



Tri-dimensional Model of the Radovna Glacier from the Last Glacial Period

Tridimenzionalni model Radovniškega ledenika iz zadnje poledenitve

Luka SERIANZ

Geološki zavod Slovenije, Dimičeva ulica 14, SI-1000 Ljubljana; e-mail: luka.serianz@geo-zs.si

Prejeto / Received 29. 6. 2016; Sprejeto / Accepted 10. 11. 2016; Objavljeno na spletu / Published online 23. 12. 2016

Key words: Quarternary, glaciation, Radovna Valley, 3D model, geomorphological mapping

Ključne besede: kvartar, poledenitev, dolina Radovne, 3D model, geomorfološko kartiranje

Abstract

The Radovna River Valley is located in the northwest of Slovenia, in the Julian Alps, and bounded by two plateaus – Pokljuka in the south and Mežakla in the north. Typical geological and geomorphological shapes in the valley indicate several glacial stages in the Pleistocene. As a result of glacial activity and river outflow, typical glacial and river terraces can be observed throughout the valley, especially in its lower and middle regions. The paper deals with the Radovna Glacier from the last glacial period, the existence of which is evidenced by certain remaining geomorphological features in the valley. Little investigative research on the Radovna Glacier, on its activity and extent, has been done in recent decades; the little that has been done has only featured the glacier as a secondary or incidental subject of research on the neighbouring Dolinka and Bohinj Glaciers. Both numerical modelling and field surveying were used for the reconstruction model, with work based on previous experiences and observations of hydrogeological conditions in the Radovna Valley. However, it must be emphasized that the model is only validated based on a few remaining traces of the glacier's activity.

Izvleček

Dolina reke Radovne se nahaja v severozahodnem delu Slovenije, v Julijskih Alpah med Poključsko planoto na jugu in planoto Mežakla na severu. Značilne geološke in geomorfološke oblike v dolini kažejo na pojavljanje poledenitev v različnih obdobjih v pleistocenu. Danes se v celotni dolini, predvsem pa v njenem srednjem in spodnjem delu, nahajajo številne ledeniško-rečne terase. V članku je predstavljen Radovniški ledenik iz zadnje poledenitve, katerega sledovi so pripomogli k rekonstrukciji nekdanjega okolja. V zadnjih desetletjih je bilo o obstoju in obsegu Radovniškega ledenika izvedenih le nekaj raziskav. Večinoma je bil ta omenjen v raziskavah sosednjih ledenikov, predvsem Dolinskega in Bohinjskega ledenika. Za rekonstrukcijski model, ki temelji predvsem na preteklih opazovanjih hidrogeoloških razmer v dolini, sta bila uporabljena numerično modeliranje in terensko kartiranje. Model je zaradi slabo ohranjenih sledov ledenika v veliki meri poenostavljen, a bo v prihodnje lahko služil kot osnova za nadaljnje podrobnejše raziskave.

Introduction

The Radovna River Valley is located in the northwest of Slovenia, in a mountainous region of the Julian Alps. It is a typical U-shaped alpine valley extending in the northwest/southeast direction and bounded by two carbonate plateaus, Pokljuka in the south and Mežakla in the north. From a geographical perspective it is divided into three parts: Spodnja Radovna (Lower), Srednja Radovna (Middle) and Zgornja Radovna (Upper). Within the latter (Upper) it is subdivided into the

Kot Valley and the Krma Valley. The Radovna Valley was formed in the late Pleistocene, mainly through glacial activity and river erosion. The shape of the valley is the result of Radovna Glacier activity; in literature and papers it is also referred to as the Radovina Glacier (MELIK, 1963). Fluvial processes also had an important role in the geomorphological forming of the Radovna Valley. Postglacial waters with high discharge levels and energy coefficients were particularly important, as accumulation and erosion processes play an important role in typical glacio-fluvial terraces

construction on both banks of the Radovna River (SERIANZ, 2013). However, due to lower average annual temperatures in the Quaternary period, which could be some 4–15 °C lower than the typical average today (SINGH et al., 2011), the upper parts of mountains in the region were also covered in snow during the summer. Subsequently, snow accumulation increased and eventually froze and turned to ice. The ice sheets slid across the valleys all the way to the equilibrium line where, due to enormous pressure, they began to melt. In Slovenia, all mountains as well as valleys in the Julian Alps – Karavanke, Kamnik-Savinja Alps (MELIK, 1963), Trnovski Gozd (ŽEBRE et al., 2013) and Snežnik (ŠIFRER, 1959) – were covered with ice in the Würmian glaciation stage. The paper presents a paleo-reconstructed 3D model of the Radovna Glacier from the last glacial period in the Würm. The concept of 3D model is based on previous hydrogeological investigations in the Radovna Valley (SERIANZ, 2013; SERIANZ, 2015; TORKAR & BRENČIČ, 2015; TORKAR, 2010).

The purpose of this paper is to:

- interpret the origin of the geomorphological features in the valley,
- confirm the existence of the glacier from the last glacial period,
- evaluate the extent of the glacier.

Pleistocene glaciations

The first theories that glaciers extended out of the Alps and onto the forelands were developed during the first half of the 19th century. VENETZ (1861) first presented the idea that glaciers approached the forelands in several stages. The idea gained credibility with PENCK & BRÜCKNER'S (1909) theory of four glaciation stages, borne out by a particular sequence of landforms in Europe called glacial series. These glacial periods were named Günz (MIS 16), Mindel (MIS 12), Riss (MIS 6) and Würm (MIS 2–4; 5a–d) after small rivers in Bavaria, while the most recent definition of glaciation stages is defined according to marine isotope stage (MIS) timescale. The well-known and widely accepted expansion theory of PENCK & BRÜCKNER (1909) was later modified and extended by three further glacial stages: Donau (EBERL, 1930), Biber (SCHAEFER, 1957) and Haslach (SCHREINER & EBEL, 1981). Each glaciation period was followed by an interglaciation period with typical postglacial waters. During the interglacial period the temperatures rose and the ice started to melt, which resulted in postglacial wa-

ters with a typically high energy index. According to PENCK & BRÜCKNER'S (1909) theory, three interglacials were observed (KUKLA, 2005; GIBBARD & VAN KOLFSCHOTEN, 2004): Günz-Mindel (MIS 13–15), Mindel-Riss (MIS 11) and Riss-Würm (MIS 5e). Variable climatic dynamics resulted in typical geomorphological structures in the Alps. These structures provide the most valuable data for paleo-glacial reconstruction and are an essential part of Quaternary investigations.

