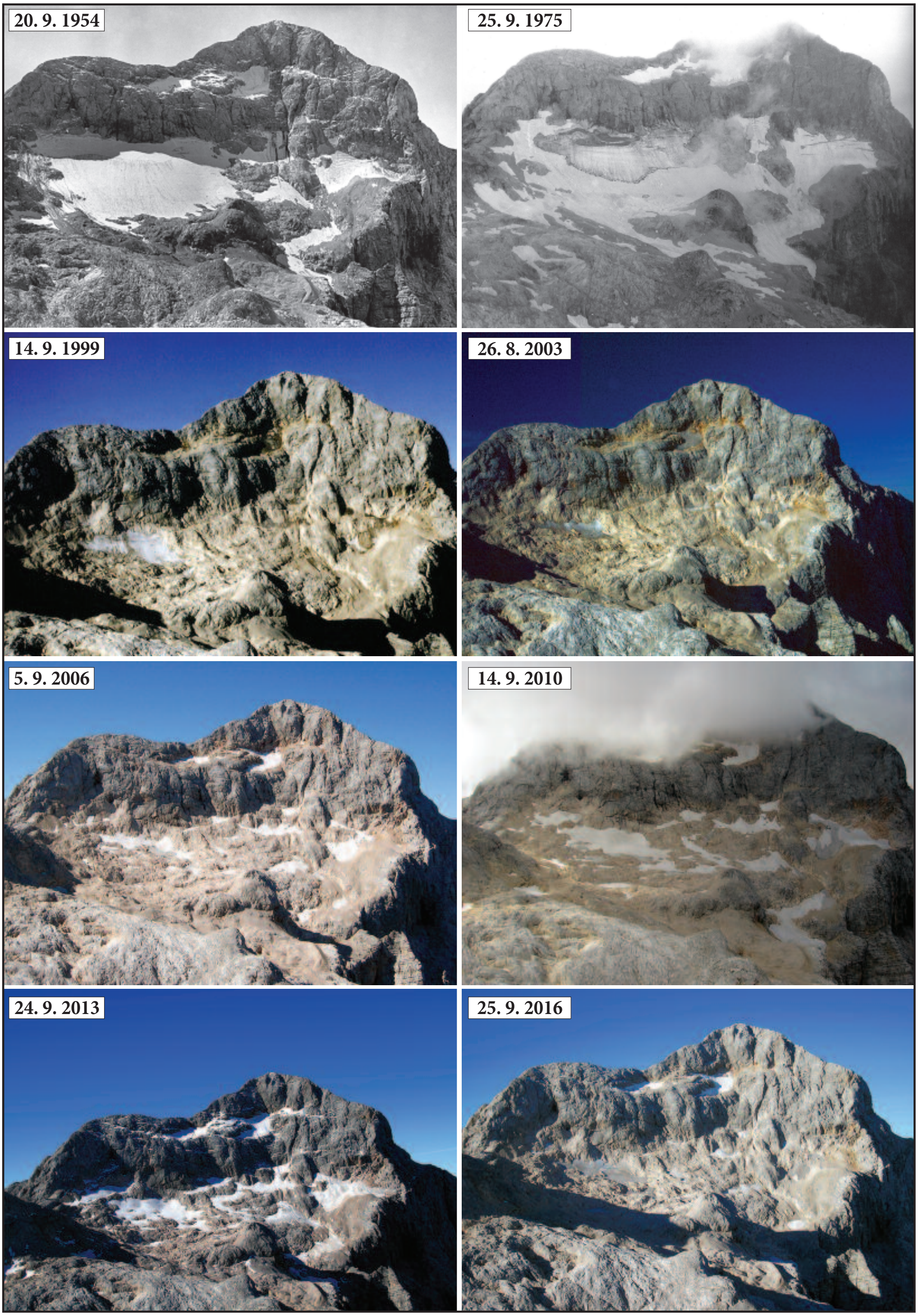

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Figure 7: The Triglav Glacier in selected years from 1954 to 2016.

Table 4 presents the inter-annual mean relative thicknesses and relative volumes of the Triglav Glacier, which were calculated for the area of 1 hectare covered by the glacier in 2016. In this area, the glacier thinned on average by 0.6 m per year between 1952 and 2016. The most significant reduction of relative thickness occurred from 1992 to 1999, when the glacier thinned on average by 1.7 m per year. Similar is reported by Gabrovec (2002a), who stated that the glacier thinned by 1 to 2 m annually in the late 1980s, and by 2 m at the beginning of the 1990s.

From 1999 to 2016, it thinned on average by 0.3 m per year, between 1999 and 2009 by 0.2 m per year, and between 2009 and 2016 by 0.5 m per year. The last can be attributed to accelerated thinning of the glacier in 2015 and 2016, when it thinned by 5 m in the glacier year 2014–2015 and 1.8 m in the glacier year 2015–2016. Figure 5 shows that all the surplus that accumulated on the glacier in 2013 and 2014 melted in 2015 and 2016.

For the Slovenian Alps, considerable changes in glacier thickness in the last half century are also reported for the Skuta Glacier (Triglav Čekada et al. 2020).

3.2 Mass balance

The mean specific mass balance between 1952 and 2007 was negative, between 2007 and 2010 it was positive, and it has fluctuated significantly in the last decade (Figure 8). The fluctuations can be explained by high accumulation of snow that fell on the glacier in favorable (i.e., snow-rich) years, and the total melting of this snow in the next (for the glacier, unfavorable) year. The annual mean specific mass balances for 1952 to 2016 are shown in Figure 9, where cumulative mass balances are also given.

The average annual specific mass balance for the entire period studied (1952–2016) was –0.45 m w.e.a^{-1}. This value is similar to the long-term average specific mass balance of –0.39 m w.e.a^{-1} for all Swiss glaciers

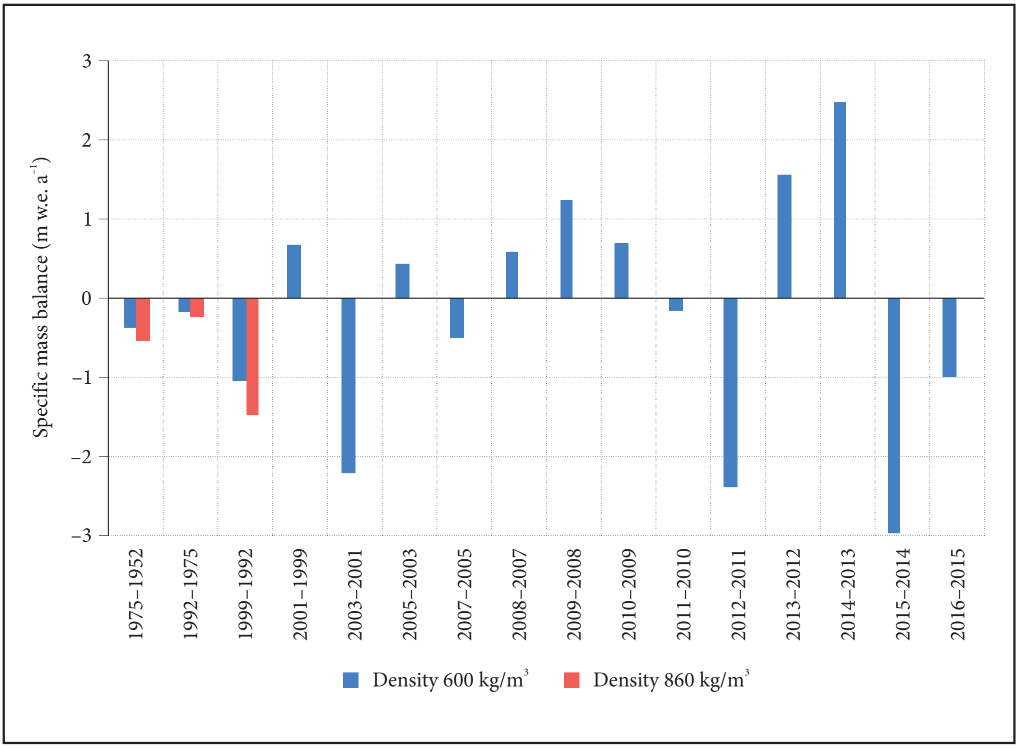

Figure 8: Mean specific mass balance for the area of 1 hectare that the Triglav Glacier covered in 2016.

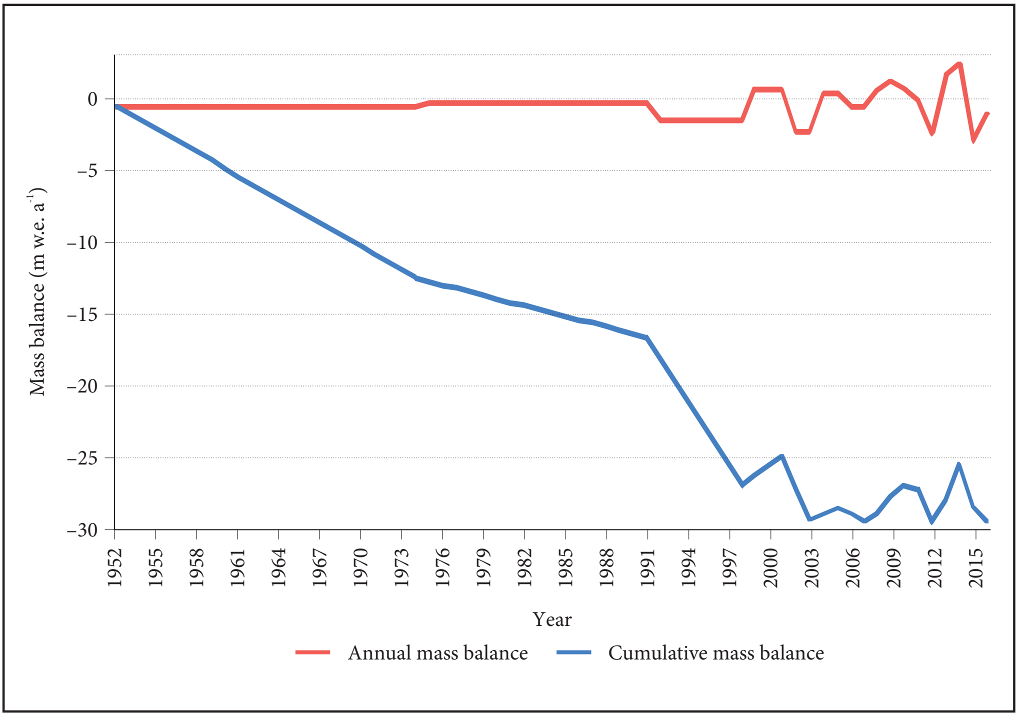

Figure 9: Annual specific mass balance and cumulative mass balance for the area of 1 hectare that the Triglav Glacier covered in 2016 (for uniform density 600 kg/m^3).

from 1969 to 2006 (Fischer, Huss, and Hoelzle 2015) and –0.62 m w.e.a^{-1} for the French Sarennes Glacier from 1952 to 2003 (Thibert et al. 2008).

After the turn of the century, the average annual mean specific mass balance on the Triglav Glacier was –0.07 m w.e.a^{-1} from 1999 to 2009, –0.26 m w.e.a^{-1} from 2010 to 2016, and –0.14 m w.e.a^{-1} from 1999 to 2016. Comparing these data with the data for other Alpine glaciers from 1999 to 2009, it can be seen that the trend of annual specific mass balances for other European Alpine glaciers was predominantly negative and higher than that of the Triglav Glacier. Huss (2012) states for entire European Alps an annual specific mass balance of –0.99 m w.e.a^{-1} and Hagg et al. (2012) give specific mass balance values between –0.9 m w.e.a^{-1} and –0.5 m w.e.a^{-1} for the group of five small glaciers in the Bavarian Alps. Zemp et al. (2015) give an average geodetically derived mass balance of –0.70 m w.e.a^{-1} for more than 100 glaciers in the central Alps and a glaciological mass balance of –1.03 m w.e.a^{-1} for a smaller number of glaciers. They also report a global geodetic mass balance average of –0.8 m w.e.a^{-1} for the same period. In summary, in the Alps, the specific mass balance was approximately –1.0 m w.e.a^{-1} in the first decade of the twenty-first century.

From 2010 to 2015, Huss, Dhulst, and Bauder (2015) give an annual specific mass balance of about –1.0 m w.e.a^{-1} for the Austrian and Italian Alps, and –0.8 m w.e.a^{-1} for the Swiss Alps. Carturan et al. (2016) give an annual specific mass balance between –1.79 and –0.76 m w.e.a^{-1} for selected Italian glaciers from 2004 to 2013. In 2013, the specific mass balance values began to increase, similar to the Triglav Glacier in 2013 and 2014.

The values of the Triglav Glacier differ to some extent from the cited cases, which can be partly attributed to the fact that those studies mentioned mainly included larger glaciers. Abermann et al. (2009) already determined that the thickness of very small glaciers decreases more slowly in comparison to larger glaciers. The lower values of the annual specific mass balances obtained for the Triglav Glacier may also be related to favorable micro-relief conditions (Kuhn 1995) that help preserve it. Other studies of changes in mass balance for very small glaciers also show a significant impact of local micro-relief on the mass balance in addition to the meteorological parameters (Kuhn 1995; Schöner and Böhm 2007; DeBeer and Sharp 2009; Shahgedanova et al. 2012; Colucci and Guglielmin 2015; Carturan et al. 2016; Huss and Fischer 2016).

4 Conclusion

The thickness and volumetric changes for the Triglav Glacier, as well as its mass balance, were determined for over six decades. During this period its maximum thickness decreased from 48.3 m (in 1952) to 5.2 m (in 2007) and its mean thickness from 39.2 m (in 1952) to 2.45 m (in 2012).

The mean annual specific mass balance was –0.45 m w.e.a^{-1} in the entire period studied (1952–2016), –0.07 m w.e.a^{-1} from 1999 to 2009, and –0.26 m w.e.a^{-1} from 2010 to 2016. The values obtained are lower if compared to the mass balances of other Alpine glaciers.

ACKNOWLEDGEMENTS: The authors acknowledge financial support from the Slovenian Research Agency research core funding Geography of Slovenia (P6-0101) and the research project funding Predictive Analytics Based on Location-Associated Context Enrichment (J2-8176). The authors are grateful to everyone that contributed to the measurements of the Triglav Glacier because this research would not have been possible without them.

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Acta geographica Slovenica, 60-2, 2020, 175–190

CHANGES IN THE SKUTA GLACIER (SOUTHEASTERN ALPS) ASSESSED USING NON-METRIC IMAGES

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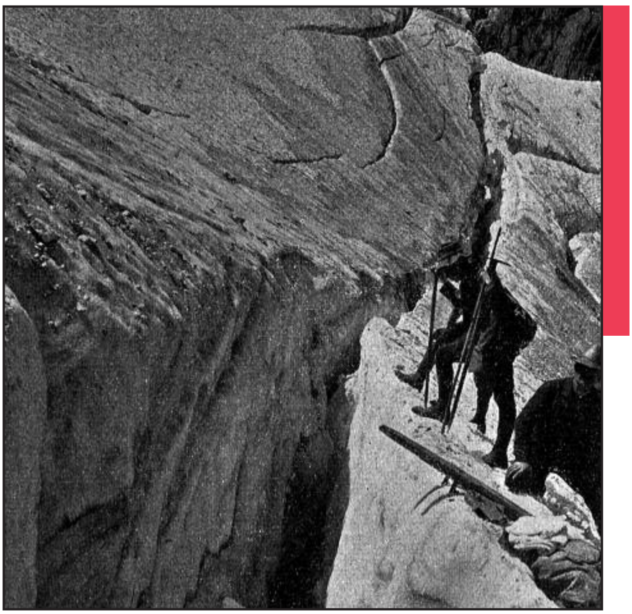
JOSIP KUNAVER

Crevasse on the Skuta Glacier in 1913 (Kunaver 1913).

