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ORIGINAL RESEARCH ARTICLE

Rinnenkarren systems and the development of their main channels

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ABSTRACT

In this study, the development of rinnenkarren systems is analyzed. During the field studies, 36 rinnenkarren systems were investigated. The width and depth were measured at every 10 cm on the main channels and then shape was calculated to these places (the quotient of channel width and depth). Water flow was performed on artificial rinnenkarren system. A relation was looked for between the density of tributary channels and the average shape of the main channel, between the distance of tributary channels from each other and the shape of a given place of the main channel. The density and total length of the tributary channels on the lower and upper sections of the main channels being narrow at their lower end (11 pieces) and being wide at their lower end (10 pieces) of the rinnenkarren systems were calculated as well as their average proportional distance from the lower end of the main channel. The number of channel hollows was determined on the lower and upper sections of these main channels. It can be stated that the average shape of the main channel calculated to its total length depends on the density of the tributary channels and on the distance of tributary channels from each other. The main channel shape is smaller if less water flows on the floor for a long time because of the small density of the tributary channels and the great distance between the tributary channels. In this case, the channel deepens, but it does not widen. The width of the main channel depends on the number and location of the rivulets developing on channel-free relief. The main channel becomes narrow towards its lower end if the tributary rivulets are denser and longer on the upper part of the main rivulet developing on the channel-free, plain terrain and their distance is larger compared to the lower end. The channel hollows develop mainly at those places where the later developing tributary channels are hanging above the floor of the main channel. Thus, the former ones are younger than the latter ones. It can be stated that the morphology of the main channels (shape, channel hollows, and width changes of the main channel) is determined by the tributary channels (their number, location and age).

Keywords: A Rinnenkarren System; Channel; Tributary Channel; Channel Shape; Discharge; Transit Time; Channel Hollow

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1. Introduction

In this study, the shape (the shape is given by the quotient of the channel width and depth) of the main channels of the rinnenkarren systems and change of width (separating the main channels being wide and narrow on their lower end) and channel hollows were investigated in order to interpret the characteristics of growth of the main channels and the morphology of rinnenkarren systems and to familiarize ourselves with the way of their development.

Karren is widespread on karst, but it is the main characteristic of the bare surfaces of the glacier valleys of glaciokarst (e.g. the Alps, the Pyrenees, the Dinarides, and the Caucasus). The most common karren features of bare surfaces are rillenkarren, rinnenkarren, wallkarren, meander karren, grikes, kamenitzas and trittkarren. Karren is main small features of karst areas that developed by dissolution. They can develop by flowing water and seeping water[1-3]. Features developing by flowing water are hydraulic forms (White, 1988) or hydrodynamically controlled[2], while features developing by seeping water are etched forms[1] or fracture controlled forms[2]. Karren of flowing origin such as rillenkarren, rinnenkarren (channel, runnel), wall karren and meander karren develop on bare surfaces, however, according to some authors[4,5] Song (1986) and Slabe and Liu (2009), rinnenkarren can develop beneath soil as well. Karren of seeping origin (for instance grikes) can form on both bare and soil (sediment) covered rocks.

On the bare surfaces of glaciokarst, karren often occur[6], mainly rinnenkarren. Thus, in the eastern Alps, in the zone of Pinus mugo, the specific width (being the width of karren features over a 1 m distance) represented by them is 67%[3]. However, they can also occur on bare surfaces of other karsts such as mediterranean and tropical karst[7-9]. Because of their widespread occurrence and large density (sometimes they determine the landscape of the karst area), several researchers have studied their occurrence, morphology and development[1,7,10-17].

Rinnenkarren are channels with downslope direction. Their lower end is connected to karst wells (pipes) and grikes. Thus, the water flowing in them is conducted beneath the surface. Their cross-section can be U-shaped, V-shaped and widening downwards[10-12]. Their width and depth are a few decimeters, while their length may be some 10s of meters.

Channels or rinnenkarren develop under rivulets[18-20]. The rivulets are fed by rainwater, the water of snow patch or that of kamenitza. The rivulets only occur in the channels during rainy season (active period). During most part of the year, the floor of rinnenkarren (channel) is completely waterless (non-active period).

Channels are complex features. On their floor, kamenitzas, pipes, small basins, hollows, karren sinkholes, karren terraces and steps may occur, while on their side walls, scallops and rillenkarren may occur[3,15,17,21,22]. Several varieties can be distinguished, such as rundkarren, Hortonian type channels, decantation runnels, simple and complex channels and type A and type B channels[2,3,15,23]. The crests between the channels of rundkarren are rounded[15,18]. The rounded crests developed by dissolution under soil[18]. The Hortonian type channels can consist of several runnels[20]. The decantation runnels can develop at point-like water supply places[20], thus, at kamenitzas[24] too. The width and depth of decantation runnels decreases downslope[2,20]. Veress (2009, 2010) distinguished simple and complex channels. The simple channel can be of Type I, II and III. The depth and width of channel Type I are some decimeters. These values are some centimetres in the case of channel Type III, while the size of channel Type II lies between the size of types I and III. In case of complex channels, Type II channels may develop in Type I channels, while Type III channels may develop in Type II channels. Karren meanders are channels with asymmetric cross-section. It is common that the lower end of the symmetric channel turns into asymmetric, thus, the lower part of the rinnenkarren transforms into meander karren[3]. Type III meander karren can occur on the floor of Type I channels[25]. Karren meanders may be looping, remnant, perishing and developing meanders[25].

According to previous investigations[3,23,26], two types of rinnenkarren can be distinguished according to their size and shape. These are the type A and type B channels. Type B channels have a greater size. Their sides are steep (U-shaped). They have a great catchment area and a great specific catchment area. Type A channels are smaller size. Their sides are more gentle (V-shaped). They have a small catchment area and a small specific catchment area. Type B channels can consist of only one channel or can create rinnenkarren systems[23]. A relation can be presented between the density of type A and B channels and the angle of the bearing slope. The density of type A channels increases by the growth of the slope angle, while that of type B channels decreases[23].