Three paleo-glaciers were observed in the Triglav range: the Dolinka Glacier, the Bohinj Glacier and the Radovna Glacier (RAKOVEC, 1928; MELIK, 1930; RAKOVEC, 1936). Among them only the extent of the Bohinj Glacier was attempted to be reconstructed (BAVEC, 2006). Some researchers attempted to provide evidence of activity of the Radovna Glacier (RAKOVEC, 1943) and evaluate its extent. It is assumed that the Radovna Glacier extended in the direction from Zgornja Radovna toward Krnica (DROBNE et al, 1975). MELIK (1963) thought that the Radovna Glacier was most active in Würm, where the most significant reconstruction of the valley's shape took place. However, such definition is very general, as the Würm covered roughly the period between 115 ka and 10 ka. Greatest glacial extension in Würm was represented by the Last Glacial Maximum (LGM). LGM is defined according to the marine isotope stage MIS 2 and is placed between 30 ka and 18 ka (IVY-OCHS et al, 2008). The altitude of the snow line during the LGM has been estimated at roughly 1300 m a.s.l. (MELIK, 1954; PENCK & BRÜCKNER, 1909; proposed 1350 m a.s.l.). Similarly, modelled geothermal data from several boreholes in Slovenia indicates temperatures are today some 7 °C higher than during the LGM. (BAVEC & TULACZYK, 2002; after ŠAFANDA & RAJVER, 2001). That would put the snow line in the Julian Alps at an altitude of 1300 – 1400 m a.s.l.

Evidence of the Radovna Glacier

It is assumed that the Radovna Glacier covered the whole of the Radovna Valley, ending in the village of Zgornje Gorje, where it was, at one point in the Würm, connected to the bigger Bohinj Glacier (NOVAK & BAVEC, 2013). Also, layers of fine grained glaciolacustrine deposits found in the Middle Radovna confirm the existence of the Radovna Glacier. In the former exploitation area in Srednja Radovna the maximum thickness of this deposits is estimated to have been 23.6 m (Iskra, 1982). Data from boreholes drilled

in the Gabrje area show some glaciolacustrine sediments also in the deepest sections of the glaciofluvial deposits (DROBNE, 1975). Radovna Glacier terminal moraine is located in the village of Zgornje Gorje. A typically shaped structure, known by its local name of Obočnica, could only have been formed by a massive amount of energy that only a glacier could produce. Along with the terminus, only a few moraine sediments can be found in the Radovna Valley. ŠIFRER (1952) stated that some moraine sediments can be found near the local forest road that runs from Stara Pokljuka to the Repečnikov rovt, at a maximum altitude of 960 m a.s.l. The same author mentioned some moraine sediments located near Krištanj, between Stara Pokljuka and Spodnja Radovna. However, this part of Stara Pokljuka was never covered by ice sheets at altitudes higher than 990 m a.s.l. (ŠIFRER, 1952). By the same token, some evidences of glacial activity are preserved in the higher reaches of the Pokljuka plateau (ŠIFRER, 1952). It is possible that these sediments belong to the small glaciers in Pokljuka plateau, which was covered with ice during the Würm glacial stage.

Furthermore, the moraine sediments occur in Stresena dolina, but only to a maximum altitude of 1150 m a.s.l. Moreover, some glacier sediments located at the Oblek meadow at altitudes of 1110–1180 m a.s.l. are mentioned in the existing literature (ŠIFRER, 1952). GAMS (1992) reported on moraine sediments near the local Zgornja Radovna-Mojstrana road. This part of the observation area, called Kosmačev preval, represents the transition valley raised above the altitudes of the Radovna Valley floor. It is assumed that at this point the Radovna Glacier was connected with the Dolinka Glacier. The latter probably covered the entire Upper Sava Valley, with accumulation areas in Tamar, Vršič and Vrata. PENCK & BRÜCKNER (1909) also claimed that the Radovna and Dolinka Glaciers were in contact. An ice mass from Krma and Kot might have damned up the Dolinka Glacier, which fact can be inferred by the steep terrain towards the Radovna Valley. MELIK (1954), however, rejected this hypothesis on the grounds that this part of the Radovna valley was too narrow. By definition (BENN & EVANS, 1998) the Radovna Glacier was a valley glacier where ice was discharged from an ice field into a deep bedrock valley. Debris could still have been deposited onto the foreland as a result of both gravity and flowing water where glacier margins were in the stage of advancing or retreating. As a

result, unequivocal evidences of the glacier's activity in the Radovna Valley rarely remains preserved or are obscured below thick layers of alluvial sediments. Consequently, it was not possible to draw up a reliable chronology of the various stages in the lifetime of the Radovna Glacier.

Methods

Conceptual model

It is assumed that almost all evidence of the existence of the Radovna Glacier may well have been destroyed or lie obscured below thick layers of alluvial sediments. In order to describe and locate the spatial distribution of the existing geomorphological indicators of glacial activity presented in the Radovna Valley a conceptual model was implemented (Fig. 1). The conceptual model was based on data from collected literature on the geomorphological and hydrogeological characteristics of the observation area and referenced in this paper. The most important geomorphological features are terraces consisting of glaciofluvial sediments. Granulometry of the sediments is crucial for determining the origin of erosion and accumulation. In order to achieve an integrated interpretation hydrogeological characteristic of deposit layers in the valley were also taken into account (e.g. permeability). Owing to the scarcity of evidence of the Radovna Glacier, implementing an extended conceptual model was key to achieving a satisfactory reconstruction scenario.

Fieldwork

Using existing data reviews from existing literature and the application of different cartographic bases, each location along the Radovna Valley was examined (shown in the chapter "Results and discussion: Fig. 4"). Geomorphological mapping was performed in the Radovna Valley in order to determine the glacier bed and its potential extent. The first fine records of terraces were mapped in the Srednja Radovna and Spodnja Radovna. Mapping was based on the spatial relationships between interpreted terraces and the surrounding natural topography. Additionally, in order to identify the terraces that were the result of glacier activity and those formed by river accumulation a simple sedimentological record of uncovered terrace profiles was assembled, which included measurements of compactness, grain size and orientation of clasts. This record makes it possible to reconstruct a glacier profile,

