Main findings of the PhD dissertation

Doctoral School of Earth Sciences

Model study of rinnenkarren development

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Pécs, 2024

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1. Introduction

Rinnenkarren are downhill arheic grooves (channels, Fig. 1.) originating from the dissolution of the bare rock surface in karst areas without soil. These are the most widespread and common type of karren in the periglacial belt of high mountain environments. In the Alps, 67% of karren features in the dwarf pine belt (periglacial belt) and 54% of karren features in the bare rock belt are rinnenkarren. Rinnenkarren channels form and develop under rivulets which feed from precipitation or melting snowpatches. Channels merge to form channel systems (Horton-type channels). The channel system consists of a main channel (the longest, frequently reach up to 30-50 m and also the largest in cross-section) and one or several adjoining tributary channel(s). Their width and depth at the most are a couple of decimeters.

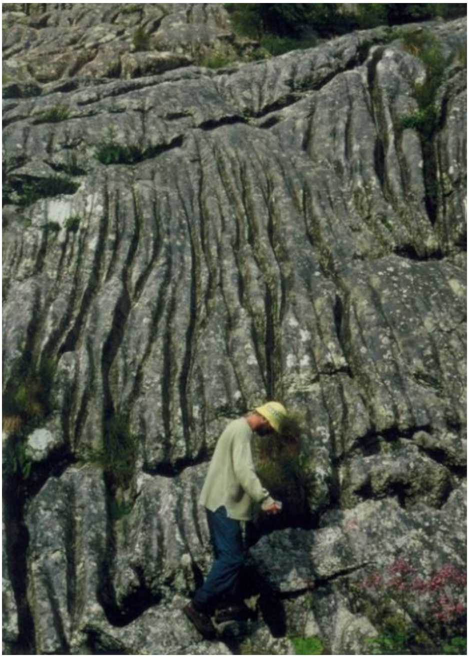

Figure 1. Rinnenkarren in the Julian Alps (Slovenia).

Although rinnenkarren were already described more than a century ago and due to the high occurrence and distribution of rinnenkarren worldwide many subsequent studies were made of these features, their development has only been studied in detail in the last few decades. Previous theories assumed that the growth of the rinnenkarren gradually increases downhill. However, rinnenkarren cross-sections are also known to locally increase at their junctions and below water inflow from catchments. Kamenitzas with various morphologies often appear in these places as well, which may be connected here to several tributary channels.

The influence of turbulent flow is significant in the development of rinnenkarren channels by dissolution. The turbulent flow allows more efficient diffusion (so-called eddy diffusion) between the limestone surface and the water, and therefore the dissolution of the limestone is much more intense. The turbulence is locally amplified where the flow in the channel is driven by external effect (water inflow). Water inflow can occur from catchment or tributary channel.

Cross-sections of adjoining channel parts with a catchment slightly increase at the sites of water inflow. At tributary channel junctions the vorticity develops a distinct local hollowing with a given length. Within the local hollowing section, the receiving channel width, depth or both of them significantly increase locally.

Since channel development is determined by the nature of the water flow, recent studies were supplemented with laboratory flow experiments. The vorticity at the site of the junctions was confirmed by laboratory model experiments. These studies allowed more refined models of cross-sectional development; however, the effect of catchment area was not investigated. The relationship between catchment area, channel development and tributary formation have not yet been studied. The previously mentioned and the recent studies neglected the study of the development as well as all characteristics of local hollowings at the junction of multiple channels.

One of the problems of high mountain rinnenkarren research is that the field cannot be accessed during snowmelt or events of strong precipitation when flow is present in the rinnenkarren. Laboratory analyses are also limited in their ability to study the effects of vorticity and catchment parameters because implementation is time-consuming and has technical limitations. The use of numerical simulations for geomorphological purposes is becoming increasingly widespread for the study of fluvial and eolian problems where field studies are limited. In karst morphology, karst hydrology and speleogenesis (e.g., including the study of channel growth) examples of numerical solutions also can be found. Such studies made of rinnenkarren, however, have not yet been sufficiently harmonized with the field observations.

2. Objectives

The goal is to study the morphology and development of rinnenkarren: to expand the available field and laboratory measurements with model studies, then to reveal relationships by joint analysis and comparison of the data.