DOI: https://doi.org/10.3986/AGS.7674
UDC: 91:551.324(234.323Skuta)
528.7:551.324(234.323Skuta)
COBISS: 1.01

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Changes in the Skuta Glacier (southeastern Alps) assessed using non-metric images

ABSTRACT: The Skuta Glacier in the Kamnik–Savinja Alps (in northern Slovenia) is one of the two remaining glaciers in Slovenia. It is located in a cirque oriented toward the northwest, which shields it from sunlight for most of the year. The glacier lies at an average elevation of 2070 m. In recent years, its average area has measured around 1.5 hectares. Monitoring of the glacier has been performed since 1946. In 1962, regular photographing of the glacier with various cameras started from various non-fixed standpoints. Using the single image interactive orientation acquisition method, in which a single photograph is compared with the projection of a modern digital terrain model, seventeen photographs covering the period from 1970 to 2015 were used to acquire the 3D-perimeters of the glacier. The data shows that the elevation of glacier's upper edge decreased by approximately 40 m in the last half-century. Changes in the glacier's area and average upper edge elevation were compared with average annual temperature and maximum seasonal snow cover depth.

KEY WORDS: very small glacier, glacieret, climate change, non-metric images, interactive orientation, Skuta Glacier, Slovenia

Ugotavljanje sprememb na Ledeniku pod Skuto (jugovzhodne Alpe) na podlagi nemerskih fotografij

POVZETEK: Ledenik pod Skuto v Kamniško-Savinjskih Alpah je poleg Triglavskega ledenika eden od dveh še ohranjenih preostankov ledenikov v Sloveniji. Leži v krnici z usmerjenostjo proti severozahodu, zato je večino leta v senci. Ledenik ima povprečno nadmorsko višino 2070 m, njegova površina pa je bila v zadnjih nekaj letih okrog poldrugega hektarja. Ledenik merijo od leta 1946, od leta 1962 pa so ga z različnimi fotoaparati tudi redno fotografirali iz različnih nestabiliziranih stojišč. S pomočjo interaktivne metode orientacije, pri kateri vsebino na fotografijah primerjamo s projekcijo sodobnega digitalnega modela reliefa, smo preučili 17 posnetkov in iz njih izmerili trirazsežnostne obode ledenika v obdobju 1970–2015. V zadnjega pol stoletja se je ledenik na zgornjem robu stanjšal za skoraj 40 m. Spremembe površine in povprečne višine zgornjega robu ledenika smo primerjali s povprečno letno temperaturo in največjo sezonsko skupno višino snežne odeje.

KLJUČNE BESEDE: majhni ledeniki, podnebne spremembe, nemerske fotografije, interaktivna orientacija, Ledenik pod Skuto, Slovenija

The paper was submitted for publication on 6th November, 2019.
Uredništvo je prejelo prispevek 6. novembra 2019.

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1 Introduction

The Skuta Glacier (Pavšek 2004, 2007) in the Kamnik–Savinja Alps is one of the two remaining glaciers in Slovenia, the other being the Triglav Glacier (Gabrovec et al. 2013, 2014; Triglav Čekada and Zorn 2020). It lies in a shady cirque, around 3 hectares in size, surrounded by rock walls. In contrast to the Triglav Glacier and the nearby Canin glaciers in Italy (Triglav Čekada, Zorn, and Colucci 2014), the past size of which can be assessed from the mid-nineteenth century onward based on various historical images (Triglav Čekada 2018), no images going back that far are available for the Skuta Glacier.

Systematic measurements of the Skuta Glacier began in 1946 (Meze 1955; Pavšek 2007), and in 1962 the glacier also began to be photographed during regular measurements at the end of the melting season (Košir 1976). Various cameras were used and photographs were taken from two positions: the lower edge of the Ledine Cirque and along the hiking trail near the fork between the routes to the Savinja Pass and the Rinka peaks, provisionally named *Ob macesnu* 'At the Larch' (Košir 1976).

This article presents the measurements of the glacier's perimeter and its upper edge acquired from the photographs taken from the standpoint »At the Larch.« The results are compared against the average annual temperature and the maximum seasonal snow cover depth. These two indicators have proven significant in similar studies of the Triglav Glacier (Triglav Čekada and Gabrovec 2013).

Today's Skuta Glacier is considered a very small glacier, or glacieret (Kumar 2011). The results of this study can thus be compared to other glaciers of similar size, especially those that lie at lower elevations in middle latitudes and are therefore heavily exposed to short-term climate changes (e.g., Djurović 2012; Colucci and Žebre 2016; Gachev and Mitkov 2019; Gachev 2020).

2 Data and methods

2.1 Field measurements

The initial observations of the Skuta Glacier included permanent marking of fixed measurement points around the glacier. At the end of each annual melting season, the glacier's retreat from these points was measured with a tape measure and a compass. Because the glacier lies in a cirque, most fixed measurement points were set on its upper edge or the rock walls surrounding the cirque. Consequently, (sub)vertical retreats were most often measured on the upper edge (Meze 1955; Košir 1976, 1986; Pavšek 2007) rather than horizontal retreats, which were typically measured in similar studies of the glaciers nearby (Triglav Čekada et al. 2012; Gabrovec et al. 2013; Colucci and Guglielmin 2015).

The (sub)vertical and horizontal retreat are published in articles covering the first four decades of measurements (Gams and Kopač 1955; Meze 1955; Košir 1976, 1986). Later the retreats were so extensive that the old fixed measurement points were no longer used. New ones were marked, but the retreats from these points are not directly comparable with the old ones (Pavšek 2007).

In 1997 and 2003, the first tachymetric surveying of the glacier was conducted and, since 2007, field surveys with annual geodetic measurements have been performed (Pavšek 2012).

In 2006, a steam drill was used to measure the thickness of the glacier (ice and firn). The average thickness was 7 m and the maximum thickness was nearly 12 m. Its volume was estimated at just under 80,000 m^3 (Pavšek 2007).

2.2 Photography

Since 1962, the glacier has also been photographed during regular field measurements (Košir 1976). Various cameras and positions have been used. This analysis only includes photographs taken from »At the Larch« (Table 1, Figure 1).

Photographic material makes it possible to reconstruct the glacier's upper edge before 1997, when the Skuta Galcier was geodetically surveyed for the first time, and it helps to reconstruct the glacier from 1997 until the next geodetic survey conducted in 2003 as well. Even though annual geodetic surveys have been conducted since 2007, photographs taken after 2007 were also studied for comparison.

Table 1: Dates and photographers of the images analyzed (Figure 1).

Date	Photographer
26 September 1970	Dušan Košir
22 September 1973	Dušan Košir
8 July 1982	Dušan Košir
22 September 1995	Miha Pavšek
10 September 1998	Miha Pavšek
28 October 1999	Miha Pavšek
3 July 2001	Miha Pavšek
5 October 2004	Miha Pavšek
19 October 2005	Miha Pavšek
23 September 2006	Miha Pavšek
15 October 2007	Miha Pavšek
11 September 2008	Miha Pavšek
7 September 2009	Miha Pavšek
21 September 2010	Miha Pavšek
30 September 2011	Miha Pavšek
29 August 2014	Miha Pavšek
2 October 2015	Miha Pavšek

2.3 Aerial laser scanning

In 2012, special aerial laser scanning (lidar) was performed twice on the Skuta Glacier: first on May 15th, at the end of the accumulation season, and on September 18th, at the end of the melting season. The scanning was performed using a Riegl LM5600 with a 1550 nm wavelength. The average point density was 8 points/m^2 and the flight altitude was 200 m above the glacier. In this analysis, a digital terrain model (DTM) with a grid size 1 m × 1 m was used, produced from the September laser scanning (Triglav Čekada et al. 2013).

On August 29th, 2014 the glacier was scanned again as part of the national aerial laser scanning of Slovenia (Triglav Čekada and Bric 2015). This scanning was performed using a Riegl LMS-Q780 with a 1064 nm wavelength at a flight altitude of 1000 m. A point cloud with a density of 5 points/m^2 and a 1 m × 1 m DTM were produced as well. Because of a mild summer and previous above-average accumulation season, there was still an abundance of snow on the glacier and therefore these data were not used in the analysis.

2.4 Meteorological data

According to Košir (1976, 1986), changes in the area covered by the Skuta Glacier depend on the mean summer air temperature, and he also established a connection with the maximum seasonal snow cover depth. Both indicators have also proved significant in the monitoring of the Triglav Glacier (Triglav Čekada and Gabrovec 2013).

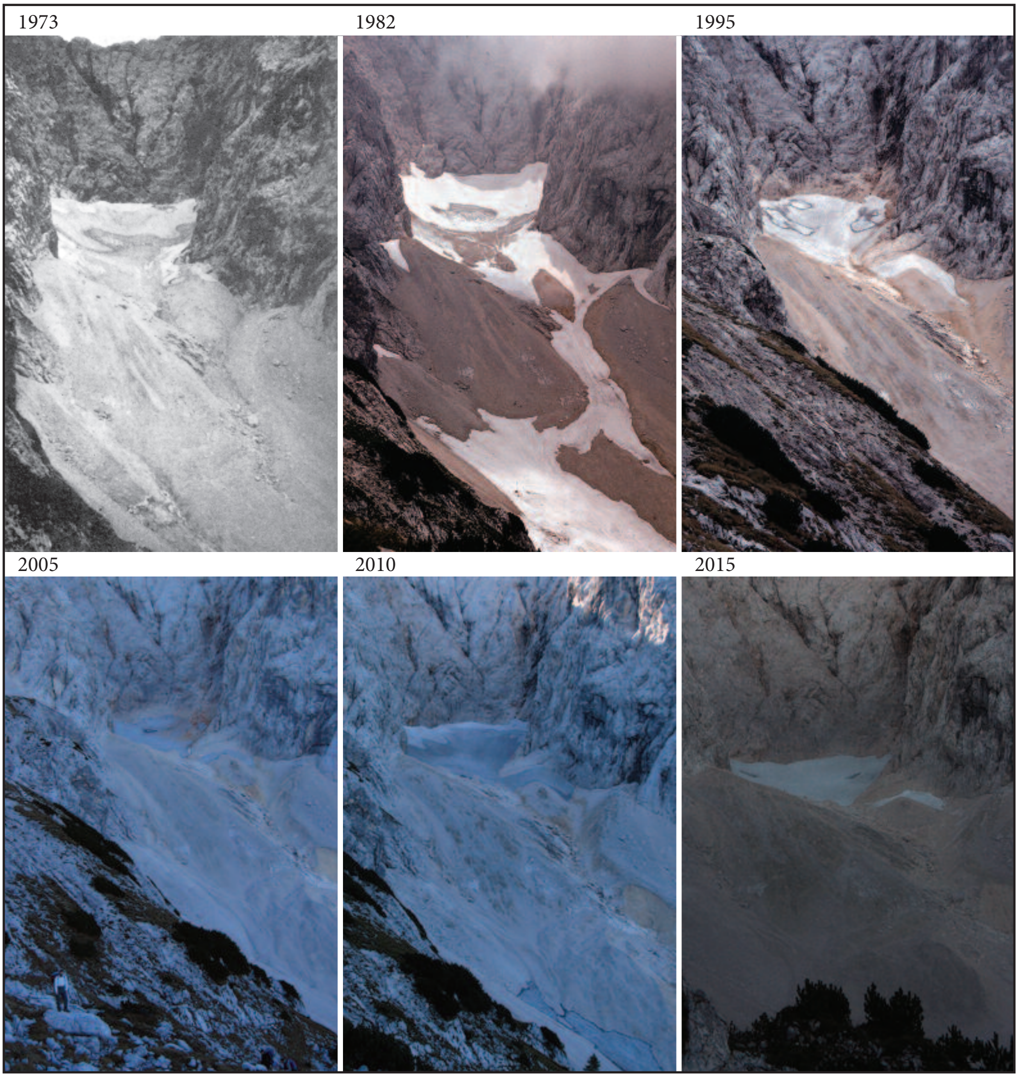
Because no direct meteorological data are available for the Skuta Glacier, approximations of the average annual air temperature and maximum seasonal snow cover depth were calculated based on data from nearby meteorological stations.

Meteorological data were obtained from the Slovenian Environment Agency (ARSO) online archive (Arhiv … 2018). The nearest Slovenian meteorological station with an extended series of measurements is the one on Mount Krvavec. Standing at an elevation of 1742 m, it has been collecting data since 1973 (marked in Figure 2 as »Krvavec 2«). It is just under 8 km as the crow flies from the Skuta Glacier. The previous meteorological station on Mount Krvavec stood at an elevation of 1478 m (marked in Figure 2 as »Krvavec 1«). Unfortunately, these stations do not provide a complete series of average annual temperatures and monthly snow cover depths for all the years studied. Data from the Krvavec 1 station covering the period from 1963 to 1973 were used for the analysis.

Because the current station stands lower than the average elevation of the Skuta Glacier, as did the previous station, data from the Kredarica meteorological station at an elevation of 2514 m were used to calculate the average annual temperature. This station is approximately 55 km from the Skuta Glacier and has complete data series from 1955 onward.

The average annual temperature from Mounts Kredarica and Krvavec were adjusted (Figure 2) using the vertical average annual temperature gradient for Zgornje Jezersko (–0.44 °C / 100 m; Ogrin, Koželj, and Vysoudil 2016). Figure 2 shows a similar fluctuation in adjusted average annual temperatures for both stations.

To obtain a more complete series of measurements, the adjusted average temperatures from Mount Kredarica were used as a better approximation of temperature conditions at the average elevation of the Skuta Glacier. From 1960 to 1990, the average annual temperature on Mount Kredarica was –1.66 °C. According to Ogrin, Koželj, and Vysoudil (2016), the average annual temperature at Zgornje Jezersko during the same period was 5.9 °C. Based on the vertical temperature gradient between Mount Kredarica and Zgornje Jezersko, or between the elevations of 2514 m and 894 m, the adjusted average annual temperature for Zgornje Jezersko is 5.46 °C.



ZRC SAZU, ANTON MELIK GEOGRAPHICAL INSTITUTE ARCHIVE; FOR AUTHORS SEE TABLE 1

Figure 1: Some of the photographs of the Skuta Glacier from »At the Larch« used for the analysis, taken in 1973, 1982, 1995, 2005, 2010, and 2015.