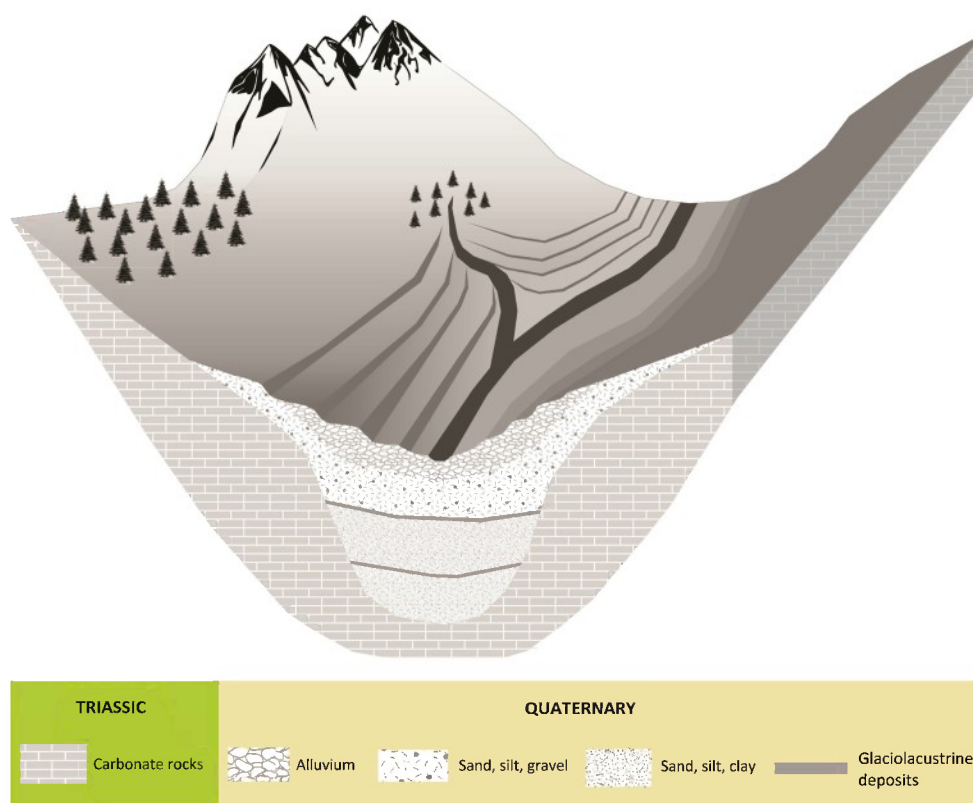


Fig. 1. Geological conceptual model of the Radovna Valley.

despite the fact that moraine sediments are not well preserved. Furthermore, moraine sediments were also mapped using the simple method of following contacts.

2D and 3D modelling and boundary conditions

The idea for a 3D geomorphological model was based on analysis performed using the Quantum GIS open source geographic information system (QGIS, 2015) with the GNU General Public license. QGIS is composed of a collection of software that enables the creation, visualization, querying and analysis of geospatial data. However, the quality of such a program cannot be compared to other licensed programs for 3D spatial data modelling that includes various statistical tools for the analysis and distribution of input data. Statistical tools available in QGIS allow the spatial analysis, but as it turns out, the design and application of the initial and boundary conditions require several adjustments. Hence, QGIS allows for 3D visualization that is limited to only relatively low resolution for modelled data.

The cartographic base used for the modelling was obtained from the freely-accessible USGS EarthExplorer (USGS, 2012) database. The location of the Radovna Glacier terminus was already known and represents the initial condition of the model. Determining the glacier head and

bed required a slightly different approach. When determining the glacier head and accumulation area it was necessary to take into account the fact that ice cannot accumulate on slope-grades of greater than 60° . Slopes were calculated in QGIS based on DEM cartographic data. Slopes greater than 60° , where ice accumulation is impossible due to gravity were modelled (Fig. 2). The result of modelled slopes identified possible areas where ice could have accumulated and slid through the valleys. The glacier bed was determined based on sediment granulometry in the glaciofluvial terraces. In order to set the coordinates for spatial modelling, several points were selected on those glaciofluvial terraces which were later interpreted as a glacier bed. The glacier bed served as the basis for the construction of the 3D mathematical model of the Radovna Glacier. The mathematical model is based only on the mechanical properties of the ice and the established equation for calculating the longitudinal profile of the glacier. The results of the modelling were later compared with the data from the field. In order to provide a more illustrative model of the conditions in the last glacial period a final 3D model also includes the ice caps of the Pokljuka, Bohinj and Dolinka Glaciers. The actual extent of the Bohinj Glacier in the 3D model is simply the result of theoretical interpolation and may differ from previously identified conditions (BAVEC, 2006).

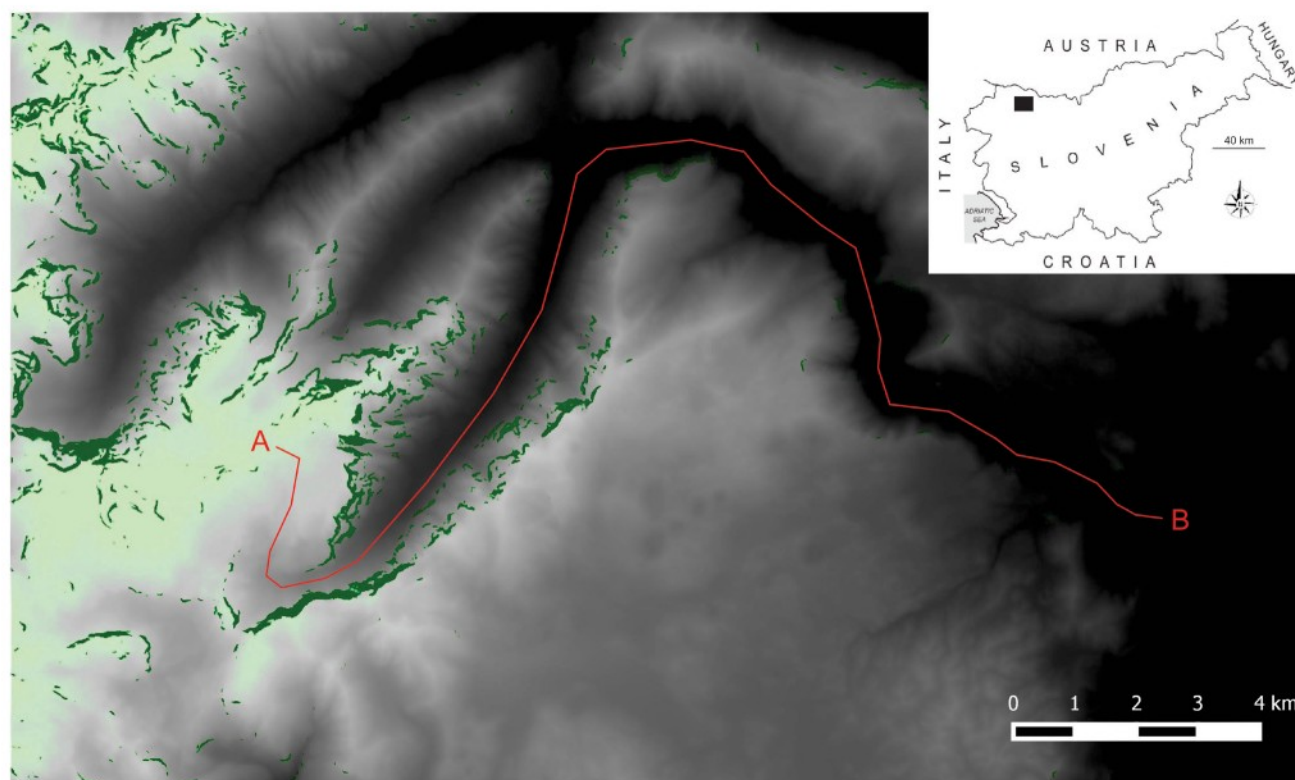


Fig. 2. Modeled values of slope above 60° (green contour) with intersection line for 2D model.

