Proceedings of the Geologists' Association xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Proceedings of the Geologists' Association

journal homepage: www.elsevier.com/locate/pgeola

# The relationship between suspended sediment settling velocity and water table sinking rates in intermittent lakes in karstic depressions

Márton Veress *, Zoltán Unger, Zoltán Mitre, István Gárdonyi, György Deák

*University of West Hungary, Faculty of Natural Sciences, Department of Physical Geography, Szombathely, Hungary*

ARTICLE INFO

*Article history:*
Received 27 February 2015
Received in revised form 29 April 2015
Accepted 3 May 2015
Available online xxx

*Keywords:*
Karstic depression
Intermittent lake
Laboratory experiment
Suspension
Sedimentation rate
Velocity of water table decline
Sediment formation

ABSTRACT

The conditions for sediment accumulation in the intermittent lakes of subsidence dolines were modelled in laboratory. For a given water table sinking rate we investigated the grain size and settling velocity of the sediment that is deposited in the basin. Two types of suspension were made that had natural-like characteristic features. In both types, the size of the single-grained, solid material was smaller than 0.063 mm and their concentration was 0.2 m/m %. One of the suspension types was also loaded with shredded vegetable residues in a concentration of 0.05 m/m % because vegetable residues occur in the intermittent lakes of dolines and in the sediment of karstic depressions too. The sedimentation rate was determined in a measuring tube for both concentrates in a water depth of 5.0, 7.5 and 10.0 cm. The sedimentation speed was greater in all water-layer thicknesses in the suspension that contained vegetable waste than in the system that only contained clay. The presence of vegetable residues increased the sedimentation rate thus, the quantity of the deposited material too. It can be concluded that sedimentation occurs in the sediment basin if the sedimentation speed of the grains of the suspension is greater than (or equal to) the velocity of water table decline in the basin. This nature of sedimentation can be regarded as a characteristic of the lakes of the bearing karstic depressions. Thus the sedimentation of the suspended material of the lake and its quantity is determined by the velocity of water table decline of the lake.

## 1. Introduction

Depressions (dolines, ponors) are common on covered karst, in which sediments of their environment can accumulate in a thickness of several metres. If we understand the evolution of the sediment of karstic depressions, it may promote the interpretation of the evolution and development of depression. In addition, this fact may help to obtain information about the surface development of their environment and to analyse the effect of human activity on karstic features. The sediments of depressions develop partly from lakes, therefore it is necessary to study the sedimentation of the lakes of depressions. The water table of the intermittent lakes of karstic depressions may sink rapidly because of the drainage from depressions. In this study, it has been examined how the water table sinking of the lakes of depressions affects the sedimentation of sediment suspended in their water. The process was studied in laboratory with the help of model experiments. During this, it was examined that in case of a given water table sinking what the sedimentation rate of the grains that settle is.

In the depressions of karst areas (doline, ponor) intermittent or permanent lakes can be formed. Permanent lakes are formed when there is impermeable filling at the bottom of the depression. The permanent lakes of the depressions can also become empty if the depression loses its impermeable layer, its filling. For example, a 20-year-old lake in Texas that emptied has been described by Beck and Sinclair (1986). Intermittent lakes can also be formed in ponors and in dolines (Ford and Williams, 2007). The intermittent lakes can be formed because the volume of water supply exceeds the drainage capacity. The decreasing drainage capacity may be due to many reasons e.g. increasing karst water level, the underdevelopment or blockage of karstic passage. Lakes can be formed as a consequence of overflow from other lake systems (Beck and Sinclair, 1986). This type of formation of the lakes can be also found at the karstic depressions of the polje.

The intermittent lakes are widespread on various karsts. They are found on taiga and tundra karst (Korzhuev, 1961; Pulina, 2005), on temperate karst (Veress, 2000), and on high mountain karst (Veress et al., 2013). The lakes, which were formed because of the increasing karst water level are also very common on

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* Corresponding author. Tel.: +36 30 500 9751; fax: +36 94 504 407.
*E-mail address:* vmarton@ttk.nyme.hu (M. Veress).

http://dx.doi.org/10.1016/j.pgeola.2015.05.001
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Mediterranean (Komac and Zorn, 2013) and on tropical karst (Lehmann, 1936; Zhang, 1980).

Karst depressions or dolines can be classified as solution dolines, collapsed dolines, caprock dolines and subsidence dolines (Waltham and Fookes, 2003; Williams, 2004; Waltham et al., 2005). The subsidence dolines are formed on covered karst if the superficial deposit is carried in the passages of the karst. Permanent lakes are developed in the solution dolines and in the caprock dolines too (Andrejchuk, 2002). While intermittent lakes are often developed in subsidence dolines and ponors with passages (Veress, 1987a, 2000).