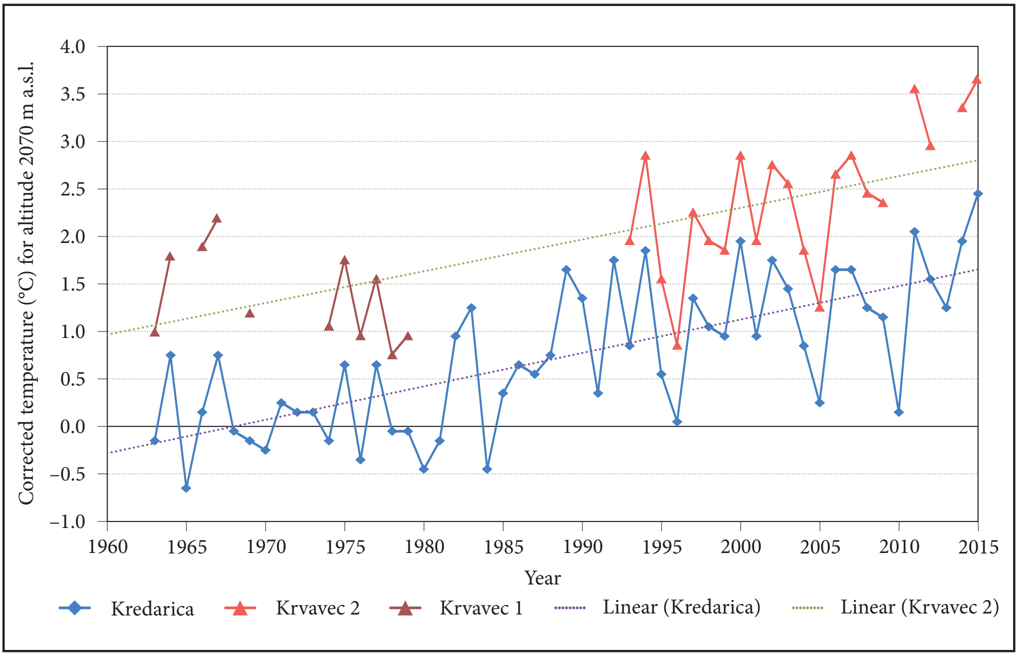


Figure 2: Average annual temperatures on Mounts Kredarica and Krvavec adjusted to the average elevation of the Skuta Glacier (2070 m).

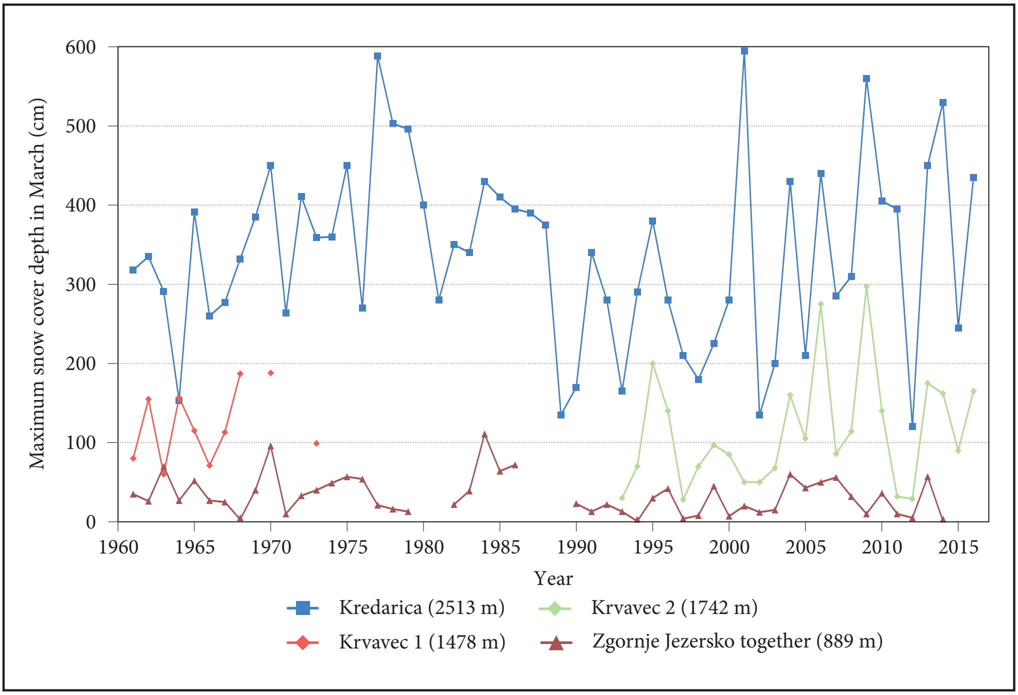


Figure 3: Maximum March snow cover depth on Mounts Kredarica and Krvavec, and at Zgornje Jezersko, based on aggregated data from the meteorological stations there.

Data on snow cover depth were also obtained from the ARSO online archive (Figure 3); the data from seven meteorological stations at Zgornje Jezersko (at elevations ranging from 876 to 912 m) were also used. The longest time series were recorded at the site at an elevation of 889 m (1977–1985, 2006–2014), therefore this elevation was used as the reference elevation for Zgornje Jezersko.

From 1969 to 1970, 1995 to 1996, in 1999, from 2004 to 2007, and in 2015, concurrent changes in the snow cover depth can be observed on Mounts Kredarica and Krvavec, and at Zgornje Jezersko in March (Figure 3). The 1993–2014 data series for the Krvavec 2 station and the aggregated data series for the Zgornje Jezersko stations are very similar; at the same time, maximums were also recorded on Mount Kredarica.

The precipitation and snow cover depth are reported to increase linearly with elevation (Asaoka and Kominami 2012; Grünewald, Bühler, and Lehning 2014). Based on the linear dependence between the elevation and the average snow cover depth (based on the data presented in Table 2; y is the average snow cover depth and x is the elevation), the average snow cover depth for the Skuta Glacier was calculated (Table 2). The maximum (March) snow cover depth calculated was 228 cm, which is 109 cm less than the snow cover depth at Mount Kredarica.

Table 2: Average March snow cover depth from 1961 to 2016 at various meteorological stations and elevations (*calculated based on linear dependence).

Station	Elevation (m)	Average snow cover depth (cm)
Kredarica	2,513	337
Krvavec 1	1,478	123
Krvavec 2	1,742	112
Zgornje Jezersko	889	33
Skuta Glacier	2,070	228*

2.5 Single image interactive orientation acquisition method

The perimeter and upper edge of the Skuta Glacier were acquired from single photographs from various years using the single image interactive orientation acquisition method, also known as monoplotting. It requires only one photograph and a detailed DTM to calculate the orientation parameters. The method was developed for measuring the Triglav Glacier (Triglav Čekada et al. 2011; Triglav Čekada, Bric, and Zorn 2014). The content in the photographs is visually compared against a modern DTM projection to obtain the best fit, in which the parameters of the external image orientation (i.e., three coordinates of the camera's projection center, three rotation angles, and the scale of the projected model) are searched for. If an image or parts of it have significant radial distortions, then these can be searched for as well (Triglav Čekada, Bric, and Zorn 2014). The basic premise, that allows us to use this method, is that there was no significant change in the terrain around the glacier between the time when the photograph was taken and the time when a modern DTM was created. If the interactive orientation is successful, the features seen in the image fit to those seen on the DTM projection. This is followed by a 3D vectorization of the glacier's edge based on the projected DTM points.

In this analysis, the September 2012 DTM was applied (Figure 4). The result of the vectorization is a continuous line showing the 3D perimeter of the glacier.

The vectorization of the Skuta Glacier was difficult because part of it is always obscured from the perspective photographed (the extreme left and right parts of the glacier in Figures 4 and 5). A similar challenge was also encountered in acquiring the sizes of the Canin glaciers (Triglav Čekada, Zorn, and Colucci 2014). The obscured part was added as follows: the glacier's edge in the visible section of the cirque was vectorized from the photograph and then the vectorization of its perimeter was continued along the isohypse in the obscured section.

By comparing the areas in three interactively oriented images, in which all three orientation angles were »distorted« by ±0.2°, the precision of the area calculations through standard deviation can be estimated at ±0.1 hectares (Barbo 2018), which corresponds to 7% of the Skuta Glacier's area per average area of 1.5 hectares.

The average elevation of the glacier's upper edge was calculated using 30 to 160 points acquired by the method used based on photographs in which the upper edge was visible. Some of the results at approximately ten-year intervals are shown in Figure 5.

To determine the glacier's perimeter, the entire area covered in snow, firn, or ice was measured, and not only the ice. The glacier's upper edge was also determined based on the same principle.

3 Results

The area covered by the Skuta Glacier remained approximately the same between 1970 and 2015 (between one and two hectares; Table 3, Figure 6). If the calculations made in this study are compared with the field measurements, it can be established that the results differ by up to 0.4 hectares, which corresponds to just under a third of the glacier's area. The method used yielded relatively smaller areas than those established through field measurements; the only exceptions were the results for 2007 and 2015.

Using this method, the largest area was measured for 1982; the photograph from this year shows a heavily snowed-in glacier and its surroundings (Figure 1). The entire area of the glacier in the cirque and the snowed-in tongue outside it was measured, which in fact covers not only the glacier, but also the adjacent snowfield. It also needs to be taken into account that the photograph was taken more than two months before the end of the melting season (i.e., in early July; Table 1).

There are no major differences in the glacier's size between the start and end of the period studied, but significant changes can be observed in the elevation of its upper edge and thus its thickness. During the period studied, the upper edge elevation decreased by nearly 40 m (Table 3, Figure 5). The elevation of the glacier's upper edge fluctuates significantly from year to year because the glacier's thickness greatly depends on the snow conditions and when the measurements are conducted in an individual year in relation to the end of the melting season. A distinct decrease in the elevation of the upper edge can be observed from the early 1970s to the end of the 1990s.

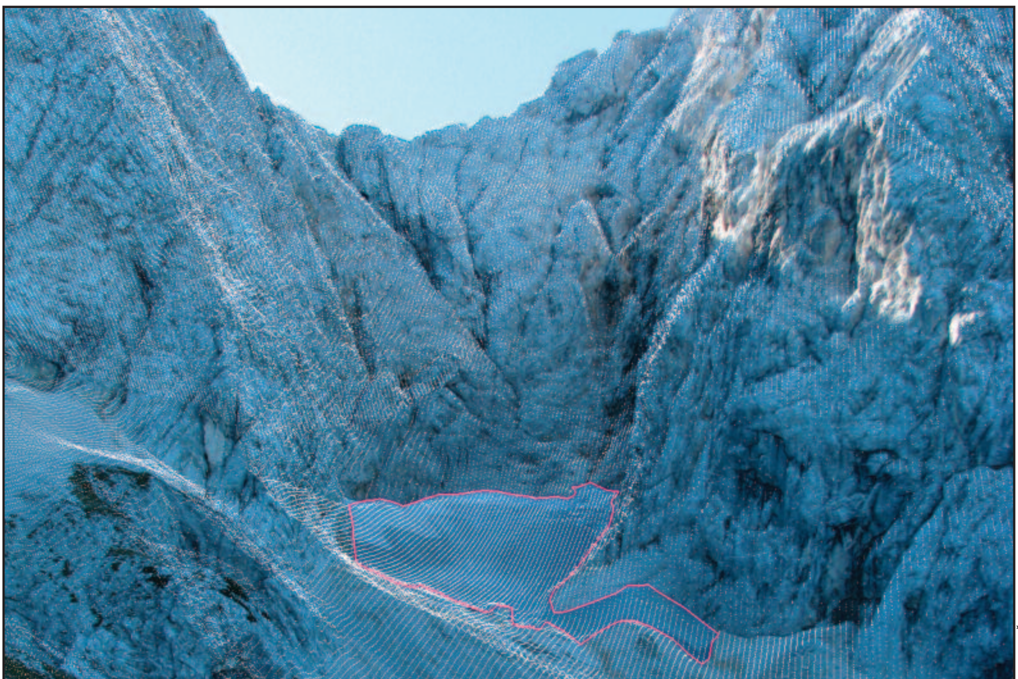


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Figure 4: The Skuta Glacier in 2010 with a vectorized edge and a matching DTM projection.

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Figure 5: Elevation of the glacier's upper edge in 1973, 1982, 1995, 2006, and 2015 projected onto a 2015 photograph.

Table 3: Area of the Skuta Glacier and the average elevation of its upper edge between 1950 and 2015 (*tachymetric survey; **survey in early July).

Year	Area based on photographs (hectares)	Area based on field measurements (hectares)	Average elevation of upper edge based on photographs (m)
1950	–	2.8	–
1970	1.8		2,153
1973	2.3		2,151
1982	4.2**	–	2,153
1989		1.1	
1995	1.8	–	2,138
1997		1.5*	
1998	1.4	–	2,114
1999	1.1	–	2,109
2001	1.0	–	2,129
2004	1.6	–	2,114
2005	1.0	–	2,100
2006	1.3	–	2,111
2007	1.5	1.1*	2,112
2008	1.0	1.4*	2,119
2009	1.4	1.8*	2,145
2010	1.7	1.8*	2,124
2014	2.1	2.1*	2,133
2015	1.6	1.4*	2,115

Changes in the glacier definitely reflect the increase in average annual temperatures (Figures 7 and 8). During the period studied, the average annual temperature at the glacier's average elevation increased from approximately −0.2 °C in 1963 to 1.7 °C in 2015. It is not only the increase of nearly 2 °C that is important, but also the temperature transition above the freezing point.

In addition to temperature, changes in the glacier are also influenced by the snow cover depth. In addition to falling snow, the majority of snow accumulates on the Skuta Glacier in the form of avalanches and to a smaller extent as drifting snow.

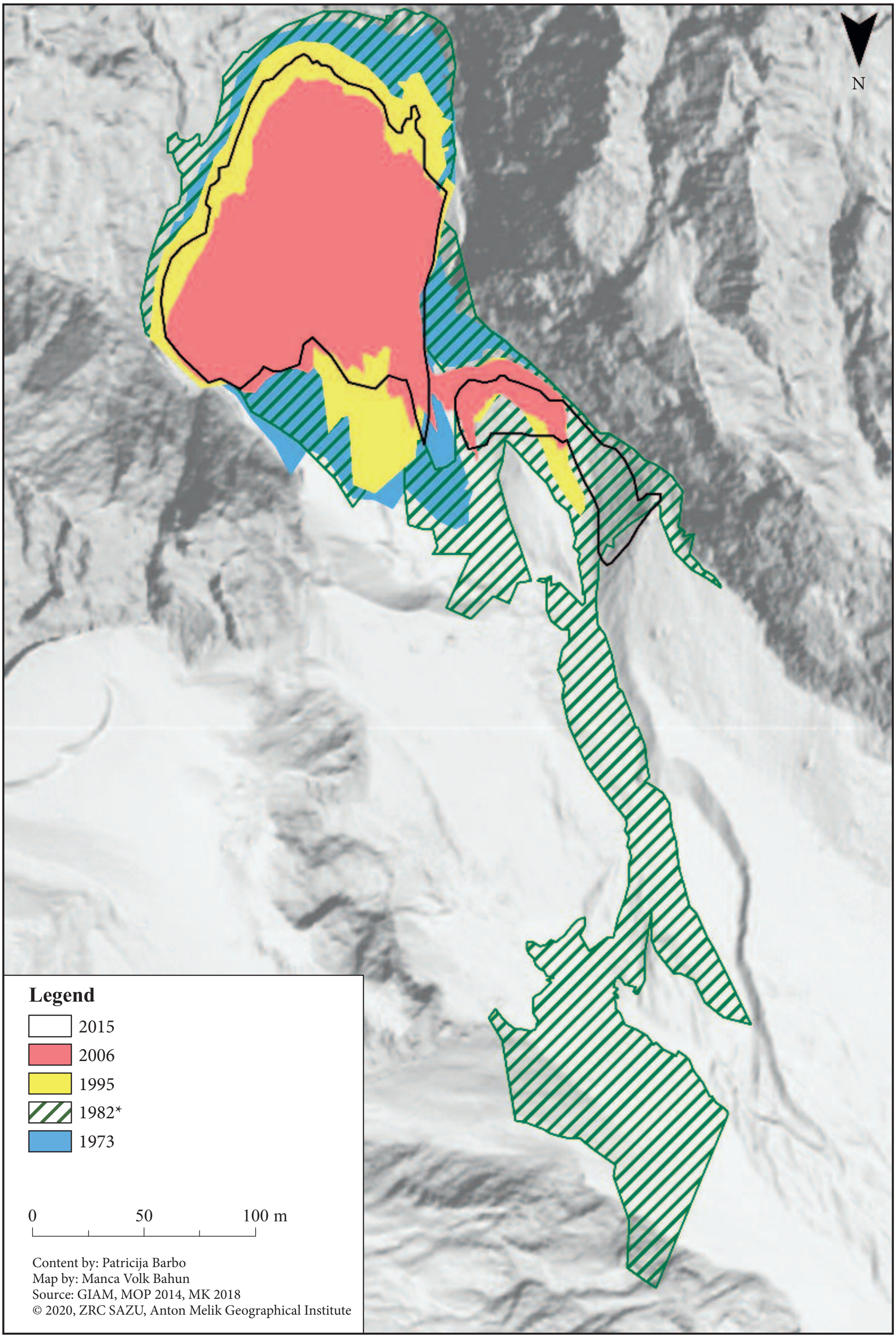
A comparison of the Skuta Glacier's area and the average annual temperature after 2003 shows that from 2008 to 2010 the glacier's area increased when the average annual temperatures were below the temperature increase trend line. However, from 2004 to 2005, when the average annual temperatures were also lower than the trend, the area was shrinking (Figure 7). The difference between the two periods results from the differences in the maximum seasonal snow cover depths on the glacier in June (Figure 9).