Determination of equilibrium-line altitude (ELA)

Equilibrium-line altitude or ELA represents the altitude where total annual accumulation is perfectly in balance with total ablation (BENN & EVANS, 1998). Therefore, ELA is an important descriptive factor in every glacial system (Fig. 3). Fluctuations in the ELA can serve as an important indicator of a glacier's response to changes in climate and allows the reconstruction of past climates. A variety of methods have been devised to estimate the steady-state ELA of vanished glaciers and to provide a means of reconstructing former climates in glaciated regions (BENN & EVANS, 1998). The most rigorous of these methods are based on a 3D model of the glacier surface using the ratio of accumulation to ablation areas. Two indirect methods were used to determine the ELA of the Radovna Glacier. The first, the toe to headwall altitude ratio (THAR) represents the empirical relationship between the highest (glacier head) and the lowest (glacier toe) border of the glacier and is used for a simple calculation of the ELA. MEIERDING (1982) found ratios of 0.35 and 0.40 produced the best results for glaciers in Colorado, USA. However, for the valley glaciers, values of 0.50 were proposed (MEIERDING, 1982). The second method is based on accumulation area ratios (AAR), which are based on the

assumption that the accumulation area of a glacier represents some fixed proportion of the total glacier area. This can be approximated from a topographic map by locating the altitude on the glacier surface that places 0.65 of the glacier area in the accumulation zone. Several studies performed on modern glaciers have shown that the accumulation area represents approximately 65 % of the glacier (MEIERDING, 1982). However, values of 0.67 were proposed (GROSS et al., 1977) for investigations of the Alpine glaciers.

Theoretical calculations

The most common method for reconstructing the extend of paleo-glaciers is based on the mechanical characteristics of ice sheets and shear stress ratios, and is independent of field data (BENN & HULTON, 2010). NYE (1952) compared the theoretical and measured longitudinal profile of the Unteraar glacier in Switzerland. He concluded that the relationship between theoretical and measured profiles was quite satisfactory using ice shear stress τ of 77 kPa. However, Nye (1952a) proposed values of ice τ between 49 kPa and 151 kPa for alpine glaciers. The τ values increase from toe to head. The model is built on the assumption that ice becomes deformed due to the weight and surface gradient of the ice only upon reaching a specified yield stress level. Given that

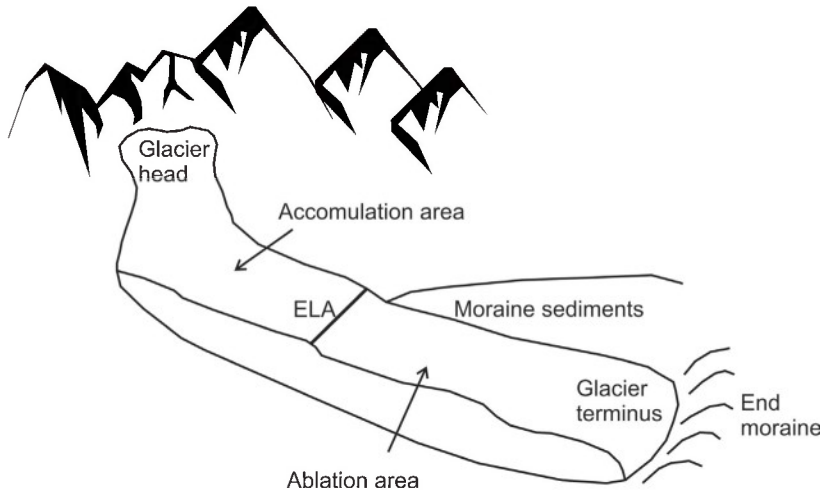


Fig. 3. Concept of the Glacier Anatomy (INTERNET 1).

assumption, the next equation (1) was introduced (NVE, 1952b):

$$\tau = \rho g h \sin \alpha \quad (1)$$

The equation is based on the assumption that the basal shear stress per unit area τ , at the base of an ice sheet is a product of ice thickness h , ice density ρ (~900 kg/m³), acceleration due to gravity g (9.81 m/s²) and glacier surface slope α . If true, the $\sin \alpha$ should be roughly inversely proportional to the depth of the ice and the horizontal axis x in the direction of the glacier's extending (Equation 2):

$$\sin \alpha = \left(\frac{dh}{dx} - \beta \right) \quad (2)$$

where β is the slope of the glacier bed.

Hence, we have a non-linear equation solved using only small values of β (Equation 3):

$$\frac{dh}{dx} + \beta = \frac{\tau}{\rho g h} \quad (3)$$

Solving out equation (3) we have (Equation 4):

$$\frac{h^2}{2} = \frac{\tau}{\rho g} x - C \quad (4)$$

Where the initial condition is presented by $h=0$ at $x=0$, hence the constant of integration C is equal to 0. Therefore, a simple equation for the calculation of ice thickness is derived:

$$h = \sqrt{\frac{2\tau}{\rho g} x} \quad (5)$$

However, for purposes of this article a different solution for equation (1) was presented as in equation (6):

$$\tau = \rho g H \frac{dh}{dx} \quad (6)$$

Where H is the glacier thickness, h is the ice surface elevation, and x is the horizontal co-ordinate with the x -axis parallel to the upward gradient glacier flow toward the glacier head (BENN & HULTON, 2010).

This equation (1) can be expressed numerically by discretizing the surface gradient as in equation (7):

$$\frac{dh}{dx} = \frac{h_{i+1} - h_i}{\Delta x} \quad (7)$$

where Δx is a specified distance interval along the x -axis. Thus, equation (7) can be rewritten so that the ice surface elevation at step $i+1$ is equation (8) (BENN & HULTON, 2010):

$$h_{i+1} = h_i - \left(\frac{\tau_y}{H} \right)_i \frac{\Delta x}{\rho g} \quad (8)$$

where $H=h-B$, B is the elevation of the glacier bed and τ_y . If we derive the previous equation differently, so as to calculate the ice thickness and shear stress for the mid-point of the interval i to $i+1$ (VAN DER VEEN, 1999) the following equation is derived:

$$h_{i+1}^2 - h_{i+1}(B_i + B_{i+1}) + h_i(B_{i+1}H_i) - \frac{2\Delta x \bar{\tau}_y}{\rho g} = 0 \quad (9)$$

where the overbar indicates that the yield stress is average for the interval.

As the shear stress significantly varies down gradient only average values for shear stress were used as input values in the model. The longitude profile of the Radovna Glacier was tested at shear stresses of 50, 100 and 150 kPa. For purposes of the modelling, however, only shear stress of 50 kPa and 100 kPa were used, because it was determined that the model would exceed the assumed glacier's thickness at a modelled shear stress of 150 kPa.