The channels often constitute rinnenkarren systems (**Figure1**). The rinnenkarren systems are made up of main channels (the length of which can be often 30-50 m) and of type A and type B tributary channels are connected to them. Type B tributary channels can also be complex. In this case, the tributary channels may have smaller type B and type A tributary channels. Both type A and type B tributary channels can be hanging and non-hanging ones. The floor of the hanging tributary channel terminates at the conjunction site, some centimetres or some tens of centimetres above the floor of the main channel. By this, a step develops at the conjunction site. The floor of the non-hanging tributary channels is located at the level of the floor of the main channels.

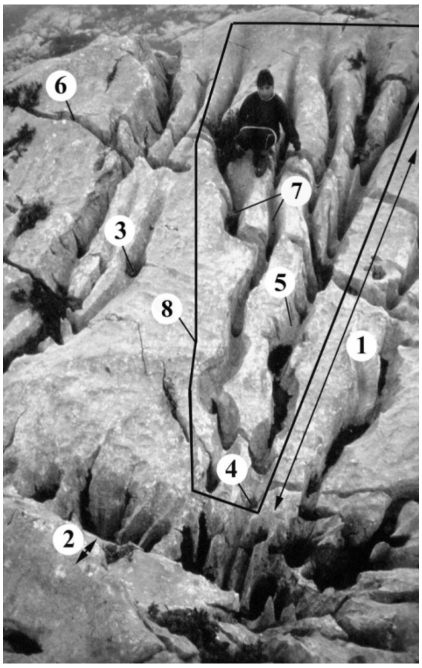

Figure 1. The main channel of the rinnenkarren system which becomes narrower on its lower part (Totes Gebirge). Legend: 1. Surface with bedding planes; 2. Step front; 3. Pipe on the floor; 4. Pipe at the end of the channel; 5. Main channel; 6. Grike; 7. Tributary channel; 8. Rinnenkarren system.

The channel shape of the main channels, which expresses what depth belongs to a given channel width, is rarely the same on its different parts. On some parts of the main channel, the width increases locally and channel hollows develop. The channel hollows develop because the water flowing from the tributary channel triggers vorticity which causes the local increase of dissolution[22]. Apart from channel hollows, it often occurs that the channels widen from their upper end towards their lower end (**Figure 1**). This can occur if the widening is of greater extent than the deepening, but in a reverse situation too. It is possible that their width decreases on their lower part, not only relatively (compared to their depth) but actually too. The decrease always happens in case of decantation runnels, but it also occurs on the lower parts of the main channels of the rinnenkarren systems (**Figures 1, 2**).

Figure 2. Channels which become narrower have a smaller cross-section downwards (Totes Gebirge). Legend: 1. dip direction of the slope.

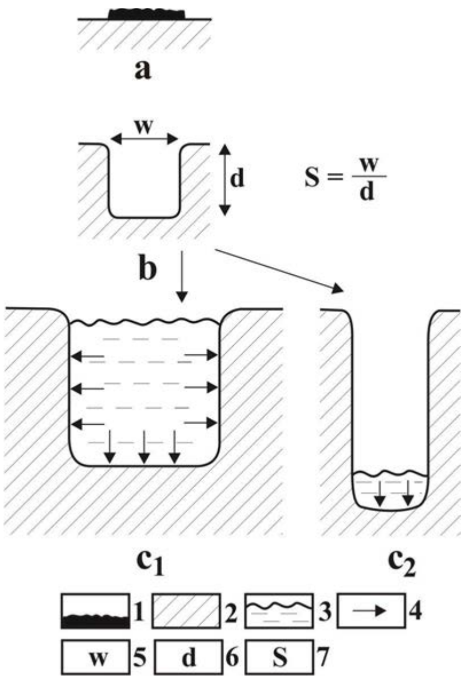

Figure 3. Model of the channel shape and its development. Legend: 1. Rivulet on the surface; 2. Rock; 3. Rivulet in the channel; 4. Place of dissolution; 5. Width of the channel; 6. The depth of the channel; 7. Shape of the channel: a. rivulet; b. development of the channel; c_1. Large channel shape (there is dissolution on the channel walls too); c_2. Small channel shape (there is dissolution on the channel floor only).

Apart from local effects of biogenic origin, the channel shape is formed by the water flowing with solution capacity (the water of the rivulet) in the channel. If a large amount of water flows (the channel is filled with water which is called large discharges later) in the channel for a longer time and it has solution capacity, both the channel wall and channel floor are solved. Thus, the channel widens and deepens too (**Figure 3c$_1$**). The cross-section of the channel grows in a way that the proportion of width and depth does not change. If a little amount of water flows in the channel for a longer time (the water just covers the floor of the channel, it is called small discharge later), solution happens on the floor only. The channel does not widen, but it deepens only (**Figure 3c$_2$**).

In a main channel, the durations of the large and small discharges changes. The proportion of the durations of the two different discharges determines the shape of the channel, that is, the proportion of width and depth. The longer the duration of the large discharge as compared to the small discharge at a given place is, the larger width and the larger cross-section the channel has. The shorter the duration of the large discharge is, the smaller width and the less large cross-section the channel has (however, because of deepening, the cross-section also increases).

In the former case, the channel shape is large or of increasing tendency, while in the latter case, it is small or of decreasing tendency during the channel development. Since transitional discharges also occur between large and small discharges, the channel sides do not necessarily dissolve uniformly[21]. It can be observed that there are channels widening towards their margins (V-shaped) and channels widening towards their floor. This study does not include the interpretation of the development of these cross-sections.