An even more direct connection between the average annual temperature and the June snow cover depth is reflected by the changes in the average elevation of the glacier's upper edge (Figures 8 and 10). If the average temperatures are low, this makes it easier for the snow to remain on the upper edge until the end of the melting season. The impact of the snow cover depth on the elevation of the glacier's upper edge can be observed in 2009 and 2010. The year 2009 was characterized by a large amount of snow and a low average temperature and 2010 was marked by a low snow cover depth and a low average temperature. Consequently, the glacier's upper edge in 2009 was higher than in 2010. The upper edge also lowered in 1998 and 1999, when the average annual temperatures were slightly below the temperature trend line and there was very little snow in June.

4 Discussion

Because the Skuta Glacier is confined in a narrow cirque, it has managed to retain its area over the past half-century. However, this stability does not apply to its upper edge, where significant changes have been observed (Table 3, Figures 5 and 6).

Figure 6: Changes in the Skuta Glacier's area in 1973, 1982 (*survey in early July), 1995, 2006, and 2015 measured using the single image interactive orientation acquisition method. ➤


N
Legend
2015
2006
1995
1982*
1973
0
50
100 m
Content by: Patricija Barbo
Map by: Manca Volk Bahun
Source: GIAM, MOP 2014, MK 2018
© 2020, ZRC SAZU, Anton Melik Geographical Institute

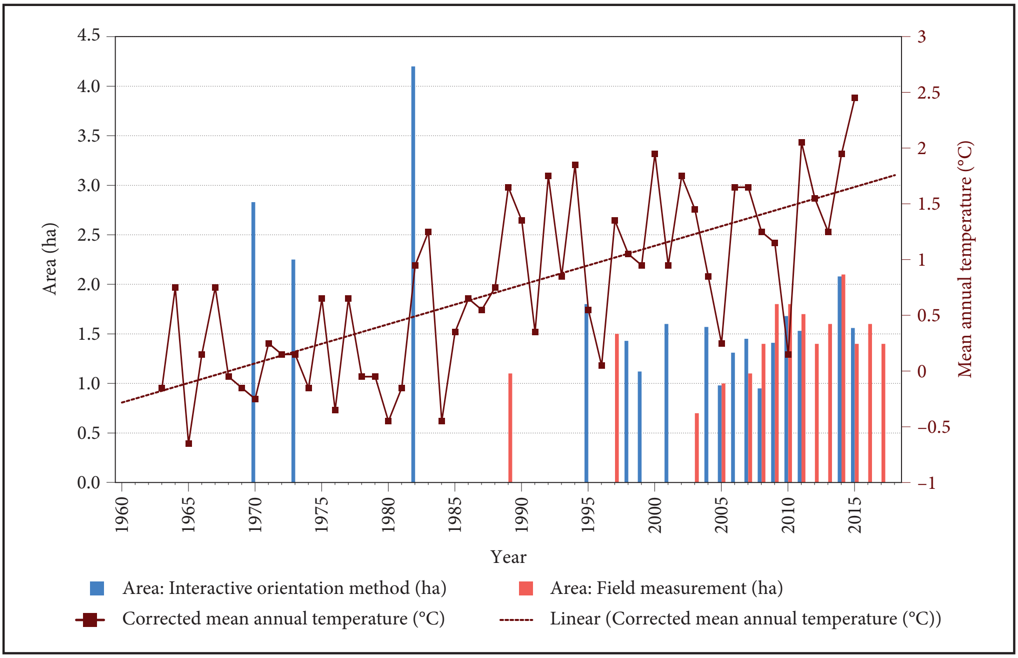


Figure 7: Areas covered by the Skuta Glacier measured using the single image interactive orientation acquisition method and field surveys and their comparison with average annual temperatures at an elevation of 2070 m, or the average elevation of the Skuta Glacier.

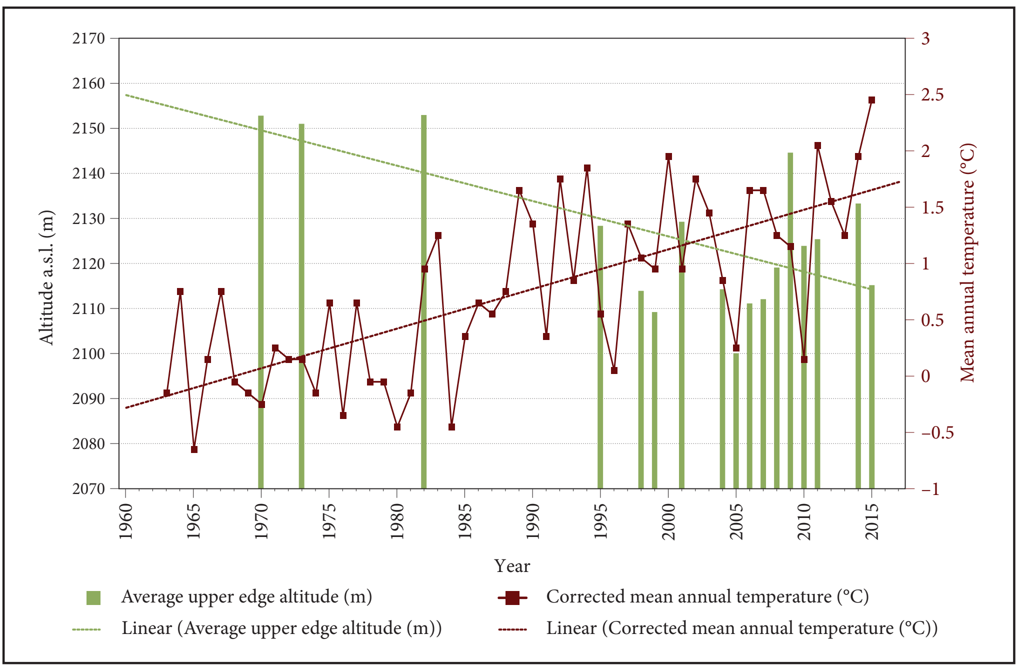


Figure 8: Annual elevations of the Skuta Glacier's upper edge determined with the single image interactive orientation acquisition method and their comparison with average annual temperatures at an elevation of 2070 m, or the average elevation of the Skuta Glacier.

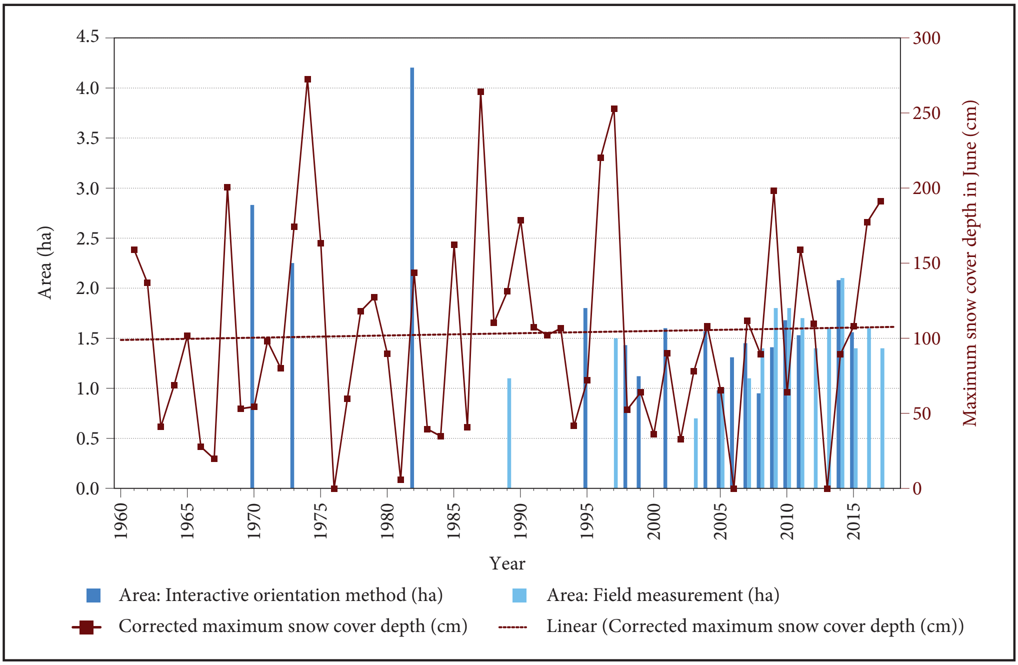


Figure 9: Areas covered by the Skuta Glacier measured using the single image interactive orientation acquisition method and field surveys, and their comparison with the maximum seasonal snow cover depth at an elevation of 2070 m, or the average elevation of the Skuta Glacier, in June.

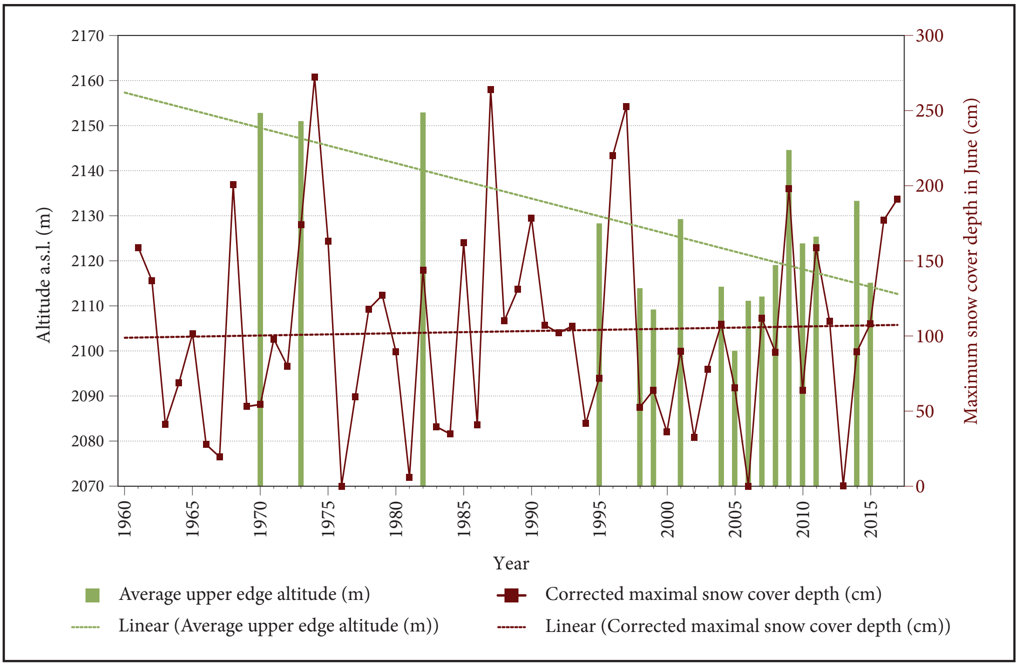


Figure 10: Annual elevations of the Skuta Glacier's upper edge determined with the single image interactive orientation acquisition method and their comparison with the maximum seasonal snow cover depth at an elevation of 2070 m, or the average elevation of the Skuta Glacier, in June.

The results of this study are based on the single image interactive orientation acquisition method (Triglav Čekada, Bric, and Zorn 2014), which has already been successfully applied to measurements of the Triglav Glacier (Triglav Čekada and Gabrovec 2013) and Canin glaciers (Triglav Čekada, Zorn, and Colucci 2014) in the Julian Alps. These measurements slightly deviate from the field surveys (Table 3) due to the poorer accuracy of the images compared to the field measurements, as well as problems in interpreting images due to poor contrast or difficulties distinguishing between snow or ice and calcareous debris. Mostly the single image interactive orientation acquisition method for the Skuta Glacier gives underestimated results compared to the area measured using tachymetric surveying. Nonetheless, the method used is useful for determining glacier changes because the size of glaciers can be measured based only on amateur photographs taken by non-metric cameras. First and foremost, the method is useful for very small glaciers, which can be documented in full in a single photo.

The data acquired for the Skuta Glacier can be compared to other very small glaciers in the southeastern Alps (Triglav Čekada et al. 2012; Colucci and Žebre 2016; Lipar et al. 2020; Triglav Čekada and Zorn 2020), southeastern Europe (Grunewald and Scheithauer 2010; Hughes 2010, 2018; Djurović 2012; Gachev, Stoyanov, and Gikov 2016; Gachev 2020), the Pyrenees (González Trueba et al. 2008), and elsewhere around the globe (DeBeer and Sharp 2009; Shahgedanova et al. 2012).

What all these studies have in common is that they connect the decrease in glaciers' size with the increase in the average annual temperature, the average temperature during the melting season, or average summer temperatures, which in reference to the Skuta Glacier has already been mentioned by Košir (1976, 1986). The likely connection between average temperatures and the snow cover depth on glaciers and snowfields in Slovenia was already discussed by Manohin and Gams (1959). In turn, contemporary authors, such as Grunewald and Scheithauer (2010), report that periods with above-average winter precipitation and cold summers can even »stabilize« very small glaciers or help them grow temporarily. This is also suggested by the data for the Skuta Glacier, which usually does not grow on the account of ice, but snow. On the other hand, Gachev and Mitkov (2019) associate the shrinking of very small glaciers with the increase in summer precipitation.

Over the past half-century, similar trends as elsewhere have been observed on very small glaciers in the southeastern Alps. The area covered by the Triglav Glacier halved from the mid-1980s to the early 1990s (it decreased from 10 to just over 4 hectares), and over the past two decades it has maintained an area between 0.5 and 1 hectares (Triglav Čekada and Gabrovec 2013). From the 1970s to the end of the century, the two Canin glaciers also halved in size, which was also assessed using the single image interactive orientation acquisition method (Triglav Čekada, Zorn, and Colucci 2014). In southeastern Europe, the size of the Debeli Namet Glacier in Montenegro, which lies at a similar elevation as the Skuta Glacier, has more than halved since the 1980s (Djurović 2012). In turn, the size of the Snežnik Glacier in Bulgaria, which lies at a similar elevation as the Triglav Glacier, more than halved from the early 1960s to the mid-1990s (Gachev, Stoyanov, and Gikov 2016). The current average annual temperature on the Debeli Namet Glacier is above 0 °C (Grunewald and Scheithauer 2010), just like on the Skuta Glacier. Over the past decade, both the Debeli Namet and Snežnik glaciers have more or less retained their size: the size of the former fluctuates between 1.5 and 3.0 hectares, and that of the latter between just under 0.4 and just over 0.6 hectares. Their relative stability is associated with the strong influence of terrain on the microclimate (Gachev, Stoyanov, and Gikov 2016; Gachev 2020). DeBeer and Sharp (2009) also establish that terrain influences how very small glaciers respond to climate change. Grunewald and Scheithauer (2010) add that in the concluding stages of glacial degradation the impact of climate factors relatively decreases, whereas the impact of terrain increases. According to the measurements conducted on both Slovenian glaciers (i.e., the Skuta Glacier and the Triglav Glacier; Triglav Čekada and Zorn 2020), these findings may apply to Slovenia's very small glaciers.