To achieve the complex goal of this research, the following properties of channel systems were investigated:

1. The relationship between the cross-section of the main channel and the catchment area by developing an approximate method for estimating the water amount, and, in connection with this, the development of the tributary channel by evaluating the dip of the slope of the substrate of the channel system.
2. The relationship between measured parameters of local hollowings in the main channel and the vorticity of the rivulets of the joining tributary channels by flow simulation, for different combinations of slope and junction angles.
3. A complex interpretation of the morphometric data of local hollowings by linking the model studies, and thus the influence of the tributary channel joining the main channel in the catchment section and the joining distance of the tributary channels on channel development and channel morphology.

3. Methods of investigation

The choice of the methods used was determined by the data of rinnenkarren and channel junctions from the bed plane surfaces of glacial valleys in the area of Totes Gebirge in Austria, as well as the results of physical laboratory experiments mimicking the flow in channels.

1. The cross-sectional area and the width-to-depth ratio (so-called shape) of the channel were calculated along each measurement profile. The averages of the values of cross-sectional area, shape and junction angles of tributary channels within the local hollowing section were calculated separately. The field data, as well as the computationally prepared data, were grouped according to various criteria and resolutions (e.g., number of tributary channel junctions to a given local hollowing feature, slope angle, junction angle). Each group was then individually averaged and plotted in an appropriate coordinate system according to the purpose of the given study. Univariate and bivariate functions were fitted by regression where necessary to examine and understand the trend of the data. The background of channel development was inferred from the obtained results.
2. The accumulation of water in the catchment was estimated using a method based on a cell division. The basic concept of the procedure was a method used in spatial informatics. The catchment area was divided into squares (i.e., catchment cells) of 0.01 m^2 area. Two values were assigned to each cell. One is the flow direction vector, which is determined by the dips of the catchment area (slope- and strike-direction), and the other is the estimated value of the water amount. Due to the continuous rainfall or slush

supply, units of water are assumed in the cells. Additionally, the amount of water from adjacent cells is added. In a given cell, the estimated water volume values from adjacent cells are summed proportionally by taking into account the flow directions given by their vectors. Using this method, the pattern of water aggregation is estimated for some example channels by continuous summation along the direction of the vectors from the edge of the catchment. From the final results of the summation at the channel edge, the volumes of water accumulating at (and flowing into) the channel at the given points were estimated. The values of this channel perimeter water volume as a function of distance were examined and compared with the values of the channel cross-sectional areas at the same points.

3. The water flow in the channel was modelled by Computational Fluid Dynamics (CFD) numerical simulation using simplified model channels. First, the numerical simulation was carried out on a channel set where each individual main channel is joined by a tributary channel with a junction angle between 10° and 90°. The model experiment was carried out between 5°-45° slope angles. The values and spatiality of the vorticity were studied and compared to the morphology of some (ideal) field channels of the same size. Using the field samples, as well as the values and local maxima of the simulated average vorticity along the main channel, intense vorticity section lengths were approximately delimited in the simulation results that could be observed in the laboratory and which longitudinal extent result in local hollowings. The one-way analysis of variance (ANOVA) was used to test whether the means of the measured values of these three types of section lengths were significantly different. If not, the mean of the values from the three sources were calculated, which is the most likely expected value for the local hollowing length. Regression of bivariate function was applied to determine the empirical function to study the trend of this section length as a function of slope and junction angle.
4. The influence of two effects on the length of the local hollowings were investigated. Before the investigations, the deviation of the local hollowing lengths measured in the field from the – previously calculated – most probable value was calculated. The resulting deviation value was then first examined as a function of the amount of water (estimated by the cell method) accumulating at the edge of the main channel. Then, secondly, the deviation value was studied as a function of the distance between the tributary junctions. In the latter case, to interpret the results obtained, further experiments were carried out by simulation in model channel systems with low and high density of junctions of tributary channels to a main channel. The values, length and structure of the eddies were studied against the data of some individual field channel system. Through these tests theoretical models for the length development and separation of

individual local hollowings were given by considering the effects of catchment and tributary channel spacing.

5. The development of the cross-section of local hollowings was investigated considering the characteristics of the tributary channels adjoined to them. The relationship between the size of average cross-sectional area of the local hollowing and the average junction angle of the channels and the slope of the ground surface was studied using an empirical bivariate function. Graphs of the average shape of local hollowings as a function of average cross-sectional area were plotted separately according to the number of tributary channels adjoining to them. The trends were examined by function fits. The results obtained from these functions were interpreted by flow simulation in such model channels where the number of tributary channels joined in the vicinity of each other in the hollowing and non-hollowing parts of the channel were gradually increased. The structure of the eddies was investigated, and a theoretical model of the cross-sectional evolution of local hollowings was interpreted and given.