Lakes and thus karstic lakes are sediment traps. The sediment of lakes can be of chemical origin (Holmes et al., 1995; Valero Garcés et al., 2014) or can be transported into the lake. The transported sediment is most often of fluvial origin (Li et al., 2010; Oliveira et al., 2008; Develle et al., 2011), but it can also be of subaerial (Develle et al., 2011) or mass movement origin (Denizman et al., 2010; Morello et al., 2009). The facies of the sediments accumulated in the lakes indicate environmental changes. Thus, climate change (Holmes et al., 1995; Oliveira et al., 2008; Barreiro-Lostres et al., 2013), the composition of the rocks of the catchment area (Oliveira et al., 2008; Develle et al., 2011), the sediment sources of various origins such as aeolian origin (Develle et al., 2011), the anthropogenic effects on the catchment area (Barreiro-Lostres et al., 2013; Schmidt et al., 2000), changes of the vegetation (Develle et al., 2011; Schmidt et al., 2000), changes of water level (Holmes et al., 1995), the intensity of sediment transportation (Barreiro-Lostres et al., 2013) and the relationship between denudation and accumulation (Li et al., 2010). However, they also reflect the change of state of the lake thus, the change of water level and water depth (Schmidt et al., 2000), that of water quality (Holmes et al., 1995; Develle et al., 2011), eutrophication (Obelič et al., 2005) or the changes of flora and fauna (Wantzen et al., 2008).

The sedimentation of karstic lakes with permanent water does not differ significantly from the non-karstic lakes with permanent water while that of intermittent karstic lakes is different to some extent because lake sediment can be transported into the karst. Thus, not the depression, but the karstic passage is the sediment trap. Another reason is that states with and without water alternate on the floor of the bearing depression. In the latter case, the sedimentation of lacustrine origin can be changed by other ways of sedimentation (transportation by water and of aeolian origin). However, the origin of lakes of two types is also different. The water of karstic lakes of permanent waters can originate from karstic springs (Develle et al., 2011), ground water (Holmes et al., 1995), rainwater (Valero Garcés et al., 2014) and karst water (Sweeting, 1973; Zhang, 1980), while the water of intermittent karstic lakes mainly originates from rainwater (Veress, 1987a, 2000) or karstwater (Sweeting, 1973).

## 2. The sediment formation model of the intermittent lakes of subsidence dolines

The intermittent lakes of the subsidence dolines are natural clarifiers. It was mentioned that the reason of the water level sinking of the ephemeral and moderate-duration lakes is the drainage of water into the karst. The suspended material also goes away with together the water through the passages. The transportation of the water and the suspended material to the karst can happen both at the falling stage of water level and at the permanent stage.

According to our sediment deposition model, the grain size of the deposited material from the doline lakes (and so partly the quantity as well) depends on two factors: the velocity of the water level sinking and the sedimentation rate of the suspended material (1–63 μm grain size). The grain sizes that settle do so when the settling rate exceeds or equals the rate of water level sinking (Fig. 1b). The grain sizes with settling velocities less than the water level sinking rate are not deposited in the doline, but with the flushing water it is transported into the karst (Fig. 1a). If the water level sinking velocity of the lake is decreasing, finer (and so more) material can be deposited. Similarly, the quantity of the deposited material from the lake is increasing if the velocity of sedimentation increases although the quantity of the transported sediment does not increase because of any effect and its grain size is unchanged. A similar phenomenon occurs during sewage treatment. In the sedimentation tank, the sedimentation of suspended substances is increased by adsorption when the anions of the solvent adhere to the suspended substance (Benedek and Valló, 1982) or the charge of the colloids is ceased and as a consequence they become coagulated (Barótfi, 2003).

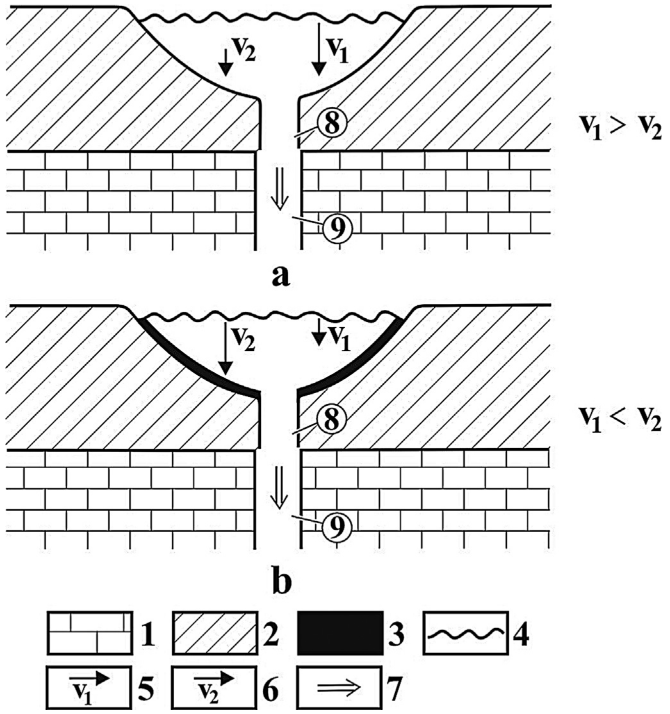

**Fig. 1.** A sedimentation model of lakes of subsidence dolines when a sediment finer than 63 μm only and vegetable waste arrives at the lake. (a) The sediment finer than 63 μm does not deposit from the lake because the water table sinking of the water is greater than the sedimentation rate of the suspended grains, (b) the sediment finer than 63 μm deposits because the water table sinking is smaller than the sedimentation rate of the suspended grains, (1) limestone, (2) superficial deposit, in which the doline developed, (3) the suspended material deposited from the lake, (4) water level of the lake, (5) the velocity of water table sinking of the lake, (6) the sedimentation rate of the suspended grains, (7) water drainage from the doline, (8) passage of the doline developed in the cover, (9) passage of the doline developed in the limestone.