5 Conclusion

Changes in the Skuta Glacier since the early 1970s were studied based on seventeen photographs taken from the same location using various non-metric cameras. The area covered by the glacier and the elevation of its upper edge were determined using the single image interactive orientation acquisition method.

During the period studied (1970–2015), the glacier's size did not change significantly, whereas the average elevation of the glacier's upper edge decreased by as much as nearly 40 m.

Because there is no meteorological station near the Skuta Glacier, data from nearby stations were used to determine the average annual temperature and maximum seasonal snow cover depth on the glacier. The maximum seasonal snow cover depth at the end of the accumulation season has proven vital for preserving the glacier's thickness.

ACKNOWLEDGMENTS: The authors acknowledge the financial support from the Slovenian Research Agency research project funding Predictive analytics based on location-associated context enrichment (J2-8176) and research core funding Geography of Slovenia (P6-0101). The authors would like to thank everyone involved in the measurements of the Skuta Glacier, without whom this study would not have been possible.

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Acta geographica Slovenica, 60-2, 2020, 191–211

SMALL GLACIERS IN THE DINARIC MOUNTAINS AFTER EIGHT YEARS OF OBSERVATION: ON THE VERGE OF EXTINCTION?

Emil Mariov Gachev

The Prokletije Massif: the great Grebaje Cirque. The lowermost perennial ice masses in southeast Europe still survive among these magnificent limestone cliffs.

DOI: https://doi.org/10.3986/AGS.8092
UDC: 551.324:551.58 (234.422.1)«2011/2018«
COBISS: 1.01

Emil Mariov Gachev[1, 2]

Small glaciers in the Dinaric Mountains after eight years of observation: On the verge of extinction?

ABSTRACT: This study presents results from regular observation of permanent and summer-persisting firn-ice bodies in the highest parts of the Dinaric Alps. The sizes of six small glaciers and two snow patches on the Prokletije Massif (in Albania) and the Durmitor Massif (in Montenegro) were measured from 2011 to 2018. In recent years, specific cycles of interannual behavior have been observed: a year of considerable snow accumulation (a »recharge« phase), followed by two to four years of gradual decrease (a »wastage« phase). At present, the small glaciers studied exist in unbalanced conditions, which in the long term may lead to their degradation. Progressive warming makes short-term cycle minimums increasingly severe. Their retreat after the summer of 2017 was probably the most pronounced since the Little Ice Age, and small glaciers are on the verge of extinction.

KEYWORDS: glacierets, snow patches, warming, winter precipitation, interannual variations, Dinaric Mountains

Majhni ledeniki v Dinarskem gorovju po osmih letih opazovanja: na robu izumrtja?

POVZETEK: Članek predstavlja rezultate rednih opazovanj trajnih malih ledenikov, ledeniških krp in snežnih zaplat v najvišjih delih Dinarskega gorstva. V obdobju 2011–2018 smo merili velikost šestih ledenikov in dveh snežnih zaplat v Prokletijah (Albanija) in na Durmitorju (Črna gora). V zadnjih letih opažamo posebne cikle medletnega kolebanja: leto velike akumulacije snega (faza »vnovičnega polnjenja«), ki mu je sledilo dve do štiri leta postopnega krčenja (faza »praznjenja«). Preučeni majhni ledeniki so trenutno v neuravnoteženih razmerah, kar lahko dolgoročno povzroči njihovo izginotje. Progresivno segrevanje še poglablja kratkoročne ciklične minimume. Njihovo zmanjšanje po poletju 2017 je bilo verjetno najmočnejše po mali ledeni dobi, majhni ledeniki pa so na robu izginotja.

KLJUČNE BESEDE: majhni ledeniki, snežne zaplate, segrevanje, zimske padavine, medletne razlike, Dinarsko gorstvo

The paper was submitted for publication on March 10th, 2020.
Uredništvo je prejelo prispevek 10. marca 2020.

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1 Introduction

Glaciers are among the best indicators of climate change. Local and regional glacier studies (Pavšek 2007; Pecci, D'Agata and Smiraglia 2008; Hohenwarter 2013; Gabrovec et al. 2014; Colucci et al. 2014; Colucci 2016; Colucci and Žebre 2016) are important because their results further improve global climate change models and make possible more accurate forecasts for environmental changes in particular locations.

The highest massifs of southeastern Europe still provide conditions marginal for glacier formation (Hughes 2009; Grunewald and Scheithauer 2010; Figure 1). Because they are located 500 to 700 m below the theoretical elevation of the present-day glacier equilibrium-line altitude (ELA), their existence is determined by local topography.

Two main categories of firn-ice bodies can be distinguished in the area: 1) small glaciers (mostly categorized as glacierets), and 2) ice/snow patches. Small glaciers are permanent tiny masses of snow, firn, and ice (measuring 0.5 to 5 hectares) that show dynamic motion of their mass under the force of gravity (Grunewald and Scheithauer 2008; 2011). Due to their modest mass, ice patches do not show signs of motion, except some minor displacements (Serrano et al. 2011); however, they can in fact be permanent. Snow patches, on the other hand, may last for up to several consecutive summers, but they melt completely at least once every few years. Small firn-ice bodies often switch between these categories due to significant short-term variations.

In the Dinaric Mountains, annual and multi-annual preservation of firn and ice occurs in a few specific locations with special topoclimatic conditions: shading (in deep glacio-karst depressions with a northern or northeastern exposure) and carbonate bedrock, which warms less due to its light color (Popov 1964; Lipar et al. 2020) and is permeable due to karst processes that hinder basal melt. Abundant winter snow is provided by considerable precipitation, along with contribution from avalanches and windblown snow, which can effectively increase snow accumulation over the glacier surface up to several times (Hughes 2007; 2008). Temperatures should be low enough in order to achieve relatively low ablation rates. Glaciers in the Dinaric Mountains appear at elevations above 1,900 m, but at lower elevations compared to most of the Alps and the mountains of Southeast Europe.

Glacial-type motion has been evidenced for a number of firn-ice bodies on the highest massifs of the Dinaric range, Prokletije and Durmitor, mainly on the basis of their morphology and the presence of fresh glacial striations on bedrock in their vicinity (Gachev 2017). This article summarizes studies of the interannual changes in selected small glaciers and snow patches in the Dinaric Mountains (Figure 1) in recent years and presents the main reasons for the trends observed as a consequence of regional climate change.

2 Study sites

The Dinaric Mountains extend along the Adriatic shores of the Balkan Peninsula, from Slovenia in the northwest to Albania in the southeast. Prokletije (2,694 m) and Durmitor (2,522 m) are the highest and second-highest massifs in this range.

2.1 The Prokletije Massif

The mountainous Prokletije Massif, measuring 70 × 40 km, is mainly located in northern Albania, on the borders with Montenegro and Kosovo. Many of its ridges rise to 2,000 to 2,400 m. The highest summit is Mount Jezerca (Alb. *Maja e Jezercës*, SCr. *Maja Jezerce*, 2,694 m).

The geology of the Prokletije Massif is diverse. Limestone dominates in the center, south, and west, whereas the eastern part is mostly built of silicate rock (Dimitrijević 1983). During the Pleistocene, the glacier extent on the Prokletije Massif was considerable. In the cold phases prior to the Last Glacial Maximum (LGM), the ELA dropped to 1,750 m, and glaciers over 10 km long flowed down from the central highest parts (Milivojević, Menković and Ćalić 2008).

The presence of contemporary glaciation in the limestone part of the Prokletije Massif north of Mount Jezerca, »an ice mass about 1 km long,« was first mentioned by Ludwig Roth von Telegd (1923). Milivojević, Menković, and Ćalić (2008) mapped three small glaciers in the same part of the mountain, with a total area of about 11 hectares, with the largest (the Koljaet Glacier) occupying about 5 hectares. Hughes (2009)

Figure 1: Location of the study sites in the Prokletije Massif and the Durmitor Massif, where monitored small glaciers are situated. Red rectangles show the sites of the present study areas.

mentioned one more glacier with an area of 4.9 hectares, and two more glaciers were described by Gachev and Stoyanov (2012). In 2012 a glacieret (2.2 hectares) was discovered in the Kolata range (2,556 m). In 2015, five small glaciers were mapped in the range south of the Valbona Valley and two in the Karanfili range (2,490 m), among them the lowest in the Balkans, at 1,910 to 1,970 m (Gachev, Stoyanov and Gikov 2016). According to the author's observations, the Koljaet Glacier should instead be referred to as a snow patch because it melted completely in 2012 and 2016. Objects of the previous study are the five glacierets and two snow patches in the central part of the Prokletije Massif (Figure 2). The glacierets lie at elevations from 2,300 to 2,480 m on a rocky terrace below the summit of Mount Jezerca (2,694 m) and have a northern to northeastern orientation. The Jezerce I and II Glacierets are located at the base of a rock wall (Figure 2, bottom left), whereas the Jezerce III Glacieret, further to the southeast, is a compound-type glacieret (Figure 2, bottom right). Its upper (northwest) section lies against a rocky wall base, and the lower section comprises a series of dolines. A set of moraines outlines the lower margins of those glacierets. For several years, Jezerce III was recorded as the largest glacieret in the Balkans. The Jezerce IV and V Glacierets occupy rocky depressions and have weakly developed moraines.

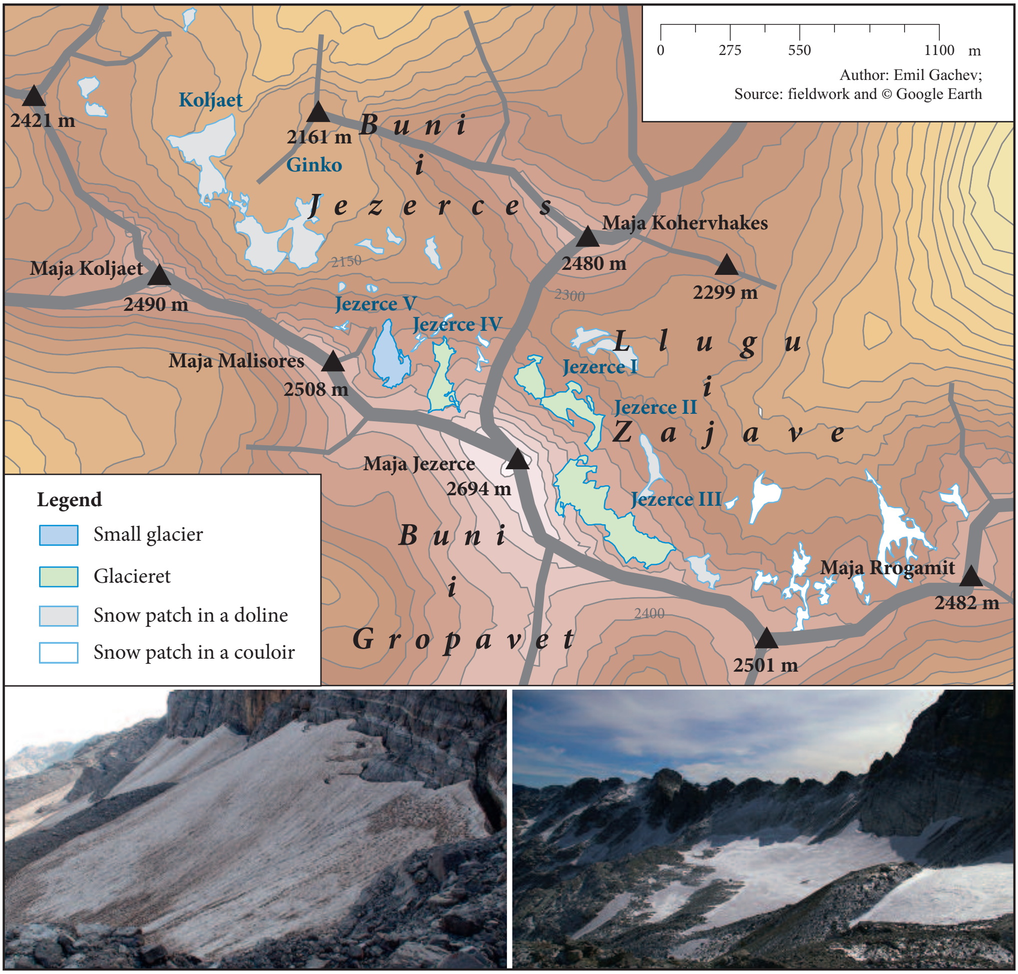

Figure 2: Small glaciers and snow patches in the Mount Jezerca area (Prokletije Massif, Albania). Top: Small glaciers and snow patches in the Mount Jezerca area, Prokletije Massif, Albania (height difference between contour lines is 50 m). Bottom left: the glacierets Jezerce I (in the front) and II (in the back). Bottom right: Jezerce III glacieret. Photos were taken by Emil Mariov Gachev.

Two long-lasting snow patches cover the floor of the Buni i Jezercës Cirque at 1,980 to 2,100 m: the *L*-shaped Koljaet Snow Patch and the double Ginko Snow Patch. In some years the snow thickness in late summer can reach 10 m, and the patch may entirely disappear in others.

2.2 The Durmitor Massif

The Durmitor Massif (with its highest peak Bobotov Kuk, 2,522 m) is a relatively small mountainous area in northwest Montenegro (123 km^2; Cerović 1991; Figure 3). It rises above a hilly karst plain with an elevation of 1,450 to 1,600 m that borders it to the east, northeast, and northwest.

The Dumitor Massif is built of carbonate rock (Mirković 1983). Thick limestones and dolostones compose its northern and central parts, including the main ridge and the highest peaks. To the southwest they make contact with flysch via a linear nappe structure (Djurović 2011).

The Durmitor Massif was heavily glaciated in the Pleistocene. The ELA of the maximum Pleistocene glaciation was at about 1,400 to 1,600 m (Djurović 2009; Hughes et al. 2011), and glaciers reached far beyond the mountain margins (Hughes and Woodward 2008). Several vast and deep cirques were carved on the northern slopes.