The potential change of the channel shape also depends on the size of the cross-section. In case of a larger cross-section, only a larger decrease (change) of discharge can cause dissolution on the floor, that is, change of shape. This is caused by the fact that in case of a larger cross section, the same amount of water covers the floor only. While in case of a smaller cross-section, a smaller change of discharge can also cause dissolution on the floor only, that is, change of shape.

If the width of the main rivulet increases towards its lower end on the terrain being exempt from channels, also the width of the main channel increases towards its lower end. If the width of the main rivulet decreases towards its lower end on the terrain exempt from channels, also the width of the main channel decreases towards its lower end.

The development of the channel hollows of the main channels is caused by the tributary channels. The rivulet of the tributary channel conjoining the rivulet of the main channel causes turbulence which increases dissolution locally[22]. Vortexes are larger, and turbulence is more intensive and thus, dissolution is larger where the tributary channels are hanging over the floor of the main channel. Hanging tributary channels develop if the rivulets of the tributary channels develop later than the rivulet of the main channel (it means that the development of the tributary channels began later than that of the main channel).

2. Method

On our sample site in Totes Gebirge, 36 rinnenkarren systems were mapped in the glacier valley under the Tragl peak near Tauplitz Alm. A various number (about 25-30) of rinnenkarren systems were included in our different processings. In some cases, the tributary channel of some rinnenkarren systems creating a more complex system (as a rinnenkarren system) was also investigated separately (thus, the number of measurements exceeded 30 during the given processings). The width and depth of the channels were measured at every 10 cm too.

The shape (S) of the channels was calculated at every 10 cm in the following way (**Figure 3b**):

$$S = \frac{w}{d}$$

Where *w* is the width, and *d* is the depth.

The cross-section area (A) of the channels was calculated at every 10 cm in case of a U cross-section in the following way:

A = wxd

While in case of a V cross-section in the following way:

A = ½ x w x d

The density (D) of the tributary channels of the rinnenkarren system was calculated in the following way (**Figure 4**):

$$D = \frac{N}{l_m}$$

Where, N is the number of tributary channels, and l_m is the length of the main channel.

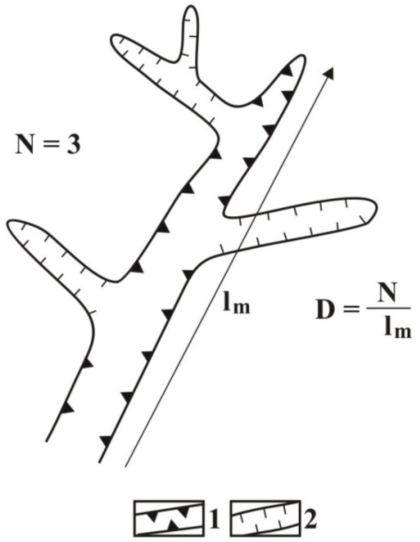

Figure 4. The calculation of the density of tributary channels**.** Legend: 1. Main channel; 2. Tributary channel: N is the number of tributary channels, and l_m is the length of the main channel.

A functional relation was looked for between the average shape of the main channel (S_0), (which was calculated from the average of the shapes calculated to the total length at every 10 cm) and the density of tributary channels.

A functional relation was looked for between the distance (l_t) of the two tributary channels from each other and the shape (S) of the place [$S(l_t)$] of the main channel which is directly above the conjunction site of the tributary channel with a lower position (**Figure 5**).

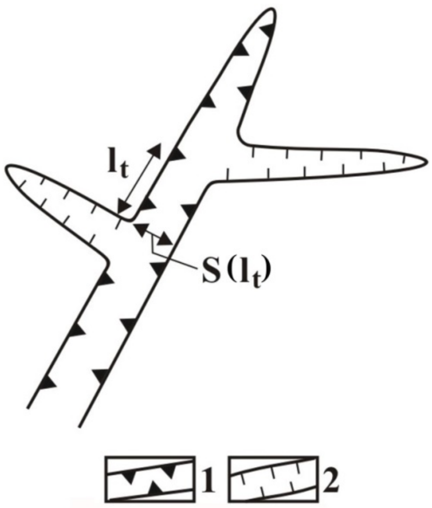

Figure 5. The distance of tributary channels from each other and the place where the data of the shape of the main channel was taken into consideration**.** Legend: 1. Main channel; 2. Tributary channel. l_t is the distance between two tributary channels. *S(lt)* is the place where the shape of the main channel was taken into account.

In laboratory, a rinnenkarren system was created on a slope with an inclination of 15° made of Plasticine (**Figure 6 and 7**). The depth of the main channels was 0.7 cm, and their width was between 0.5 and 1 cm, while the depth of the tributary channels was 0.5 cm and their width was 1 cm. The length of the main channel was 200 cm that of the tributary channels was 30 cm. The number of tributary channels was 4, the distance between them was 40 cm, and the junction angle into the main channel was 45°. We let 1.7 cm^3 water into the channels separately from a pipette with free fall and we measured the transit time (actual transit time) of the incoming water at the lower end of the main channel by calculating the difference between the beginning and the end of the transit time. First, we only got water into one channel (first experiment series). In the followings, we got 1.7 cm^3 - 1.7 cm^3 water into 2 channels (second experiment series), then into 3 channels (third experiment series) and into 4 channels (fourth experiment series) simultaneously. Finally, we got water into 5 channels simultaneously (fifth experiment series). Water supply was always carried out at the upper end of the channels. As it can be seen in **Table 1**, 5 experiments belong to the first experiment series, 10 experiments belong to the second and third experiment series, 5 experiments belong to the fourth experiment series and 1 experiment belongs to the fifth experiment series.