Results and discussion

Geomorphological conditions

Glaciofluvial terraces

Based on observations and several investigations in the Radovna Valley, it can be assumed that its geomorphological characteristics are largely the result of glacier activity and river outflow. Therefore the river channel was formed directly in the glaciofluvial sediments. Both accumulation and erosion resulted in the construction of river terraces. Today, a series of terraces can be observed along the middle and lower part of the Radovna Valley. The average height of the terraces is estimated at between 5 and 10 m. The younger terraces near the river channel have a small slope but are well preserved, while with the distance from the river channel the slopes increase. However, the oldest terraces stand higher than the younger terraces, even though they are almost totally eroded or covered with gravel. The morphology of the river terraces shows typical glacial and alluvial deposits, while in the upper part of the valley, where only processes of erosion were observed, there are no terraces. It is assumed that the riverbed gradient and river discharges were so high that terrace construction was impossible. According to that line of thinking a simple hypothesis can be proposed – that the shape of the valley floor has not significantly changed since the retrograding stage of the last glacier. As the highest terraces contain glacier sediments it is considered that only processes of river erosion were present during the first phase of the interglacial period. Therefore, it is believed that the upper or highest terrace represents the bed of the Radovna Glacier.

A series of terraces can be observed near the Zmrzlek spring in Srednja Radovna (Fig. 4, point a). The highest terraces are filled with glacial sediments, while the lowest contain only gravel. The terraces near the Lipnik spring were

also investigated in detail (Fig. 4, point b). A fresh profile was uncovered in the upper terrace, which contains horizontally laminated fine silt fractions in the upper horizon. It would seem that the river did not have any particular influence on the given profile. Furthermore, two terraces in Jela (Fig. 4, point c) were investigated in detail. These contain gravel with some fine sandy fractions, while a transverse terrace profile near the local Hotune – Voje road contains mostly gravel that can locally pass into a conglomerate. To conclude, four terraces were indicated in the Radovna Valley. The first three terraces contain alluvial sediments, mostly gravel and sand. However, the highest terrace contains glacial sediments, mostly silt, sand and clay. As a result it can be assumed that the highest terraces were formed by glacial activity and might indicate the altitude of the last glaciation bed.

Moraine sediments

Geomorphological mapping was performed at several locations along the Radovna Valley, starting in Zgornja Radovna. The most remote location in the valley, where the moraine sediment was indicated, lies in the valley between Kot and Vrata (Fig. 4, point h). A local road climbs from the narrow valley bed up to the small plateau. A small hill is located immediately at the top, to the east, between the road and the Mežakla plateau. It is covered with moraine sediments. South of the hill the topology is directed very steeply down to the Radovna Valley. Typical geomorphology may indicate contact between two glaciers. The steep slopes rising out of the Radovna Valley can be interpreted as the result of lateral erosion from ice sliding in the direction of Kot and Krma.

Furthermore, the whole of Stresena dolina in Srednja Radovna was mapped (Fig. 4, point g). A local forest road, which runs from the bottom of the valley up to the Pokljuka plateau, uncovers glacial sediments. On the other side of the valley location near Oblek (Fig. 4, point f) was mapped, where some glacial sediment was also found. The area near Krištanec (Fig. 4, point e), between Lipne peči and Stara Pokljuka in Spodnja Radovna has been significantly transformed through a number of sediment-gravitational processes. It is assumed that these processes might obscure the evidence of glacial activity. However, typical glacial sediment was indicated in the forest road profile near Krištanec. The investigated

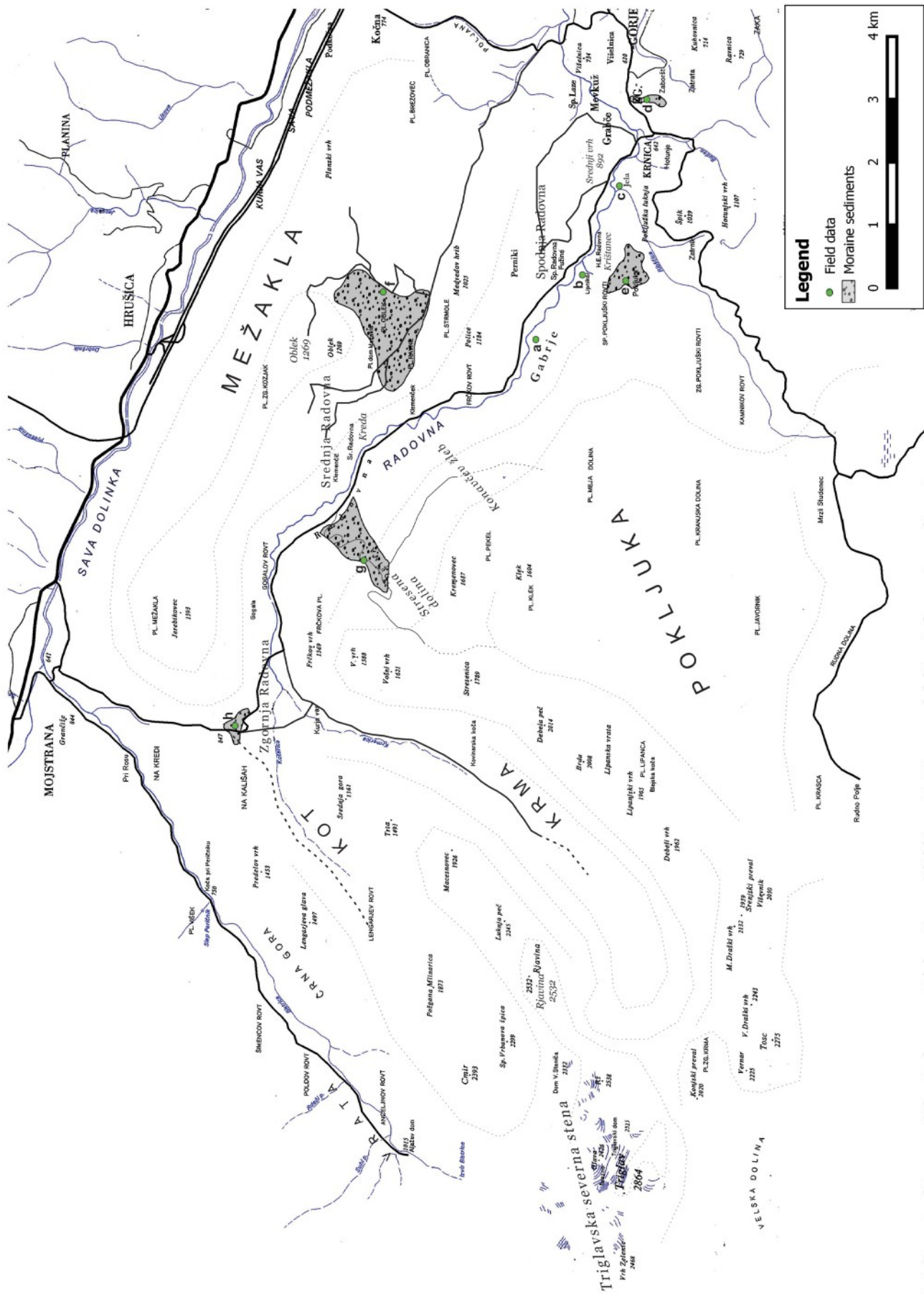


Fig. 4. Topographic map of the study area with locations of field investigations and delineated moraine sediments.

profile was followed at an altitude of 800 m a.s.l. Remarkable evidence of glacial presence is located in the village of Zgornje Gorje. A small topographic rise presents a terminal moraine of the former glacier. However, lateral glacial moraines are rarely preserved in the valley. The most pronounced is the outmost terminal moraine of the Radovna Glacier, located in the village of Zgornje Gorje (Fig. 4, point d).