Today only one tiny glacier exists on the Durmitor Massif: the Debeli Namet Glacier in the deep Velika Kalica Cirque (Figure 3). The glacier lies at an elevation of 2,035 to 2,200 m and is oriented to the north-northeast. Its length is usually about 300 to 320 m and its width 120 to 140 m. A concave upper section and a convex lower part, surrounded by a high moraine, are distinguished. The glacier lies at the base of a rock wall 200

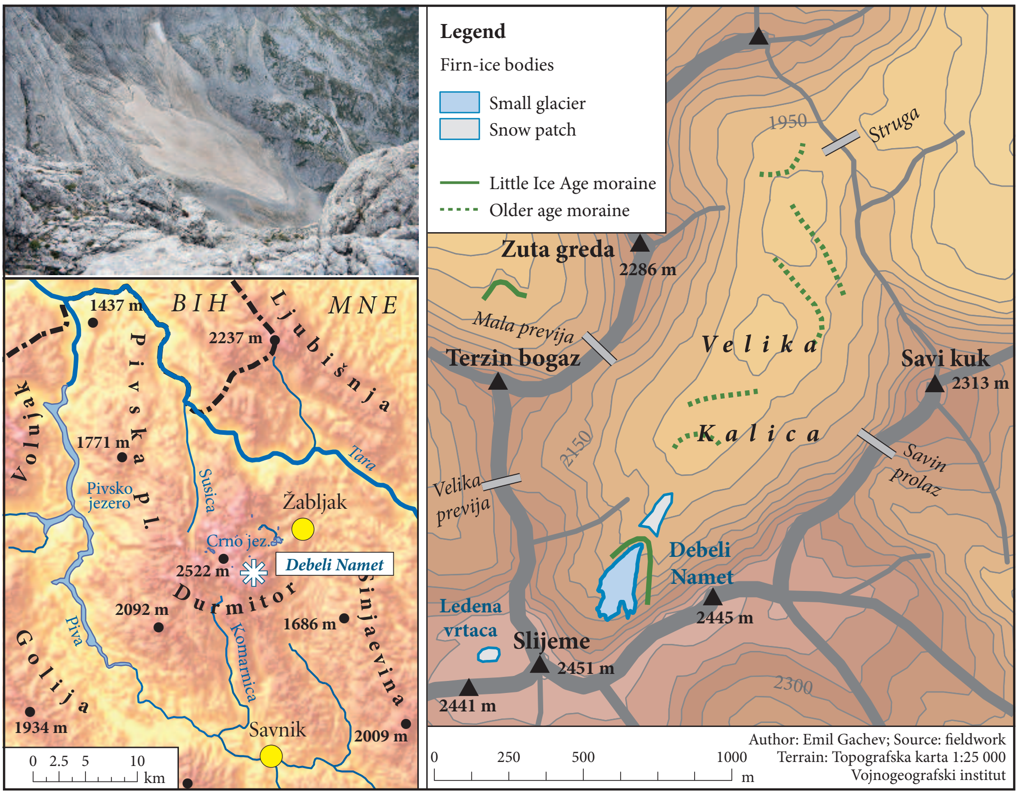

Figure 3: Location of the Durmitor Massif and the Debeli Namet Glacier. Botton left: location of the Durmitor Massif and the Debeli Namet Glacier (digital elevation model by US Geological Survey). Right: a map of Velika Kalica cirque with firn-ice bodies (height difference between contour lines is 50 m). Top left: the Debeli Namet glacier in October 2018. Photo was taken by Emil Mariov Gachev.

to 250 m high. On top of it a small plateau serves as an additional snow source area during winter. The glacier was researched by Nicod (1968), Djurović (1999), and Kern et al. (2007). Hughes (2007) studied the surrounding moraines using lichenometry and dated it to 1878–1904. Later, Hughes (2008) presented size measurements of the glacier for the period from 2003 to 2007 and analyzed the climate factors for glacier existence. The most detailed information on the glacier's morphology and size was provided by Djurović (2012).

3 Methods

The research for this study was carried out from 2011 to 2018 and consisted of three stages: examining satellite images and maps, fieldwork at the end of the annual glacier mass balance cycle (usually in October), and data analysis and summarizing the results.

Figure 4: Meteorological stations in Montenegro (with elevations) referred to in this paper (image background: ASTER DEM by earthdata.nasa.gov).

Good-quality Google Earth images are available for the Prokletije Massif for October 29th, 2006, October 4th, 2013, September 30th, 2016, and August 31st, 2018. They were used to set the targets for fieldwork.

The areas of the observed glacierets and snow patches in the Prokletije Massif were calculated based on field measurements, GPS recordings, and photographs from fieldwork. A laser range finder was used to measure the lengths, widths, heights, and slope tilts of landforms. Changes in firn/ice levels were recorded in the field using paint marks. For the Debeli Namet Glacier, rope measurement of its greatest length and width was performed in 2011, and then the area was calculated by digitizing a photograph taken in the field from a remote position. Between 2012 and 2018, areas were processed by overlaying photographs taken from the same position. The area for 2019 was calculated based on a photograph from September 30th, available on the website of the Institute of Hydrometeorology and Seismology of Montenegro (*Zavod za hidrometeorologiju i seizmologiju Crne gore*; Internet 1). The size for September 1998 was calculated from our photograph.

For the analysis of climate, temperature data are available for Podgorica from 1949 to 2009 (Internet 1, 2). Monthly temperatures and precipitation for five stations (Figure 4) were retrieved from the annual bulletins of the Montenegrin institute (Godišnjak… 2010; 2011; 2012; 2013; 2014; 2015; 2016; 2017; 2018), as well as data on monthly snow cover thickness for Plav, Žabljak, and Šavnik. Since the autumn of 2017, the ground temperature at the moraine near the Debeli Namet Glacier has been monitored on an hourly basis by a temperature logger with an accuracy of 0.3 °C.

Simple positive degree-day models were calculated for the sites of the Debeli Namet Glacier and for an altitude of 2,400 m in the area of Mount Jezerca from 2011 to 2018, on the basis of extrapolated temperature data from the stations at Žabljak and Plav, respectively, using a lapse rate of 0.55 °C / 100 m.

For the analysis, climate data were summarized in accordance with the glacier mass balance year, which lasts from November to October (Gachev, Stoyanov and Gikov 2016). The accumulation season is presented by the data from December to March, and the ablation season by the data from June to September.

4 Results

4.1 Size of firn-ice bodies

Changes in the total area of the glaciers and snow patches monitored on the Prokletije Massif in the autumn (Table 1, Figure 5) show a gradual decrease in size, followed by a sharp increase.

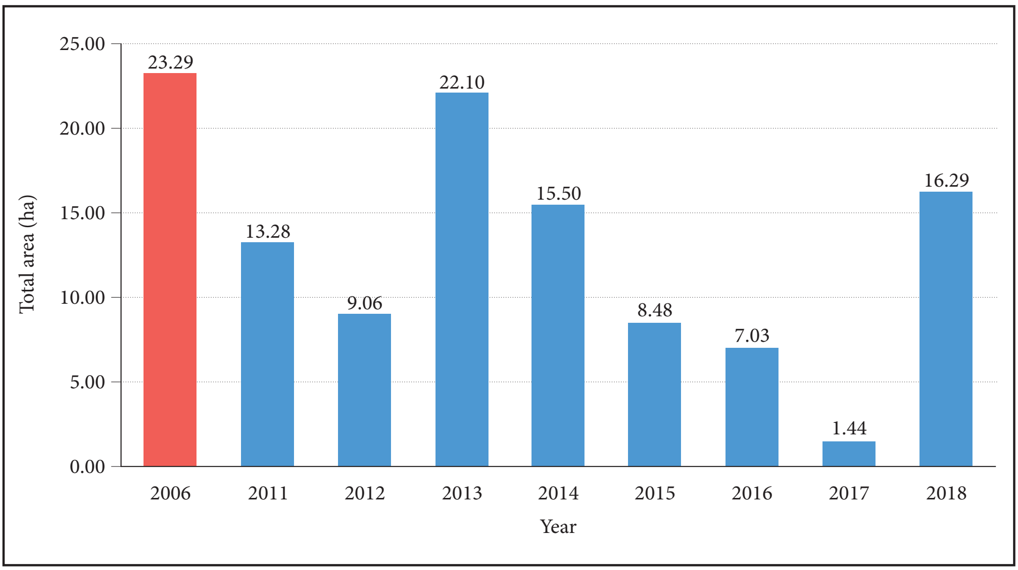

Figure 5: Total area of monitored glacierets and snow patches near Mount Jezerca (Prokletije Massif) for 2006 and 2011–2018.

Table 1: Size of the glacierets and snow patches monitored in hectares.

Name	Year and source									
	2006, S	2011, F	2012, F	2013, S+F	2014, F	2015, F	2016, S+F	2017, F	2018, S+F	CV
Debeli Namet*	3.10	2.74	2.22	3.00	2.70	1.78	1.59	0.10	2.38	0.40
Jezerce I	1.21	1.08	0.84	1.31	0.98	0.70	0.63	0.24	0.96	0.35
Jezerce II	2.26	1.77	1.34	2.45	1.66	0.93	0.83	0.37	1.62	0.43
Jezerce III	6.64	4.26	3.59	6.72	4.74	3.47	2.89	0.45	5.23	0.43
Jezerce IV	1.85	1.07	0.78	1.74	1.12	0.69	0.26	0.05	1.34	0.58
Jezerce V	2.22	1.69	1.40	2.68	2.13	1.30	0.92	0.33	2.03	0.42
Ginko Snow Patch	5.13	2.41	0.77	4.06	3.09	0.57	1.05	0.00	2.88	0.71
Koljaet Snow Patch	3.98	1.01	0.32	3.14	1.78	0.81	0.04	0.00	2.22	0.90
Snezhnika**	0.77	0.55	0.34	0.65	0.38	0.53	0.51	0.33		0.27
Banski Suhodol**	1.40	1.33	0.93	1.42	1.14	1.04	1.13	0.97		0.14

S = satellite, F = fieldwork, CV = coefficient of variation, *real area (others are projected areas), **small glaciers in Pirin (Bulgaria) given for reference (Gachev and Mitkov 2019)

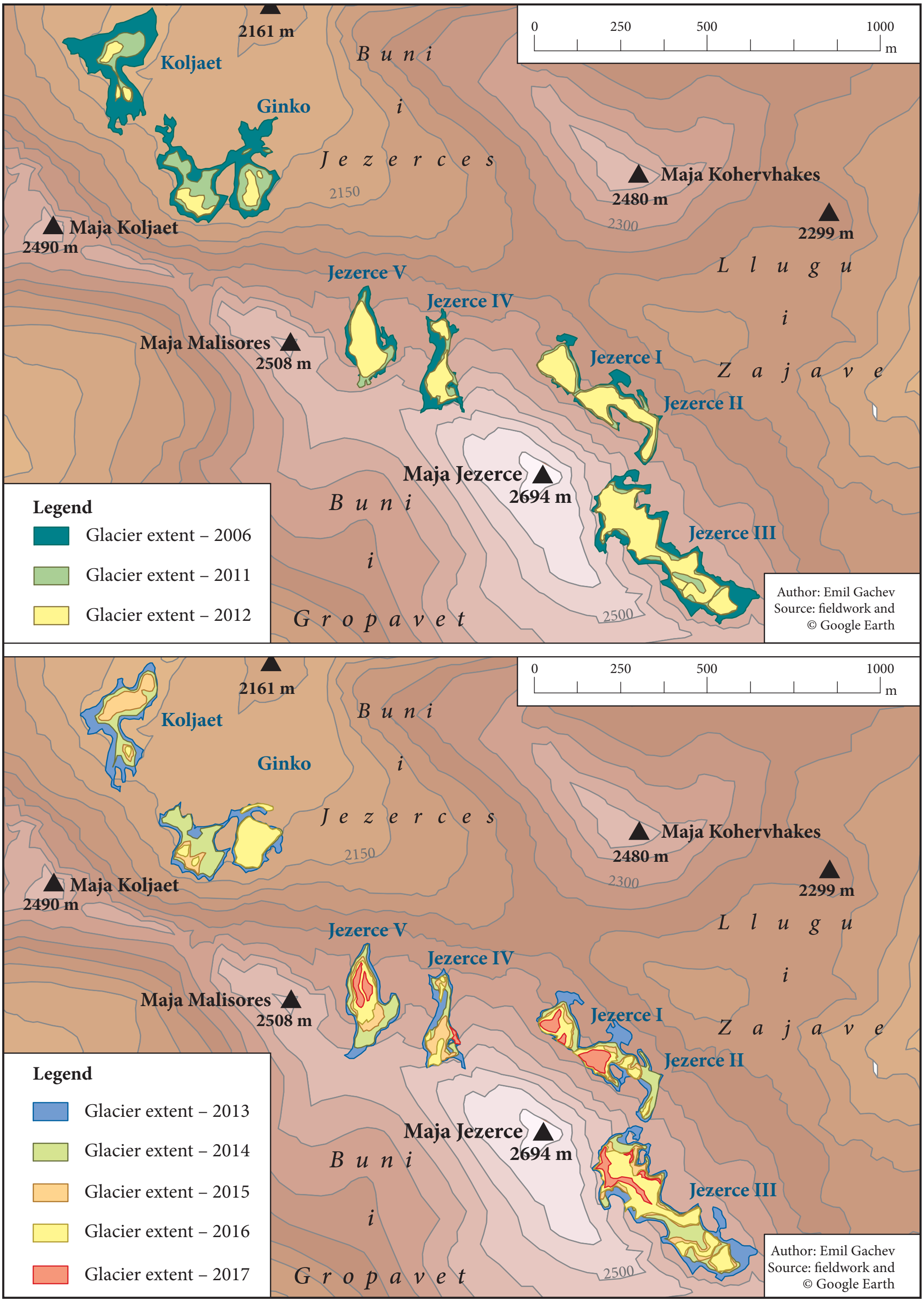

Figure 6: Spatial extent of small glaciers and snow patches in the area around Mount Jezerca (Prokletije Massif) for 2006, 2011, and 2012 (above) and 2013–2017 (below). Height difference between contour lines is 50 m.

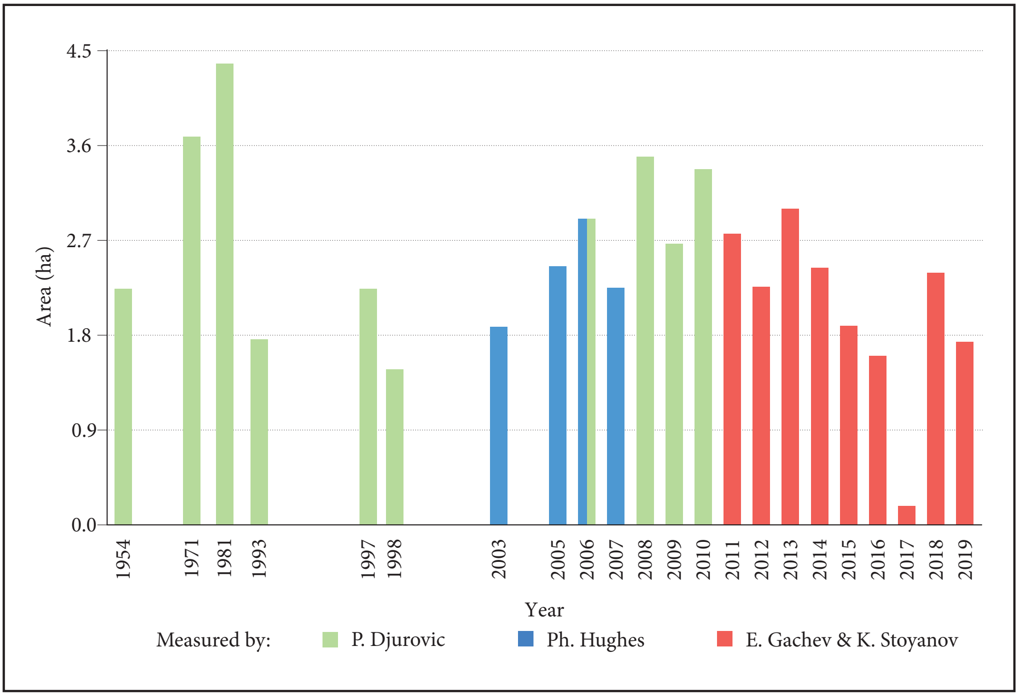

Figure 7: Area of the Debeli Namet Glacier from 1954 to 2019 in hectares.