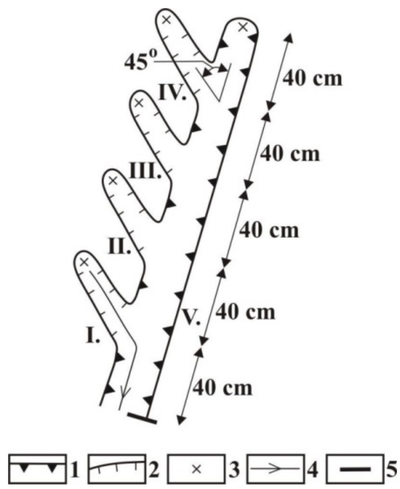

Figure 6. The theoretical figure of the rinnenkarren system of the laboratory experiment**.** Legend: 1. Main channel; 2. Tributary channel; 3. Place of water supply; 4. Water flow; 5. Place of measurement of the transit time, I-IV. tributary channels, V. main channel.

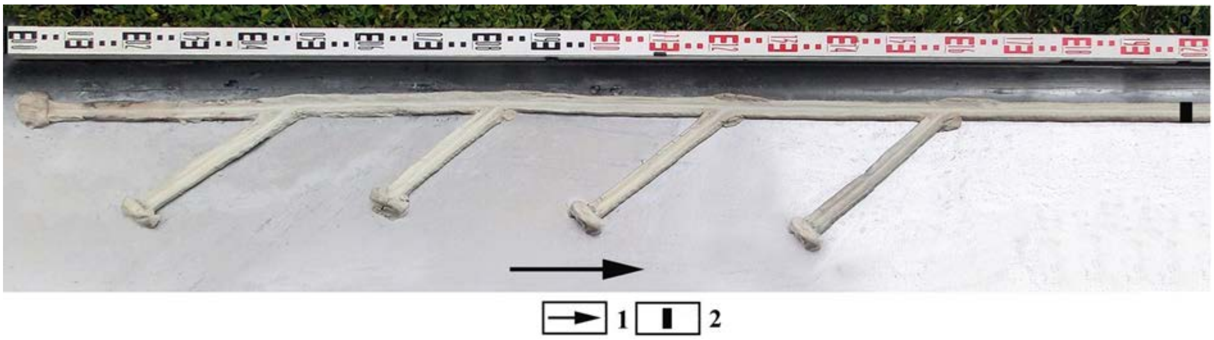

Figure 7. Rinnenkarren system created in laboratory**.** Legend: 1. Dip direction of the tray; 2. Place of measurement.

Table 1. Transit times measured on the experimental rinnenkarren system

Experiment series	The number of experiment series	Places ofwater supply	The number of placesof water intake	Total waterflow lengthcompared to the measurement place [cm]	Beginning of waterflow	End of water flow	Actual transit time [sec]	Total transit time[sec]
1	1	I	1	70	1.33	4.113	2.783	2.783
	2	II	1	110	1.916	5.903	3.987	3.987
	3	III	1	150	2.6	6.94	4.34	4.34
	4	IV	1	190	3.2	8.21	5.01	5.01
	5	V	1	200	3.297	8.61	5.313	5.313
2	1	I,II	2	100	1.356	3.452	2.096	6.77
	2	I,III	2	140	1.404	4.512	3.108	7.123
	3	I,IV	2	180	1.406	3.974	2.568	7.793
	4	I,V	2	190	1.34	4.012	2.672	8.096
	5	II,III	2	140	2.084	4.168	2.084	8.327
	6	II,IV	2	180	1.846	4.084	2.238	8.997
	7	II,V	2	190	1.862	3.922	2.06	9.3
	8	III,IV	2	180	2.51	4.226	1.716	9.35
	9	III,V	2	190	2.566	4.298	1.732	9.653
	10	IV,V	2	190	2.926	5.816	2.89	10.323
3	1	I,II,III	3	170	1.424	6.846	5.422	11.11
	2	I,II,IV	3	210	1.332	8.172	6.84	11.78
	3	I,II,V	3	220	1.368	8.034	6.666	12.083
	4	I,III,IV	3	210	1.396	8.564	7.168	12.133
	5	I,III,V	3	220	1.41	8.178	6.768	12.436
	6	I,IV,V	3	220	1.378	8.786	7.408	13.106
	7	II,III,IV	3	210	1.924	8.828	6.904	13.337
	8	II,III,V	3	220	1.928	8.952	7.024	13.64
	9	II,IV,V	3	220	1.904	9.008	7.104	14.31
	10	III,IV,V	3	220	2.466	8.992	6.526	14.663
4	1	I, II, III,IV	4	240	1.362	8.212	6.85	16.12
	2	I,II,III,V	4	250	1.352	8.742	7.39	16.423
	3	I,II,IV,V	4	250	1.458	8.474	7.016	17.093
	4	I,III,IV,V	4	250	1.308	9.114	7.806	17.446
	5	II,III,IV,V	4	250	1.886	8.714	6.828	18.65
5	1	I,II,III,IV,V	5	320	1.392	9.032	7.64	21.433

In case of the laboratory experiment (first experiment series), a functional relation was looked for between the transit time and the distance between the place of water supply and the place of measurement.

We investigated how the duration of the actual transit time and the total transit time compared to each other changed when we increased the density and distance of water supply places (second, third, fourth and fifth experiment series).

The actual transit time is calculated, as it was already mentioned by the difference of the beginning and end of the water flow at the place of measurement. The total transit time is calculated by adding the different actual transit times measured at certain channels (thus, those involved in experiment series 2, 3, 4, 5) during the first experiment series.

The relation between discharge (and thus, the extent to which the channel is filled with water) and the actual transit time was analyzed. If the amount of water supply increases, but the actual transit time is smaller at the measurement site as compared to a smaller amount of water supply, the rate of flow and thus, the discharge increases too. If the amount of water supply increases or it is of the same degree, but the actual transit time increases or is the same at the measurement site as compared to a smaller amount of water supply, the velocity of flow and thus, the discharge decreases too. The extent to which the channel is filled with water is larger in the former case, while it is smaller in the latter.