4. Summary of the results

1. The catchment determines the development of main channel and channel system. In the field, the cross-section of the main channel increases not only gradually downslope – as previous studies concluded –, but increases along those sections too where a large catchment adjoins the channel section (Fig. 2a). This channel section with enlarged cross-section is locally (intermittently) dissected by local hollowings, kamenitzas, pits at tributary junctions (Fig. 2b). According to the previous studies, the establishment and development of the channel occurs downslope a rivulet. Our results suggest that rivulet-controlled channel development is increasingly influenced by its catchment. The common effect of tributary channels and catchments influence the development of rinnenkarren (Fig. 2b). When the catchment area is small, its influence on the development of the main channel is weak. When the catchment is large, the increase in cross-section of the main channel follows the proportion of the amount of water inflow estimated to the channel edge. A tributary channel develops in the catchment at the same place where water can concentrate on the surface of the bedrock. Large catchment areas significantly affect channel cross-section growth along stretches where slope angle decreases. Along these parts a significant amount of water can accumulate at the edge of the main channel. Additionally, the establishment of tributary channels is more characteristic along these sites (Fig. 2a., 2b., 2c).

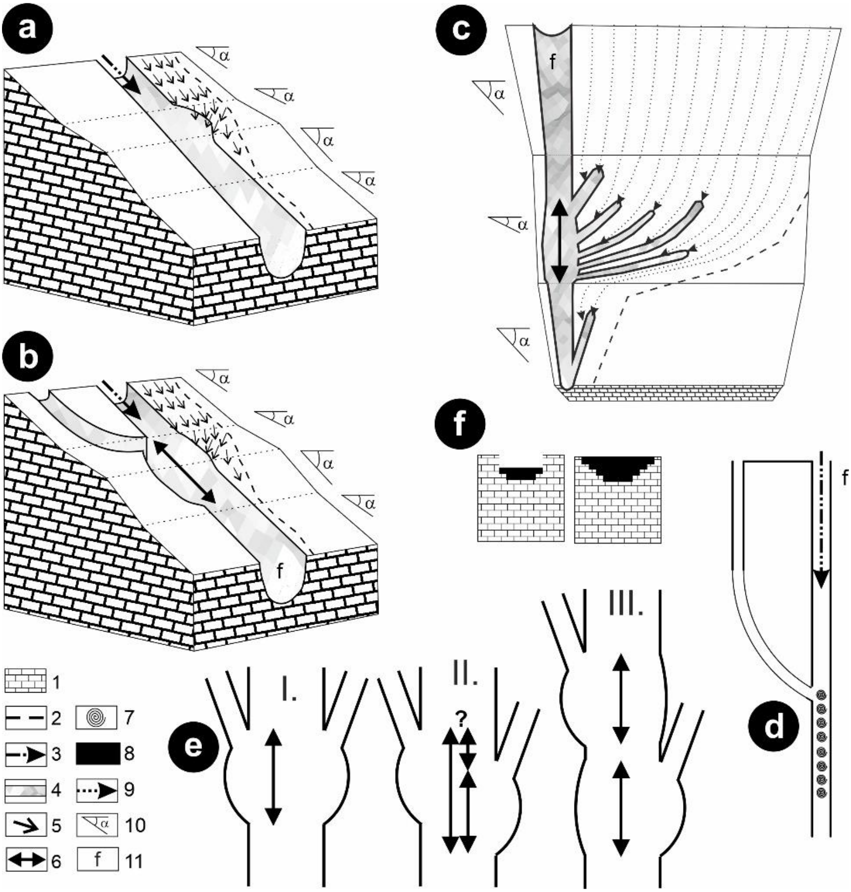

Figure 2. Summary of field influences on channel development (conceptual illustrations). (a). The catchment develops cross-sectional growth (developing local hollowing). (b). Local hollowing is developed as a result of tributary-induced vorticity, its morphometry is influenced by the amount of water inflow from the catchment. (c). Water concentration, sections with increased tributary channel density and presence of common local hollowing characterize the sections with lower dip. (d). The flow simulation shows that the vorticity (hence the eddy diffusion) always occurs at the junctions along a section of specific length. (e). The more distal the adjoining tributary channels (I→III), the more distinct the local hollowing occurs. (f). The higher the water flow in the hollowing feature, the more considerable the dissolving effect on its sidewall and hence the more considerable is its widening.