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Figure 8: The Debeli Namet Glacier in October 2017.

Snow patches have a much higher amplitude of size variation than glacierets, which is demonstrated by the values of the coefficient of variation (CV) in Table 1. The severe reduction of glaciers and their transition into ice patches is often accompanied by fragmentation into parts (Del Gobbo et al. 2016), fragmentation itself depending on the topography of each site. In the area of Mount Jezerca, fragmentation reached its maximum in 2016, when the six firn-ice bodies were scattered into seventeen fragments (Figure 6).

The Debeli Namet Glacier on the Durmitor Massif has been studied much more in terms of size (Figure 7). Here again, several series can be outlined, which start with a sharp increase in area and continue with a gradual decrease in the following few years. Due to its simpler glacier topography, no fragmentation has been observed, only perforation of the middle section in some years.

The results from Table 2 and Figures 5 and 6 demonstrate negative trends in the development of all firn-ice bodies for the period observed. In the autumn of 2017, the snow patches completely melted and all the glacierets turned into minor ice patches. Debris fields partly cemented with ice were largely exposed on the surface. Corroded by the melt streams, the residual ice at the Jezerce III Glacieret still had a visible thickness of at least several meters. Exposed ice-cemented debris was also recorded at the bottom of the melted Koljaet Snow Patch. Only a tiny white spot measuring 0.1 hectare was left from the Debeli Namet Glacier. Again, some ice layers several meters thick were recorded under the debris in the lower section of the glacier depression (Figure 8).

Another recovery of glaciers was witnessed in 2018, when in September up to 5 m of the previous winter's snow was measured in the cirques on the Prokletije and Durmitor Massifs. The latest observations from the autumn of 2019 show that the Debeli Namet Glacier shrank by about 30% compared to the previous year, and the record low snow for the winter or 2019/2020 (Internet 1) is a prerequisite for a further reduction.

4.2 Characteristics of climate

Warming since the second half of the nineteenth century has led to severe glacier retreat worldwide. However, climate change at the regional and local scale can differ from what is observed globally. This also applies to the reaction of small glaciers, which greatly depends on topography (Zemp et al. 2008).

In the area studied on the Prokletije Massif, traces of fresh moraines below the Koljaet Snow Patch (Wilkinson 2011) and the Jezerce III Glacieret indicate that during the Little Ice Age (LIA) the glaciation was much larger. Evidence for large LIA glaciers in several other cirques on the Durmitor Massif were confirmed by Hughes (2007, 2010).

In the last sixty years, the mean annual air temperature at Podgorica (Figure 9) rose by 1.2 °C, but the warming has been much more pronounced during the last four decades (0.45 °C per decade). Comparing the period from 2010 to 2018 with the standard (1961–1990), the greatest rise has been for summer temperatures (2.4–3.0 °C), and the lowest for winter temperatures (0.3–1.6 °C).

From 1951 to 2010, no trend was observed in annual precipitation, but the following general episodes can be outlined: dry (1951–1957), wet (1958–1985), dry (1985–2003), and wet (2004–2010; Ducić et al. 2011). The period from 2005 to 2014 was rather wet, and from 2015 to 2018 the precipitation amounts were around the average for the period 1951 to 2010 (Internet 2). A very weak negative trend was observed from 1951 to 1990 for winter precipitation (Ducić et al. 2011), but a considerable rise was recorded after the dry period at the beginning of the 1990s.

The climate fluctuation between dry/wet and warm/cool conditions determined smaller glacier sizes in the 1950s, larger in the 1960s and 1970s, and a strong recession in the 1980s and 1990s (Figure 7).

In the last decade, average temperatures were 1.3 to 1.8 °C higher than those for the standard period, and the climate showed notable variations (Godišnjak … 2010; 2011; 2012; 2013; 2014; 2015; 2016; 2017; 2018; Burić, Micev and Mitrović 2012).

Summer temperatures determine the overall rate of ablation. The hottest was the summer of 2012, followed by 2015 and 2017 (Figure 10). In a long-term context, at Žabljak the »normal« summer temperatures (June–September) for 2010 to 2018 are 2.1 °C higher than for 1961 to 1990. On the other hand, the average winter precipitation (December–March) was 37% higher than that of the standard period, whereas summer rains decreased by 16%. Therefore, small glaciers and snow patches continued to exist in the second decade of the twenty-first century, despite the pronounced warming (with smaller sizes than during the 1970s and 1980s).

Precipitation from 2010 to 2018 was quite variable. For the period from December to March, maximum amounts were recorded in 2013 and 2018, and for June to September in 2014 (in western Montenegro) and in 2016 (to the east).

Based on snow cover data for Žabljak, Šavnik, and Plav, the winter of 2011/2012 can be defined as »very snowy,« 2012/2013 and 2014/2015 as »snowy,« 2010/2011 and 2017/2018 as »moderate,« 2015/2016 and 2016/2017 as winters with »little snow,« and 2013/2014 as a »snowless« winter. At Plav, at 930 m, the record snow thickness, registered in February 2012 (176 cm), approached that at Žabljak (208 cm), situated at 1,450 m. The local conditions around glaciers, however, are quite different from those on a free slope. In 2017/2018 the temperature logger at the Debeli Namet Glacier at 2,035 m registered 247 days with snow, compared to only 149 days at Žabljak (Internet 1).

4.3 Glacier fluctuation and climate

The correlation between precipitation for the glacier accumulation season (November–April) at Žabljak and the size of the Debeli Namet Glacier for the 2009/2010 to 2017/2018 balance years is strong, reaching +0.70. When compared to precipitation at Nikšić, which is in a windward position to the moist air masses from the southwest, the correlation is +0.86. Similar is demonstrated by the relationship between the sizes of glacierets on the Prokletije Massif and precipitation at Plav for the same period: the correlation is between +0.74 and +0.81. On the other hand, simple degree-day models for the Žabljak and Plav stations do not show any appreciable relationship between glacier size variations and ablation temperatures. Although the observation period is quite short, these results indicate the leading role of winter precipitation for short-term glacier fluctuations.

A detailed analysis of the relations between glacier size and climate year by year is presented below. For reference, interannual size changes of firn-ice bodies and the main climate factors, presented in relative units, are shown in Table 2.

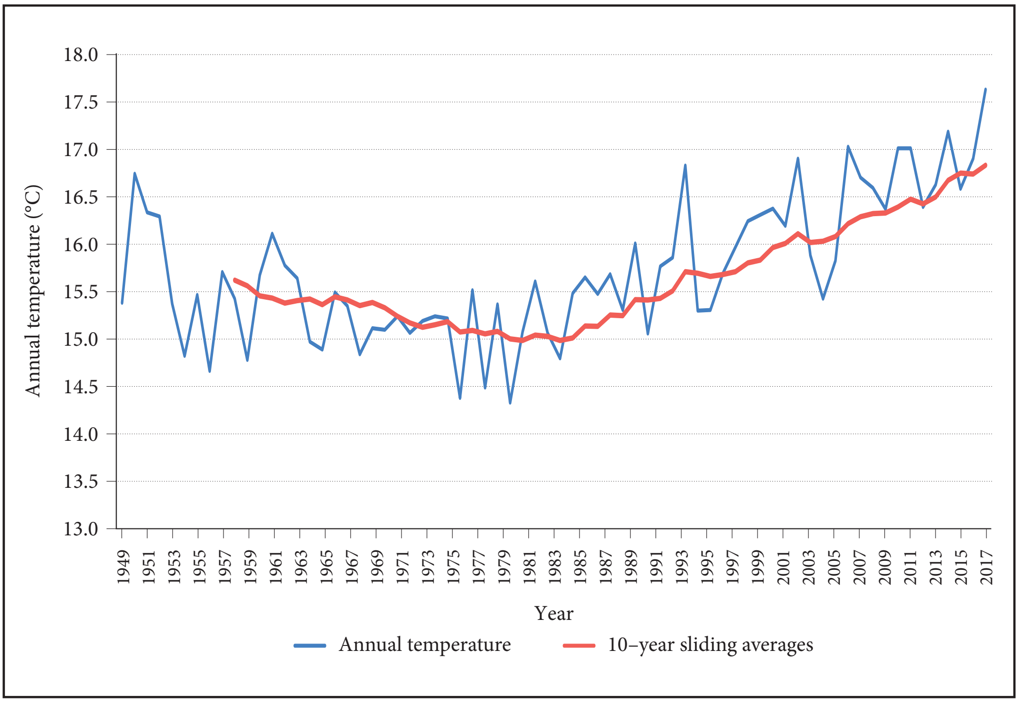

Figure 9: Annual air temperature at Podgorica, 1949–2018 (Internet 1).

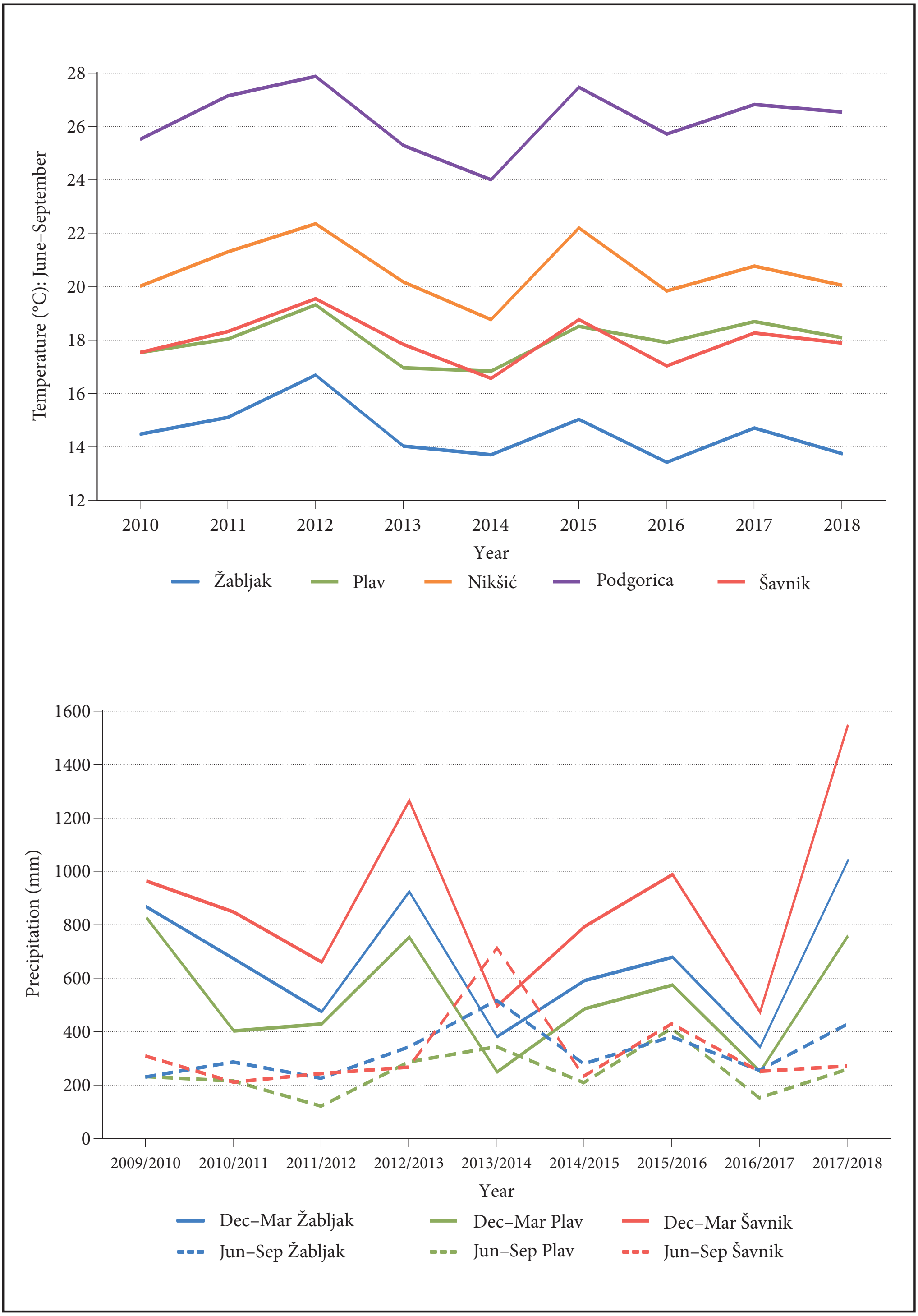

Figure 10: Summarized temperature and precipitation data for the 2010/2011 to 2017/2018 glacier mass balance years (Internet 1).

Table 2: Relative climate data for Žabljak, Šavnik, and Plav, and the size changes of firn-ice bodies for the balance years 2009/2010 to 2017/2018: anomalies based on the 2010–2018 average.

	Winter						Summer							Area change rel. to previous year, %		
														Prokletije		Durmitor
	Snow, % avg. cm × days, Oct.–May			Winter precipitation, %, Dec.–Mar.			Summer temp., ±°C, Jun.–Sept.			Precipitation, %, Jun.–Sept.						
Balance year	Ž	Š	P	Ž	Š	P	Ž	Š	P	Ž	Š	P	Glacier mass balance	Snow patches	Glacierets	Glaciers
2009/10	–	–	–	136	–	–	–0.1	–0.4	–0.5	59	–	–	+	NA	NA	+27
2010/11	96	115	73	106	96	82	0.6	0.3	0.0	73	72	100	–	NA	NA	–15
2011/12	143	259	261	74	75	88	2.1	1.6	1.3	58	110	99	– –	–68	–19	–21
2012/13	154	107	98	145	143	155	–0.5	–0.1	–1.0	87	106	113	+ +	+556	+87	+36
2013/14	41	23	41	60	56	51	–0.8	–1.4	–1.2	133	144	106	–	–32	–29	–17
2014/15	134	100	135	93	90	100	0.5	0.8	0.5	71	84	79	–	–71	–33	–28
2015/16	54	38	41	106	112	118	–1.1	–0.9	–0.1	98	130	153	–	–8	–22	–17
2016/17	61	66	72	54	53	51	0.2	0.3	0.7	66	67	68	– – –	–100	–74	–93
2017/18	117	92	79	163	175	156	–0.8	–0.1	0.1	110	87	84	+ + +	Not calculable	+675	+2,300

Ž = Žabljak, Š = Šavnik, P = Plav, NA = not applicable

2009/2010: a 27% increase in the size of the Debeli Namet Glacier was caused by a snowy winter, a cool summer, and rare summer rains.
2010/2011: At Žabljak, winter precipitation was 22% lower than during the previous winter but still moderate, and the summer temperature was 0.7 °C higher than in 2010. The Debeli Namet Glacier shrank by 15%, despite the deficit of summer rains. On the Prokletije Massif, the winter was a little drier, and summer precipitation was higher, which was compensated by lower summer temperatures. However, the size of glacierets remained considerable.
2011/2012: December and March were dry, but in February a record heavy snow fell across Montenegro. The snow cover remained deep for a long time because of very low temperatures, weak snow compaction, and low melt rates. Nonetheless, the total amount of winter precipitation was low. The heavy snowfall triggered avalanches that piled deep snow on cirque floors. This lengthened the melt period in the spring and helped small glaciers survive the extremely hot and dry summer, with only around 20% area loss. However, the snow patches on the Prokletije Massif were greatly affected by the heat.