Parallel laboratory and field studies are simultaneously necessary, since we can only measure transit time in case of the laboratory experiment. We do not get data for channel shape and its change in lack of dissolution. However, in case of the field investigation, we draw a conclusion to dissolution from the shape only, since we do not know the transit time (this could not be measured because of the intermittent nature of the rivulet).

From the area of the above mentioned glacier valley, further main channels were investigated. 11 channels were being narrow towards their lower end and 10 channels were being wide towards their lower end. (These latter ones were chosen from the above mentioned 30 rinnenkarren systems.) In the case of the first ones, the rate of the length being narrow at the lower end as compared to the total length was determined and its average was calculated. With the help of this rate, the length of the lower part was marked on the main channels being wide at their lower end.

In case of both varieties (main channel being narrow and being wide at the lower end), the density, the total length of tributary channels were calculated regarding the lower and upper sections as well as the proportional distance of the non-hanging tributary channels from the lower end of the main channel (the average of the distance of each non-hanging tributary channel was calculated). Proportional distance means at what proportion (as compared to the lower end of the main channel), the non-hanging tributary channel is located on the main channel regarded as one unit. Average proportional distance means the average of the proportional distance of tributary channels occurring at main channels being wide and being narrow on their lower end.

The number of non-hanging and hanging tributary channels having a channel hollow was determined. The length and width of the channel hollows were measured. The average width and length of the channel hollows occurring at the hanging and non-hanging tributary channel were calculated separately.

3. Results

According to the result of the laboratory measurement, if the distance of water supply increases (first experiment series), the actual transit time (**Table 1**) increases at the measurement place which can be explained by the "stretching" of the water of the rivulet. Because of the growth of the actual transit time, the duration of cove redness with water increased on the channel floor (**Figure 8**). As apart from the place of intake, the amount of water intake was the same in all cases at the measurement place. The discharge decreased by the increase of the actual transit time.

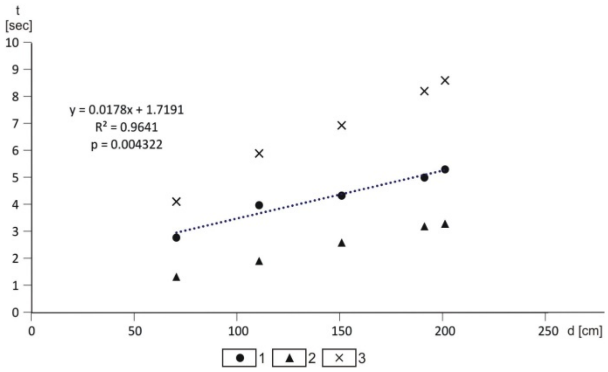

Figure 8. The functional relation between the place of water supply and the actual transit time at the model experiment when there was a water supply simultaneously at one place only (first experiment series). Legend: 1. Actual transit time; 2. The beginning of the arrival of the intake water at the place of measurement; 3. The end of the flow of the intake water at the place of measurement; t. duration of measurement; d. distance between the place of measurement and the place of water supply.

It can be stated that by the increase of the distance of the place of water intake, the actual transit time increases and thus the discharge decreases. Under natural circumstances, it means that in case of increasing distances between the tributary channels as compared to the given place of the main channel and in case of the same water inflow (water intake), the actual transit time increases on the lower part of the main channel and thus discharge decreases. Therefore, dissolution is more and more concentrated to the channel floor.

This statement is in harmony with the data of the field measurements. The larger the distance between two tributary channels is, the smaller the shape of the main channel above the tributary channel in a lower position is (**Figure 9**). This can be explained by the fact that with the growth of the distance between the tributary channels, the water coming from the upper tributary channel flows for a longer time (thus, the discharge will be smaller and smaller) through that part of the main channel which is above the junction site of the lower tributary channel. This results in the two things: the dissolution time will become longer and the dissolution will be focused to the channel floor. Since the shape decreases logarithmically in the function of distance, the dissolution time on the channel floor increases to a growing extent with the increase of the distance. From **Figure 9**, we can read that in case of a distance smaller than 100 cm, the average shape of the main channel changes from value 1 to almost 1.8 with the increase of the distance. However, in case of distances between 2 and 5 meters, even though the shape is smaller, its value shows a slight change. At 2 m, shapes between 0.6-0.8 occur, while at 5 m, a value close to 0.4 can be seen. From the above mentioned things, it can be concluded that in case of small water supply distance, a larger change of shape belongs to the same section change as compared to the same change of section in case of a larger water supply distance. This can be attributed to the fact that at a smaller water supply distance, the discharge decreases to a larger degree even in case of a larger water supply than in case of a larger water supply distance. By this, with the increase of distance, the duration of the small discharge increases at the expense of the duration of large discharge. Because of the increase of the duration of the small discharge, the dissolution is more and more concentrated to the floor of the main channel farther and farther from the place of water supply.

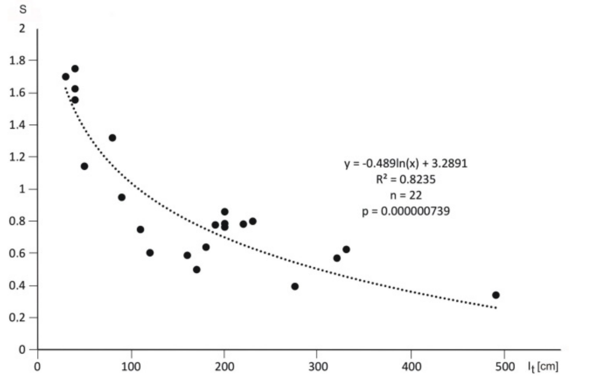

Figure 9. The functional relation between the distance of two tributary channels of the main channel from each other (l_t) and the shape (S) calculated at the place of the lower tributary channel of the main channel $S(l_t)$**.**

During studying the relation between the density of the tributary channels of the rinnenkarren systems and the shape of the main channel, it turned out that the average channel shape increases with the increase of the density (**Figure 10**).