2D model and validation

A longitudinal 2D profile of the glacier was calculated as the basis for the 3D spatial model. The Radovna Glacier's longitudinal profile was tested for two different shear stresses (τ) typical for Alpine glaciers, at 50 kPa and 100 kPa. Results show that ice thickness increases rapidly with distance from the terminus. In the village of Krnica the ice is already roughly 140 m thick. At its thickest the Radovna Glacier could reach thicknesses of 300–446 m. The surface of the Radovna Glacier displays a smaller dip in the middle, while the dip increases constantly from the terminus. Furthermore, the 2D profile (Fig. 5) shows that the glacier's maximum thickness (446 m at $\tau = 100$ kPa and 300 m at $\tau = 50$ kPa) is located at a distance of 11 to 12 km from the terminus. This represents the area between the Jerebikovec (1593 m a.s.l.) and Frčkov

vrh (1369 m a.s.l.), or right at the contact point of the ice masses, which slid from the Krma Valley and the Kot Valley. Here, the dip of glacier bed is small, while in the Kot and Krma valleys, parallel to the Rjavina ridge (2532 m a.s.l.), the dip of the glacier bed grows substantially all the way to the Kredarica (2539 m a.s.l.). Here the ice starts to become proportionally thinner with the greater dip of the glacier bed. Both the field data and existing literature indicate that the glacier did not exceed altitudes greater than 900 m a.s.l. at Krištanec, 1110 m a.s.l. at Oblek and 1150 m a.s.l. in Stresena dolina. Taking this into account it is clear that the calculated longitudinal profile of the glacier at $\tau = 100$ kPa was most appropriate. From this profile of the glacier it is evident that the thickness of the ice rapidly increases in the initial distances from the glacier terminus. Already at the village of Krnica, the ice surface reached altitudes of 140 m higher than the level of the Radovna River today. At a distance of about 1300 m from the terminus the glacier surface raised up to the altitude of 810 m a.s.l., – roughly 80 m lower than Srednji vrh.

3D model

3D modelling was performed in order to optimize the visualization of the glacier extent. Two 3D models are presented, calculated using two dif-

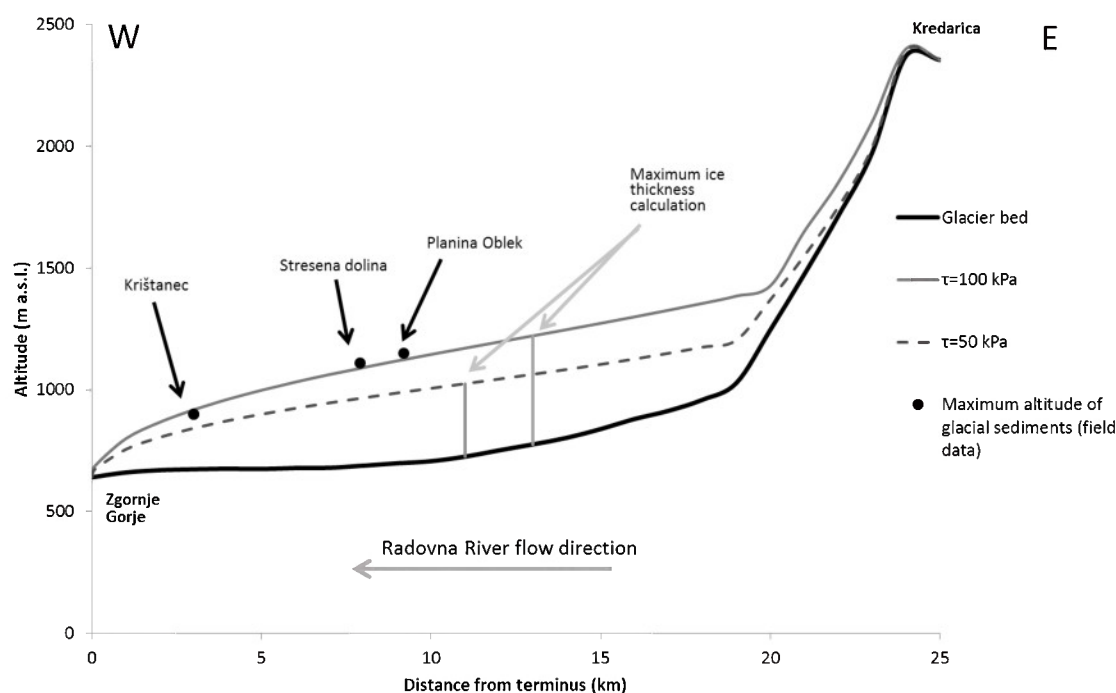


Fig. 5. Longitudinal profile of the Radovna Glacier with topographical units versus the distance from glacier terminus in the village Zgornje Gorje.

ferent shear stress values, of 50 kPa and 100 kPa (Fig. 6). Comparing the theoretical calculations with field data indicates that the $\tau = 100$ kPa model is more relevant for the field data scenario. Equilibrium altitude line (ELA) was also calculated using two methods: (1) toe to headwall altitude ratio (THAR), and (2) accumulation area ratio (AAR). The THAR method locates the ELA at an altitude of 1498 m a.s.l. The second (AAR) method suggests an altitude of 1150 m a.s.l. Total glacier area was calculated to be 58 km²; given AAR=0.65 the accumulation area of the Radovna Glacier should cover an area of 37.7 km². Therefore, the given catchment area of the Radovna Valley is entirely appropriate for a glacier of such dimensions. The glacier covered two valleys in the upper part of Radovna, Kot and Krma. Accordingly, the extent of the accumulation area was interpreted. The first accumulation

area was located all the way under the southern wall of Mount Triglav, Kredarica and Mount Rjavina, from where the ice sheets slid into the Krma Valley. The second accumulation area was located on the smaller slopes above the northern wall of Mount Triglav, where a small ice sheet called the Triglav Glacier remains today. It is assumed that this local area above the northern wall of Mount Triglav represented one of the largest accumulation areas of ice during the Würmian glaciation. The ice slid into the Vrata Valley and extended into the Mojstrana, where it was connected with one of the largest Pleistocene glaciers in Slovenia, the Dolinka Glacier, named after the Sava Dolinka River. The typical pyramidal horns and ridges of the upper part of Mount Triglav can still be observed today, as the result of several active glaciers sliding into the surrounding valleys.