Legend: 1. Limestone. 2. Catchment boundary. 3. Direction of water flow in the main channel. 4. Rinnenkarren. 5. Direction of waterflow in the catchment. 6. Section length of field local hollowing induced by tributary channel. 7. Section of intense vorticity. 8. Water fill in the feature. 9. Rivulets in the catchment. 10. Slope of the surface (section). 11. Main channel.

2. Flow simulation modelling of the channel flow confirmed that the intense vorticity in the main channel is induced by the rivulet arriving from the tributary channel (Fig. 2d). Based on the spatial analysis of the morphology of simulated vorticity the presence and value of vorticity in the main channel is the highest at the tributary channel junction on the junction side of the channel cross-section. In some cases, vorticity may also briefly penetrate into the tributary(s). The vorticity value gradually decreases by the increasing distance from the tributary junction(s) section. The novelty of the flow simulation used, and the comparison and simultaneous evaluation of data collected by several methods, allowed a detailed understanding of channel development than previously possible.
3. The development of local hollowing at the junction of the channels is determined by the vorticity at the junction of the rivulets (Fig. 2d). When the tributary channels are established, the cross-section of the main channel is locally and distinctly increased at their junction into the main channel along the vorticity section caused by the confluence of the two rivulets (Fig. 2b). The simulated model experiments allowed the identification of the intense vorticity section (Fig. 2d). The lengths of the intense vorticity sections measured in the simulation are in accordance with the lengths of the local hollowings identified by field measurements. The similarity of the averages of the section length data collected by the three different methods (field, physical laboratory and simulation) confirms the relationship between intense vorticity and local hollowing. A combined interpretation of the simulated model experiments and field samples also suggests that there may be a proportionality between the size of the local hollowing cross-section (i.e., the rate of dissolution) and the average rate of turbulence.
4. The development of the main channels, tributary channels and thus the whole channel systems is determined by the slope of the terrain and terrain-sections. On gentle slopes, the chance of water convergence into the main channel increases, thus increasing the probability of the development of tributary channels and densely tributary sections (Fig. 2c). The development of the main channel is more efficient on sites with lower slope angle, which due to the junctions of the tributary channels. At high slope angles, tributary channel junctions, and hence the vorticity induced channel development of tributary channel origin, has less occurrence (Fig. 2c). The lengths of the intense vorticity sections simulated by the model experiments and the lengths of the local hollowings measured in the field are largest at low slope angles. Considering the junction angles, on average, tributary channels that are adjoined to the main channels with

increased junction angles cause longer intense vorticity section lengths. The probability of such junctions is higher at small slope angles (Fig. 2c).

5. The catchment in the environs of the tributary channel junctions and the density of tributary junctions determine the morphometry and development of the hollowing sections. The differences between the lengths of intense vorticity sections and field local hollowings in proximity of tributary channel junction are determined by the size of the catchment, according to the results from the cellular approximation of the catchment. The smaller the size of the direct catchment area along the main channel, the more distinct are the local hollowings from other channel parts (Fig. 2b). Typically, sites with high density of tributaries are those sections of the main channel where the angle of the slope is locally decreased. In this case, extensive and continuous vorticity develops along the junction stretch in the main channel, resulting in a common local hollowing (or pit and kamenitza) that appear as a continuous feature (Fig. 2c). Taking into account the vorticity sections obtained in the model experiment, the potentially continuous hollowing gradually subdivides into individual local hollowings as the density of tributary channels decreases (Fig. 2e). When the separation of field tributaries exceeds a distance of one meter, the individual local hollowing sections are completely separated.
6. Similarly, to the channel along its entire length, the general direction of development of the channel cross-section at the junctions is also deepening. This means that the (common) local hollowing that evolves in the initial stage will develop into a pit over time. However, the more tributary channels are connected in close proximity to one another (i.e., the greater the water supply), the greater the lateral growth (widening) in the development of the channel cross-section (Fig. 2f) and the more kamenitza-like the shape. The development of the cross-section is already determined by the junction of only one tributary channel. In this case, the junction angle of the tributary channel is crucial, the greater the angle, the higher the deepening rate of the local hollowing in the main channel. Model experiments show that a smaller scale of vorticity is also present in the other non-hollowing sections of the channels. This is due to the flow characteristics of the rivulet. This also results in a moderate increase in channel cross-section between local hollowing sections, as described by previous research.

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