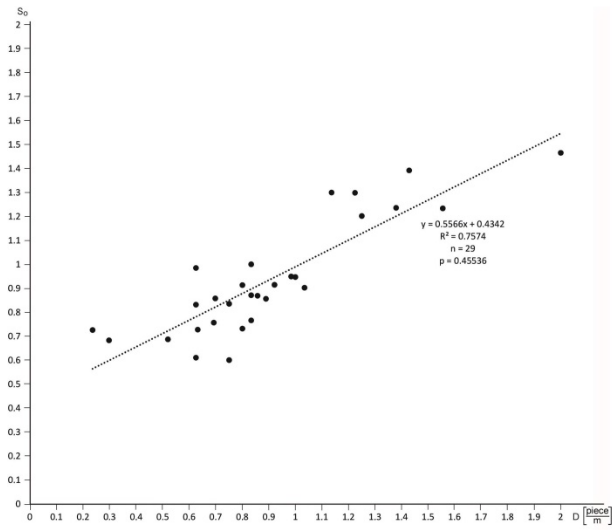

Figure 10. The functional relation between the average density of tributary channels (D) and the average shape of the main channel (S_0)**.**

This is possible if the more densely tributary channels occur, the better the water of the rivulets flowing from them confluence and it causes a growth of discharge in the main channel. The same can be seen in case of channels developed under superficial deposit or soil. According to Song (1986), the channels widen at those places where the water seeping through the cover is led to the water flowing between the bedrock and the cover. If the density of tributary channels is small or becoming smaller and smaller, the discharge will be smaller and smaller too, because the water flowing from the tributary channels is not added up. This results in the fact that in the main channel, in case of an increasingly smaller density of tributary channels, a smaller and smaller amount of water flows for an increasingly longer period. In other words, the dissolution on the floor will be more dominant and thus the channel will become more and more deep while, but its width will be the same.

The confluence of tributary rivulets is also proved by our laboratory measurements. In the experimental rinnenkarren system, the actual transit time is smaller than the total transit time in case of a larger amount of water supply (**Table 1**). With the increase of the number of places of water supply, the difference of the two is increasingly larger (**Figure 11**). In the followings, there are some examples for this.

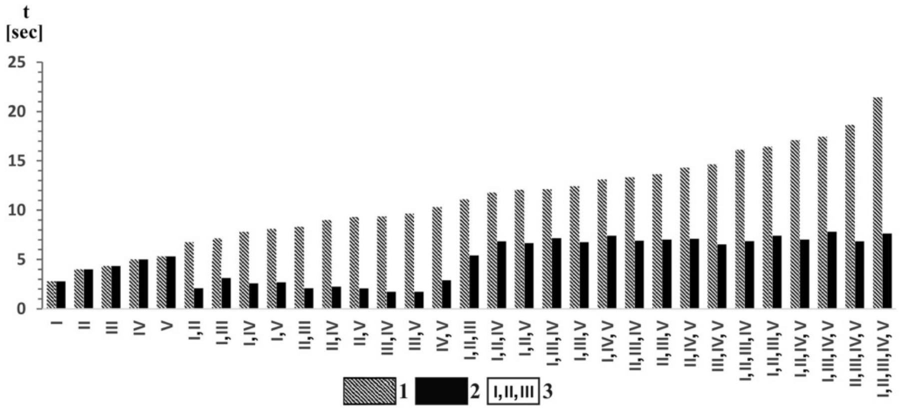

Figure 11. Transit times measured in the artificial rinnenkarren system**.** Legend: 1. Total transit time; 2. Actual transit time; 3. The number of the Roman numerals shows the number of places from where water supply occurred.

In case of a separate water supply of tributary channels I, II, and III, the actual transit time is 2.78 sec., 3.99 sec, and 4.34 sec. (first experiment series). When a simultaneous water supply was carried out from these three tributary channels into the main channel, the amount of water intake was added up and 5.1 cm^3 water was flowing during an actual transit time of 5.42 sec (during the first experiment of the third experiment series, **Table 1**, **Figure 11**). If we look at the total transit time, its value is 11.11 sec. In other words, the total transit time will be larger than the actual transit time. In case of a water supply at four tributary channels (at the first experiment of the fourth experiment series), the total transit time (16.12 sec.) will be even larger than the actual transit time (6.85 sec.). The difference of the two will be larger, because in case of an increasingly larger number of water supply places, the confluence of the rivulets will be of larger extent.

However, the tributary rivulets can not only have a role hindering drainage, but also a role accelerating drainage. In the experiment, the accelerating role can mainly be experienced in case of water supply at two places (**Figure 11**). In this case, the transit time also decreases actually (thus, discharge increases in the main channel) as compared to the transit time of water supply from one tributary channel. It is likely that if the distance between the tributary channels and their distance from the observation place increase simultaneously, it decreases the actual transit time. Experiments III and V of the second experiment series can be good examples for this (**Figure 11**). However, in case of water supply at four or five places, the actual transit times did not increase either as compared to the transit times of water supply at three places as it would have been expected. In spite of the fact, the amount of water supply increases. All of these draw attention to the fact that the water of the tributary channel entering the main channel can not only accelerate but also hinder the water flow in the main channel. Various actual transit times and various discharges may occur in the main channel depending on the fact in how many tributary channels water flows and in those channels where it does what the distribution and position of the tributary channels is. Thus, if we take into consideration the experimental rinnenkarren system, if water flows in tributary channels I and III, the discharge of the main channel will be smaller (since the actual transit time is larger) as compared to the situation when water flows in channels III and V only.