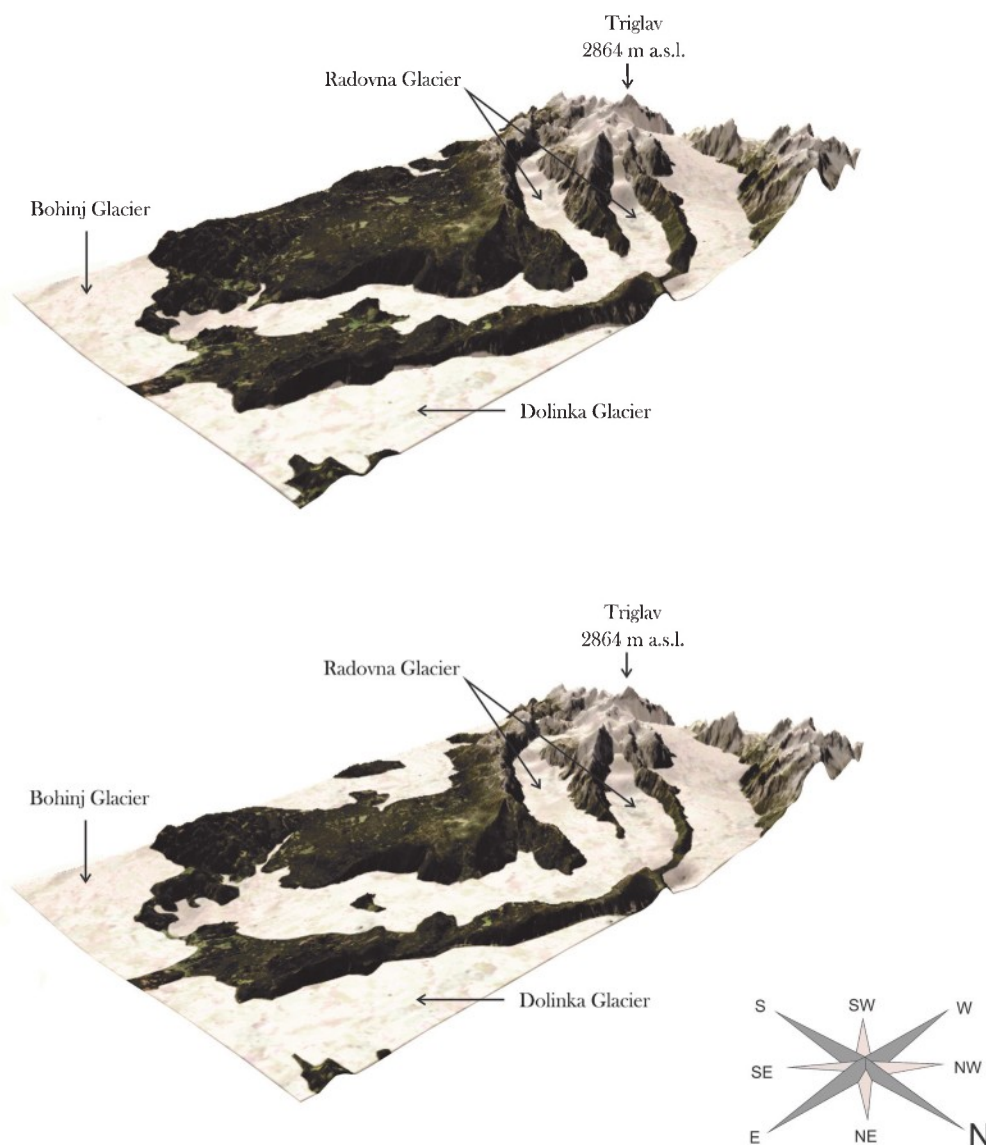


Fig. 6. 3D model of the Radovna Glacier in last glacial period with the modelled shear stress 50 kPa (upper figure) and 100 kPa (lower figure).

Conclusion

The 3D geomorphological model of the Radovna Glacier presented herein constitutes a basis for further investigation of the glacier extent. This is the first integrated investigation into the very existence and scope of the Radovna Glacier. The open source QGIS program has proved as a valuable tool in the given modelling approach and process. By the same token, the creation and implementation of a conceptual model is essential, because the selection of input data and boundary conditions is central to gaining a better understanding of the issue at hand. As a result it can be concluded that the Radovna Glacier did exist. Its accumulation area extended from the Triglav massive all the way through Krma and Kot. Glacier extending some 25 km covered the whole part of Radovna Valley. At some distance from the terminus the ice reached thicknesses of more than 400 m; however, with no field data available the model could not be validated on this point. The thickness of the ice in this model was calculated independently of any field data.

Thick layers of glaciofluvial sediments cover the valley floor, which may indicate an extensive period of Pleistocene glaciation; PENCK & BRÜCKNER's theory (1909) of four glaciations stages may also be valid in the case of Radovna glaciation. The reconstruction of the glacier leaves some questions unanswered, answers to which may hold the key to identifying past glaciation at the catchment. A scenario whereby glaciers moved across the Pokljuka plateau may well still remain a distinct possibility. The fact that typical geomorphological features are present in the upper reaches of Stresena dolina and Pokljuška soteska lends credence to such a scenario. Ice sheets may have extended from Klečica (1889 m a.s.l.) to Stresena dolina and from the Klek meadow (1604 m a.s.l.) through Konavčev žleb (ŠIFRER, 1952). Furthermore, ice sheets may have covered the upper, steeper regions of the Triglav summit, where some typical pyramidal horns and ridges can still be observed.

Acknowledgments

The author is grateful to Matic Rifi for his assistance with field investigations, dr. Nina Rman for her help with the context and structure of the paper, dr. Miloš Bavec and Assoc. Prof. dr. Mihael Brenčič for their review of the paper.