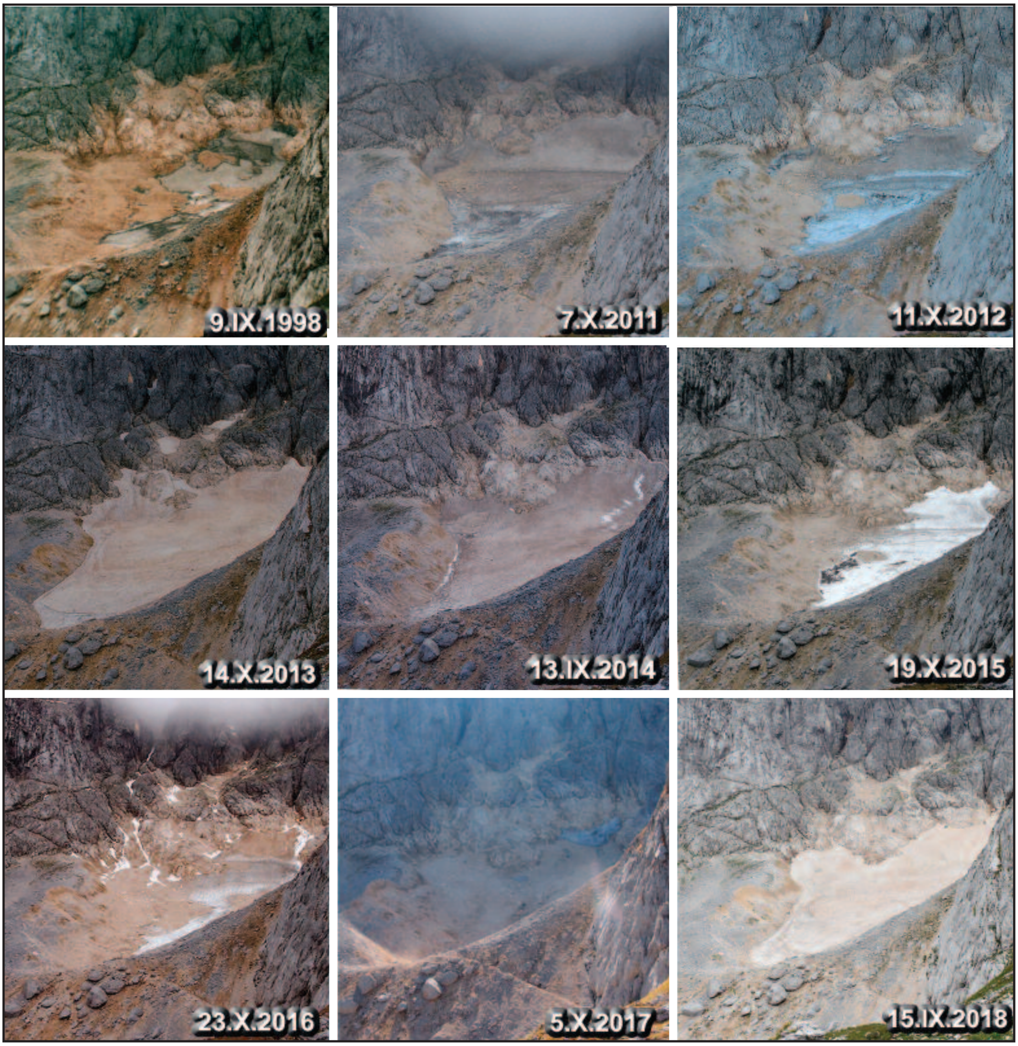

Figure 11: The Debeli Namet Glacier at the end of the balance year: 1998 and 2011–2018.

2012/2013: The snow cover was thinner than in 2011/2012, but it lasted longer due to the much higher and evenly distributed winter precipitation. The damp and moderately cold winter was followed by a cool summer. All firn-ice bodies expanded, reaching sizes comparable to those in 2006.
2013/2014: a very warm winter (+3 to +5 °C anomalies in February) with very low precipitation and extremely low snow cover provided modest accumulation. The summer was the coldest in the period studied, which was crucial for preserving glaciers from severe shrinkage. Abundant summer rains contributed to a glacier retreat in the range of 17 to 32%. The retreat was more due to rains than temperature.
2014/2015: Moderate winter accumulation (precipitation around and below average with a short episode of heavy snow in March) combined with a warm summer resulted in another shrinkage of small glaciers by 28 to 33%, and 71% of low-elevation snow patches.
2015/2016: Winter precipitation was average but the snow cover was very thin. Precipitation was evenly distributed, and avalanche activity was low. This caused earlier ablation. Summer temperatures were low, but the amounts of rain were above average. As a result, a slight decrease was recorded (from 8 to 22%).
2016/2017: The driest winter with the least snow during the period analyzed was followed by a dry and warm summer (July and August were had even higher temperatures). This resulted in catastrophic shrinkage and the disappearance of almost all firn-ice bodies (Figure 11). This situation was supported by their very low starting size from the previous autumn.
2017/2018: a high positive mass balance of all firn-ice bodies was determined by the wet winter and a cool to moderate summer. Avalanche snow delayed the start of active ablation in cirques.
2018/2019: The winter was moderately wet (with much less snow than in 2017/2018), whereas the summer was warm, with little rain. As a result, a negative mass balance and recession was again recorded (the Debeli Namet Glacier shrank by a third).

5 Discussion

Firn-ice bodies in the highest parts of the Dinaric range have recently demonstrated a specific pattern of short-term variations: considerable accumulation in a particular year (»recharge«) followed by several years of gradual decrease. Such behavior is mostly determined by short-term fluctuations in winter precipitation.

Interannual changes in small firn-ice bodies across southern Europe typically have high amplitudes (Hughes 2008). In the wider region, variations are sometimes synchronous but often demonstrate a »staggered« pattern, determined by different climate factors.

Glacierets in the Pirin Mountains of Bulgaria with a more continental climate are less variable, in both the long and short terms (see Table 1). Their short-term fluctuations are mainly driven by changes in summer temperature, and winter precipitation plays a secondary role (Gachev 2016). The heatwaves in the summers of 2012, 2017, and 2019 caused record minimums of those glacierets, but in the last twenty-five years interannual changes have been more often controversial, and gradual decrease series were rarely recorded.

In contrast, the firn-ice patches in the High Tatras show contrasting patterns of short-term variation among themselves, which are not closely related to temperature, due to the strong effect of intensive summer rains, which are of an accidental character and might affect only particular sites (Gądek 2008).

In a longer-term context, the post-LIA recession of the glaciers in the Mediterranean has comprised periods of rapid retreat, separated by episodes of relative stagnation, and even minor advances. Many of the very small glaciers today on the southeast periphery of the Alps, the Apennines, and the Pyrenees had much larger extents in the past and underwent immense shrinkage between the 1970s and the 2000s, mainly as a result of temperature rise (D'Orefice et al. 2000; Gabrovec et al. 2014; Colucci et al. 2014; Pecci, D'Agata and Smiraglia 2008). In the last two decades, many of those glaciers have turned into glacierets and entered a stagnation phase: being restricted to only the most favorable locations, these tiny bodies came under increased topoclimatic control, and they »decoupled« to some extent from the global climate.

»Decoupling« depends on size. The threshold size depends on the particular topography of each site, and it is usually not larger than 1 to 5 hectares. The glaciers in the Dinaric range underwent this stage much earlier than those in the southeastern Alps and the Apennines, probably in the first decades of the twentieth century, and those in the Pirin Mountains were probably in a »decoupled« state already during the

LIA. Since the 1950s, small glaciers in the Balkans have demonstrated relatively modest trends of shrinkage (Djurović 2012; Grunewald, Scheithauer and Gikov 2008). In contrast, some of the larger cirque glaciers in the Mediterranean, such as Mount Perdido in the Pyrenees or Mount Marmolada in the Dolomites, still have not reached the decoupling size threshold. However, they have been subject to rapid recession in recent decades (Lopez-Moreno et al. 2016; Santin et al. 2019).

Despite the fact that glacierets demonstrate enhanced resistance to climate change due to strong topoclimatic influences, they are not in a balanced state under the conditions of recent active warming. This is evidenced by the fact that in years with climate conditions close to average for the last decade, the net mass balance of firn-ice bodies at all locations was negative. As a result, long-term decline trends have been observed for very small glaciers everywhere in the mountains of Southern Europe. It is expected that the minimums in the interannual variation of glaciers' size will become increasingly expressed.

For the Debeli Namet Glacier, the size in 2017 was the smallest on record, far beyond the reduced sizes in the 1990s. The data available for firn-ice bodies on the Prokletije Massif, as well as the position of moraines, indicate that it is very likely that in 2017 they also reached their absolute minimum, at least since the beginning of the LIA, or perhaps even since earlier stages of the Holocene, as suggested for the Triglav Glacier by Lipar et al. (2020).

6 Conclusion

In the highest mountain massifs of the Dinaric range, there are still many permanent firn-ice bodies. Their recent interannual behavior reflects the effects of regional climate change. Recently, six small glaciers and two sustainable snow patches have demonstrated great short-term variations of size and a downward long-term trend.

Winter precipitation is of major importance for short-term glacier variations. In recent years, the variation pattern of winter precipitation consisted of separate winters with a high volume of snow, when small glaciers and snow patches increased, followed by two to four drier winters. The rising temperatures increase ablation and make the minimums in the size of snow patches and glaciers increasingly severe.

In years when climate conditions were around the averages for the latest period (2010–2018), small to moderate glacier shrinkage was observed. Therefore, current average conditions do not support the long-term existence of small glaciers in the highest mountain regions of the Dinaric range.

From 2013 to 2017, the eight monitored firn-ice bodies underwent gradual recession, effectively turning into ice patches. After the summer of 2017, six of them had completely melted, leaving only fields of debris mixed with ice at some locations. Considering the temperature changes, this has probably been the smallest ice extent since the beginning of the LIA. The reason was the observed sequence of four years with scant winter precipitation, thin snow cover, and relatively small avalanche activity, when the earlier disappearance of the snow cover caused longer ablation times across glacier surfaces. During the summers of 2014 to 2017, small glaciers and snow patches were subjected to enhanced ablation either by heat waves (in 2015 and 2017) or by abundant rains (in 2014 and 2016).

Summer temperature is a leading factor in the long-term evolution of firn-ice bodies. This is why, despite the recent increase in average winter precipitation, the continuing rise of temperatures will likely lead to the disappearance of small glaciers in the Dinaric Mountains in the foreseeable future if present trends persist. Glacierets will be downgraded to ice patches and snow patches sooner than the glacierets in the Pirin Mountains due to the higher amplitude of their size variation. This might become a fact in the next decade.

ACKNOWLEDGEMENTS: I am very grateful to the Southwest University of Blagoevgrad for providing funding for this research through the following grants: SRP-B3/2012, SRP-B4/2013, SRP-B3/2014, SRP-A10/2015, RP-B4/2016, RP-A13/2017, and RP-A4/2018. The research results are also connected with the project FNI 02/70 (BMES, 2014-2016). I would also especially like to thank Matija Zorn from the ZRC SAZU Anton Melik Geographical Institute in Slovenia and Predrag Djurović from the University of Belgrade in Serbia for their support and encouragement, and also the journal reviewers and editors for their constructive remarks.

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- Gams, I. 1994b: Changes of the Triglav glacier in the 1955-94 period in the light of climatic indicators. Geografski zbornik 34.
- van Hall, R. L., Cammeraat, L. H., Keesstra, S. D., Zorn, M. 2016: Impact of secondary vegetation succession on soil quality in a humid Mediterranean landscape. Catena, In press. DOI: https://doi.org/10.1016/j.catena.2016.05.021 (25. 11. 2016).
- de Kerk, G. V., Manuel, A. R. 2008: a comprehensive index for a sustainable society: The SSI – the Sustainable Society Index. Ecological Economics 66-2,3. DOI: https://doi.org/10.1016/j.ecolecon.2008.01.029
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- Šifrer, M. 1997: Površje v Sloveniji. Elaborat, Geografski inštitut Antona Melika ZRC SAZU. Ljubljana.

5.5 Citing online material with authors and titles

- Bender, O., Borsdorf, A., Heinrich, K. 2010: The interactive alpine information system GALPIS. Challenges for mountain regions, Tackling complexity. Internet: http://www.mountainresearch.at/images/Publikationen/Sonderband/bender-borsdorf-heinrich.pdf (4. 8. 2014).

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- Internet 1: http://giam.zrc-sazu.si (18. 11. 2016).
- Internet 2: http://giam.zrc-sazu.si/ (22. 7. 2012).
- Internet 3: http://ags.zrc-sazu.si (23. 7. 2012).

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- Popis prebivalstva, gospodinjstev, stanovanj in kmečkih gospodarstev v Republiki Sloveniji, 1991 – končni podatki. Zavod Republike Slovenije za statistiko. Ljubljana, 1993.
- WCED – World commission on environmental and development: Our common future – Brundtland report. Oxford, 1987.

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- Buser, S. 1986: Osnovna geološka karta SFRJ 1 : 100.000, list Tolmin in Videm (Udine). Savezni geološki zavod. Beograd.
- Digitalni model višin 12,5. Geodetska uprava Republike Slovenije. Ljubljana, 2005.
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5.9 Citing official gazettes

- 1999/847/EC: Council Decision of 9 December 1999 establishing a Community action programme in the field of civil protection. Official Journal 327, 21.12.1999.
- Zakon o kmetijskih zemljiščih. Uradni list Republike Slovenije 59/1996. Ljubljana.
- Zakon o varstvu pred naravnimi in drugimi nesrečami. Uradni list Republike Slovenije 64/1994, 33/2000, 87/2001, 41/2004, 28/2006 in 51/2006. Ljubljana.

5.10 In-text citations

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6 Tables and figures

Number all tables in the paper uniformly with their own titles. The number and the text are separated by a colon, and the caption ends with a period. Example:

Table 1: Number of inhabitants of Ljubljana.

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Tables should contain no formatting and should not be too large; it is recommended that tables not exceed one page.

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PUBLISHER

Anton Melik Geographical Institute
Research Center of the Slovenian Academy of Sciences and Arts
PO Box 306
SI–1001 Ljubljana
Slovenia

SOURCES OF SUPPORT

The journal is subsidized by the Slovenian Research Agency and is issued in the framework of the Geography of Slovenia long-term core research programme (P6-0101). The journal is also supported by the Slovenian Academy of Sciences and Arts.

JOURNAL HISTORY

Acta geographica Slovenica (print version: ISSN: 1581-6613, digital version: ISSN: 1581-8314) was founded in 1952. It was originally named *Geografski zbornik / Acta geographica* (print ISSN 0373-4498, digital ISSN: 1408-8711). Altogether 42 volumes were published. In 2002 *Geographica Slovenica* (ISSN 0351-1731, founded in 1971, 35 volumes) was merged with the journal.

Since 2003 (from volume 43 onward) the name of the joint journal has been *Acta geographica Slovenica*. The journal continues the numbering system of the journal *Geografski zbornik / Acta geographica*.

Until 1976, the journal was published periodically, then once a year, from 2003 twice a year and from 2019 three times a year.

The online version of the journal has been available since 1995. In 2013, all volumes of the magazine were digitized from the beginning of its publication to 1994 inclusive.

All papers of the journal are available free of charge in digital form on the journal website http://ags.zrc-sazu.si.

Those interested in the history of the journal are invited to read the paper »The History of *Acta geographica Slovenica*« in volume 50-1.

ISSN: 1581-6613
UDC – UDK: 91
ACTA GEOGRAPHICA SLOVENICA
GEOGRAFSKI ZBORNIK

60-2
2020

Print/tisk: Present, d. o. o.

Ljubljana 2020

ACTA GEOGRAPHICA SLOVENICA
GEOGRAFSKI ZBORNIK
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Contents

ISSN 1581-6613
9 771581 661010