During drainage, discharge can be divided into large and small discharges. A small discharge can occur both at the beginning and at the end of water flow. Thus, if the value of the large discharge can change, its transit time changes too. The value and thus, the time of the small discharge can change too. Because of this, the duration of the transit times of the two discharges as compared to each other is modified too. The proportion of the two discharges also depends on the size of the cross-section. In case of a larger cross-section, the duration of the small discharge also increases at the same water input. Therefore, the pattern of the rivulet of the tributary channels (by this, we mean in which of the existing tributary channels, there is a water flow) and the growth of the cross-section affect the proportion of the duration of the large and small discharges. Therefore, during the growth of the main channel, the duration of the small discharge can be different at the same density of the tributary channels too. Because of this, in case of the same densities of tributary channels, very diverse channel shapes may also occur. Thus, for example, shapes of 0.6 or even 1.0 also belong to a density of tributary channels between 0.6 and 0.7 (**Figure 10**).

On the wide part of the studied main channels being narrow towards their lower end (n = 11), the density of the non-hanging tributary channels is 0.001477 piece/cm (piece number is 8), and their total length is 3813 cm. On the narrow lower end of the main channels, the density of the non-hanging tributary channels is 0.0008577 piece/cm (piece number is 3), and their total length is 550 cm. It can be stated that both the density and the length of the non-hanging tributary channels are smaller on the lower, narrow part of the main channel than on its upper, wide part. However, the average proportional distance of the tributary channels (0.629) is larger than in the case of the main channels being wide at their lower end (0.5485). Thus, both the density and the length of the tributary rivulets were also smaller here when neither a main channel nor a tributary channel existed on the bearing terrain. A smaller amount of water arrived at the lower end of the main rivulet (because of the smaller number of the tributary rivulets, but also because their catchment area was smaller because of their smaller length). Thus, its width did not increase as compared to the upper part of the rivulet. Towards the lower end of the main rivulet, the decrease of the density and length of the tributary rivulets does not mean the decrease of the width of the main rivulet. But it means that the width of the rivulet does not increase towards the lower end of the main rivulet. However, since the tributary rivulets are farther from the lower end of the main rivulet (main channel), which is presented by the relative large average proportional distance of tributary channels, the transit time increases because of the larger distance of water supply. Thus, the width of the main rivulet can decrease actually too.

On the upper part of the main channels being wide at their lower part (n = 10), the density of the non-hanging tributary channels is 0.001595 piece/cm (piece number is 7), and their total length is 650 cm, while the density of the non-hanging tributary channels on their lower part is 0.003974 piece/cm (piece number is 17), and their total length is 4381 cm. On the lower part of the main channels, the large density and the great total length of the tributary channels refer to the fact that before the development of the channels, both the density and the length of the tributary rivulets were larger on the lower part of the main rivulet than on the upper part of the main rivulet. Although the confluence of the rivulets could occur in this case too, the channel wall, since it does not exist, could not limit the widening of the rivulet. This resulted in the fact that the lower part of the main rivulet got more water than the upper part and thus, it became wide because the developing main channel became wider on it lower part than on its upper part.

On the lower part of the main channels being narrow at their lower end, there are no channel hollows either at the conjunction sites of the hanging (n = 18), or that of the non-hanging tributary channels (n = 3). However, on their wide, upper part, where there are altogether 40 hanging channels, 26 have channel hollows, while 2 out of 8 non-hanging tributary channels have them.

The distribution of the channel hollows presented above refers to the fact that they develop mainly in case of steps of hanging tributary channels, but they can also develop at non-hanging tributary channels. At the steps, the effect of the gradient of the rivulet is reflected in the different size of the channel hollows. Thus, in case of the hanging tributary channels, the average width of the channel hollows (n = 53) is 54,07 cm, and their length is 70,07 cm, while in case of the non-hanging ones (n = 13) average width is 39,3 cm, and the average length is 51,46 cm (the size of the channel hollows of the main channels becoming narrow towards their lower end was not taken into account since the number of measurements of the channel hollows related to the non-hanging tributary channels is only 2). Thus, vorticity and the local hollow on the main channel is mainly caused by the increase of the gradient of the rivulet at the steps, but it can also develop with a smaller possibility though, during the joining of rivulets without gradient. Since on the narrow part of the main channels being narrow at their lower end, they do not develop either at hanging, nor at non-hanging tributary channels, the condition of their development can be the fact that the main channel is wide enough.

4. Conclusion

The tributary rivulets of the channel-free surface control the width relations of the later developing main channel. (These former rivulets are represented by the present non-hanging tributary channels.) The developed tributary channels have an effect on the shape of the developing main channel and on the rate of growth of the width and depth of a main channel with a given width. Mainly, the later developing tributary channels (these are the hanging tributary channels) are responsible for the development of channel hollows.

The discharge of the channels is affected by the stretching of the rivulet, the confluence of the rivulets and the impeding and accelerating effect of the tributary rivulet to the flow of the main rivulet. The more the rivulet stretches, the lesser the different rivulets confluence and the lesser a rivulet impedes another in its flow, the smaller the discharge of the rivulet is. These conditions exist if the rivulet is in channel.

The shape of the main channels of the rinnenkarren systems depends on the duration of their large discharges and that of their small discharges. However, the duration of the small and large discharges depends on the density of the tributary channels and on the place of the tributary channels on the main channel (the distance of a tributary channel measured from a given place of the main channel). Therefore, the rarely tributary channels occur, the longer their distance from a given section of the main channels is, the more the dissolution to the channel floor focuses since the small discharge is of an increasingly longer duration. Because of the dissolution on the floor, a small channel shape is created. The longer the duration of the larger discharge is, the greater the chance for the development of a large channel shape in the main channel is because dissolution takes place not only on the channel floor, but in the sides of the channel too. This occurs if the density of the tributary channels is high or the distance of the tributary channel from the given place of the main channel is small.