References

- BAVEC, M. & TULACZYK S. M. 2002: Matematični model kot pomoč pri oceni obsega mlajšepleistocenskega dolinskega ledenika v Zgornjem Posočju = New simple mathematical model to help evaluating the extent of the late-Quaternary valley glacier in the Upper Soča Region (NW Slovenia). *Geologija*, 45/1: 255–268, [doi:10.5474/geologija.2002.019](https://doi.org/10.5474/geologija.2002.019).
- BAVEC, M. 2006: Razsežnost in dinamika Bohinjskega ledenika v poznem Pleistocenu = The extent and the dynamics of the Late Pleistocene Bohinj glacier. In: Zbornik povzetkov: 35–36, 2. slovenski geološki kongres, Idrija, 26.–28. september 2006.
- BENN, D.I. & HULTON, N.R.J. 2010: An Excel™ spreadsheet program for reconstructing the surface profile of former mountain glaciers and ice caps. *Comp Geosci*, 36: 605–610.
- BENN, D. I., & EVANS, D. J. A. 1998: *Glaciers & glaciation*. London, Arnold: 734 p.
- DROBNE, F. 1975: Geološke in geotehnične raziskave k idejni študiji »Akumulacija Radovna«. Arhiv Geološkega zavoda Slovenije, Ljubljana: 43 p.
- EBERL, B. 1930: *Die Eiszeitenfolge im nördlichen Alpenvorland*. Augsburg: Benno Filser Verlag.
- GAMS, I. 1992: Prispevek k mladokvartarni geomorfologiji v Zgornjesavski dolini = A contribution to the young Quaternary geomorphology in the Upper Sava Valley. *Geografski zbornik*, 32: 5–49.
- GIBBARD, P. & VAN KOLFSCHOTEN, T. 2004: The Pleistocene and Holocene Epochs. In: GRADSTEIN, F. M., OGG, J. G., SMITH, A.G. & GILBERT, A. (eds.): *A Geologic Time Scale 2004*: 441–452, incl. 10 Pls.
- GROSS, G., KERSCHNER, H. & PATZELT, G. 1977: Methodische untersuchungen über die Schneegrenze in Alpinen Gletschergebieten. *Zeitschr. Gletsch. Glazialgeol.*, 12: 223–251.
- ISKRA, M. 1982: Elaborat o klasifikaciji, kategorizaciji in izračunu zaloga jezerske krede na območju odkopa v Srednji Radovni. Arhiv Geološkega zavoda Slovenije, Ljubljana: 22 p.
- IVY-OCHS, S., KERSCHNER, H., REUTHER, A., PREUSSER, F., HEINE, K., MAISCH, M., KUBIK, P. W. & SCHLUCHTER, C. 2008: Chronology of the last glacial cycle in the European Alps. *J. quat. sci.*, 23 (6-7): 559–573, [doi:10.1002/jqs.1202](https://doi.org/10.1002/jqs.1202).
- KUKLA, G. 2005: Saalian supercycle, Mindel/Riss interglacial and Milankovitch's dating. *J. quat. sci.*, 24/14-15: 1573–83, [doi:10.1016/j.quascirev.2004.08.023](https://doi.org/10.1016/j.quascirev.2004.08.023).

- MEIERDING, T. C. 1982: Late pleistocene glacial equilibrium-line altitudes in the Colorado Front Range: A comparison of methods. *Quat. Res.*, 18/3: 289–310.
- MELIK, A. 1954: Nova glaciološka dognanja v Julijskih Alpah. *Geografski Zbornik*, 2: 5–49.
- MELIK, A. 1930: Bohinjski ledenik. *Geografski vestnik*, 1–4: 39 p.
- NOVAK, M. & BAVEC, M. 2013: Geološke značilnosti Bleda in okolice = Geological characteristics of Bled and its environs. *Scopolia*, Suppl., 6: 1–31.
- NYE, J. F. 1952a: A comparison between the theoretical and the measured long profile of the Unteraar Glacier. *J. Glaciol.*, 2: 103–107.
- NYE, J. F. 1952b: A method of calculating the thickness of ice sheets. *Nature*: 169(4300): 529–530.
- PENCK, A. & BRÜCKNER, E. 1909: Die Alpen in Eiszeitalter 3. C. H. Tauchnitz, Leipzig: 717–1199.
- RAKOVEC, I. 1928: Postglacialne terase Blejskega jezera v zvezi z njegovo morfogenezo. *Geografski Vestnik*, IV: 21 p.
- RAKOVEC, I. 1936: Triglavsko pogorje v ledeni dobi. *Proteus*, 3s: 133–137.
- RAKOVEC, I. 1943: O razvoju porečja v Blejskem kotu in nastanku Vintgarja. *Zbornik Prirodoslovnega društva III*: 87 – 94.
- SCHAEFER, I. 1957: Erläuterungen zur Geologischen Karte von Augsburg und Umgebung 1: 50,000. Bayerisches Geologisches Landesamt München.
- SCHREINER, A. & EBEL, R. 1981: Quartärgeologische Untersuchungen in der Umgebung von Interglazialvorkommen im östlichen Rheingletschergebiet (Baden-Württemberg). Hannover: Bundesanstalt für Geowissenschaften und Rohstoffe und den Geologischen Landesämtern in der Bundesrepublik Deutschland.
- SERIANZ, L. 2013: Hidrogeologija izvira Zmrzlek v dolini reke Radovne. Diplomsko delo, Faculty of Natural Sciences and Engineering, University of Ljubljana, Ljubljana: 37 p.
- SERIANZ, L. 2015: Hidrogeološka analiza vodne bilance reke Radovne = Hydrogeological analysis of river Radovna water balance. Magistrsko delo, Faculty of Natural Sciences and Engineering, University of Ljubljana, Ljubljana: 70 p.
- SINGH, V. P., SINGH, P. & HARITASHYA, U. K. 2011: Encyclopedia of snow, ice and glaciers. Dordrecht: Springer, <http://site.ebrary.com/id/10480367>.
- ŠAFANDA, J. & RAJVER, D. 2001: Signature of the last ice age in the present subsurface temperatures in the Czech Republic and Slovenia. *Global and Planetary Change*, 29, 3/4: 241–257.
- ŠIFRER, M. 1959: Obseg pleistocenske poledenitve na Notranjskem Snežniku. *Geografski Zbornik*: 27–83.
- TORKAR, A. 2010: Hidrogeologija doline reke Radovne. Diplomsko delo, Faculty of Natural Sciences and Engineering, University of Ljubljana, Ljubljana: 68 p.
- TORKAR, A. & BRENČIČ, M. 2015: Spatio-temporal distribution of discharges in the Radovna River valley at low water conditions. Prostorsko-časovna porazdelitev pretokov v dolini reke Radovne v obdobju nizkih vod. *Geologija* 58/1: 47–56, [doi:10.5474/geologija.2015.003](https://doi.org/10.5474/geologija.2015.003).
- USGS (United States Geological Survey), 2012: »EarthExplorer«. Internet: <http://earthexplorer.usgs.gov/> (29.3.2016).
- VAN DER VEEN, C.J. 1999: Fundamentals of Glacier Dynamics. Balkema, Rotterdam: 462 pp.
- VENETZ, I. 1861: Mémoire sur l'extension des anciens glaciers. Zurich: s.n.
- QGIS, 2015: Geographic Information System. Open Source Geospatial Foundation Project. Development Team. Internet: <http://qgis.osgeo.org> (29.3.2016).
- ŽEBRE, M., STEPIŠNIK, U., KODELJA, B. & MORRIS, M. 2013: Sledovi pleistocenske poledenitve na Trnovskem gozdu. *Dela*, 39: 157–170.

Internet resource:

INTERNET 1: <http://climatica.org.uk/moraines-piles-dirt-record-glacier-fluctuations> (17.6.2016)