The type of the width change of the main channels depends on the development age of the tributary channels compared to that of the main channels. A width change in its total length is only characteristic of the main channel if the tributary channel and the main channel developed simultaneously. The main channel widens from its upper end to its lower end if the density of the tributary channels increases downwards and on the lower part of the main channel, the total length of these tributary channels is larger than on the part above this section. Because of these characteristics, the discharge of the rivulet of the main channel increases on the still channel-free terrain, towards its lower end, which results in the increase of the width of the main channel from its upper end towards its lower end. The width of the main channel decreases towards its lower end if the density and total length of the tributary channels being the same age as the main channel are smaller on the lower section than on the part being above this section and if the proportional distance of the tributary channels is large as compared to the lower end of the main channel. In this case, the discharge of the rivulet being responsible for the development of the main channel does not increase on the lower, narrowing part of the main channel, or the still channel-free terrain, but it decreases because of the relatively large transit time. This results in the actual narrowing of the main rivulet and thus, the development of a narrower channel section.

Channel hollows develop with a larger number and size on the main channel, mainly if the development of the tributary channels is younger than that of the main channel or if their deepening is slower. In this case, at the steps of the tributary channel, the larger gradient of the tributary rivulet enhances the vorticity originating from the confluence of the rivulets and thus, the increase of channel hollows too.

Conflict of interest

The authors declare that they have no conflict of interest.

References

1. White WB. Geomorphology and hydrology of karst terrains. New York: Oxford University Press; 1988. p. 464.
2. Ford D, Williams P. Karst hydrogeology and geomorphology. Chichester: John Wiley & Sons, Ltd; 2007. p. 562.
3. Veress M. Karst environments: Karren formation in high mountains. Berlin: Springer Science & Business Media; 2010. p. 230.
4. Song L. Origination of stone forest in China. International Journal of Speleology 1986; 15(1-4): 3–13.
5. Slabe T, Liu H. Significant subsoil rock forms. In: Ginés Á, Knez M, Slabe T, *et al.* (editors). Karst Rock Features. Karren Sculpturing. Postojna: Založba ZRC, ZRC SAZU; 2009. p.123–138.
6. Smart C. Glacierized and glaciated karst. In: John Gunn (editor). Encyclopedia of Caves and Karst Science. London: Taylor & Francis; 2004. p. 388–390.
7. Hutchinson DW. Runnels, rinnenkarren and mäanderkarren: Form, classification and relationships. In: Fornos Asto JJ, Gines Gracia A (editors). Karren Landforms: Proceedings of the International Symposium on Karren Landforms: Sóller on 19-24th of September 1995. Palma de Mallorca: Universitat de les Illes Balears; 1996. p. 209–224.
8. Ginés J, Ginés A. Mid-mountain Karrenfields at Serra de Tramuntana in Mallorca Island. In: Gines A, Knez M, Slabe T, *et al.* (editors). Karst Rock Features. Karren Sculpturing. Postojna: Založba ZRC, ZRC SAZU; 2009. p. 375–390.
9. Veress M, Lóczy D, Zentai Z, *et al.* The origin of the Bemaraha tsingy (Madagascar). International Journal of Speleology 2008; 37(2): 131–142.
10. Eckert M. Die Karren oder Schratten. Peterm. Mitteilangen 1898; 69–71.
11. Wagner G. Around Hochifen and Gottesacker area. An introduction to the growth and decay of an alpine landscape (in German). Öhringen: Verlag der Hohenloheschen Buchhandlung Rau, Öhringen; 1950. p. 161.
12. Sweeting MM. The landforms of north-west Country Clare, Ireland. Transactions and papers (Institute of British Geographers) 1955; 21: 33–49.
13. Haserodt K. Investigations into the height and age structure of the karst forms in the Northern Limestone Alps (in German). Regensburg: Michale Lassleben Verlag; 1965. p. 169.
14. Louis H. General geomorphology (in German). 3rd ed. Berlin: Walter de Gruyter & Co.; 1968. p. 109.
15. Bögli A. Die Wichtigsten Karrenformen der Kalkalpen. In: Karst Processes and Relevants Landforms. Berlin: International Speleological Union, Symposium on karst denudation; 1976. p. 141–149.
16. Jennings JN. Karst Geomorphology. 2nd ed. Oxford, UK; New York: Basil Blackwell; 1985. p. 293.
17. Gladysz K. Karren on the Quatsino Limestone [Bachelor’s thesis]. Hamilton: McMaster University; 1987.
18. Bögli A. Kalklösung und Karrenbildung. Zeitschrift für Geomorphologie. Suppl 1960; 2: 4–21.
19. Trudgill S. Limestone geomorphology. Geomorphology texts. London: Longman; 1985. p. 196.
20. Ford DC, Williams PW. Karst geomorphology and hydrology. London: Chapman & Hall; 1989. p. 601.
21. Veress M. Rinnenkarren. In: Gines A,Knez M, Slabe T, *et al.* (editors). Karst Rock Features, Karren Sculpturing. Postojna: Založba ZRC, ZRC SAZU; 2009. p. 211–222.
22. Veress M, Zentai Z, Péntek K, *et al.* Flow dynamics and shape of rinnenkarren systems. Geomorphology 2013; 198: 115–127.
23. Veress M, Unger Z. Baradla-domica: Large cave system on the Hungarian-Slovak border.In: Dénes L (editor). Landscapes and Landforms of Hungary. Switzerland: Springer International Publishing; 2015. p. 167–175.
24. Sauro U. The geomorphological mapping of “Karrenfelder” using very large scales: An example. Karst Processes and Relevant Landforms 1976; 189–199.
25. Veress M, Tóth G. Types of meandering karren. Zeitschrift Für Geomorphologie 2004; 48(1): 53–77.
26. Kozma K, Mitre Z. Variations of type A channels in Totes Gebirge. Zeitschrift Für Geomorphologie 2012; 56(2): 37–46.