## 3. The method

Modelling is widespread for the research of the phenomena of karsts. Model experiments have been carried out by Curl (1966), Quinif (1973), Glew and Ford (1980), Fabre and Nicod (1982), Dzulynski et al. (1988), Veress et al. (1998), Slabe (2005, 2009), and Deák et al. (2013, 2014). We investigated sedimentation with the following model experiments.

The sedimentation speed of grains was examined in a measuring tube. A settling pool was used to examine how the sedimentation is affected by the rate of water level sinking and the settling speed of the grains. In the settling pool, at the

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**Table 1**
The determination of sedimentation rate in different depths (at 5.0, 7.5, 10.0 cm).

| Sample | Sample $A_1$ | | | Sample $A_2$ | | |
|---|---|---|---|---|---|---|
| Composition of suspension | $1\ dm^3 + clay \approx 0.2\ m/m$ % | | | $1\ dm^3 + clay \approx 0.2\ m/m$ % + veg. waste $\approx 0.05\ m/m$ % | | |
| Examined depth (cm) | 5.0 | 7.5 | 10.0 | 5.0 | 7.5 | 10.0 |
| Half-life of sedimentation time (min) | 23.9 | 39.9 | 42.9 | 15.7 | 21.1 | 27.6 |
| Sedimentation rate (cm/min) | 0.209 | 0.187 | 0.233 | 0.318 | 0.355 | 0.362 |

**Table 2**
The evaluation of measurement data in the suspension with an $A_1$ suspension (2 g clay/1 $dm^3$ water).

| Sample number | Time (min) | Time logarithm | Measured mass in 5 $cm^3$ (mg) | Mass of L to 1 $dm^3$ (mg) | Mass of Ik to 1 $dm^3$ (mg) |
|---|---|---|---|---|---|
| 1 | 1 | 0 | 9.80 | 1.96 | 0.04 |
| 2 | 5 | 1.60 | 8.00 | 1.60 | 0.40 |
| 3 | 15 | 2.70 | 6.30 | 1.26 | 0.74 |
| 4 | 30 | 3.40 | 5.50 | 1.10 | 0.90 |
| 5 | 60 | 4.09 | 4.20 | 0.84 | 1.16 |
| 6 | 120 | 4.78 | 3.70 | 0.74 | 1.26 |
| 7 | 180 | 5.19 | 3.00 | 0.60 | 1.40 |
| 8 | 360 | 5.88 | 2.50 | 0.50 | 1.50 |
| 9 | 600 | 6.39 | 1.70 | 0.34 | 1.66 |

*Notes*: L: floating material content of the pipetted suspension at a given time; ek: constant (2 g/$dm^3$) the original concentration of the suspension; Ik: the concentration of floating material in the glass tube at a given depth which is the difference of the original concentration of the suspension (ek) and of the momentary concentration.

sedimentation places, the sedimentation speed is equal with the measured sedimentation speed in similar depth in the measuring tube. This parameter (sedimentation speed) was constant in the settling pool during the investigations.

A sample was taken of non-cohesive sediment and it was separated into fractions according to grain size after drying with sieving. The suspensions ($A_1$ and $A_2$) were made from the smallest grain size (smaller than 63 μm) fractions. From this substance 2–2 g was suspended then the suspension was filled to 1–1 $dm^3$ so we had got two ($A_1$ and $A_2$) solutions with 0.2 m/m %. The $A_2$ suspension system was loaded forward with shredded vegetable waste (1–0.5 mm parts of wheat, straw), so that the solution in terms of vegetable waste becomes 0.05 m/m % (Table 1).

We measured the content of the suspended material in the homogenous solutions with the "*pipette method*" (Stefanovits, 1981), in the liquid 5.0, 7.5, and 10.0 cm depth at exponential increasing intervals (1, 5, 15, 30, 60, 120 min, etc.; Fig. 2). Every time a 5 $cm^3$ volume sample was taken and the dry matter content was determined (Table 2). The dry matter content of samples each with a 5 $cm^3$ volume obtained from different depths (5.0, 7.5, 10.0 cm) and at different times (1, 5, 15, 30, 60, 120 min. etc.) was determined. Then this amount was applied to 1 $dm^3$ in a way that the above mentioned amounts were multiplied by 200 (Table 2).

The concentration of suspended matter was determined at the different points of time. A function was fitted to the data series (Fig. 3 curve 2). The other function (Fig. 3 curve 3) was derived by subtracting the measured concentration on each observation from the original concentration. The measurements were completed for both suspension $A_1$ and suspension $A_2$ and we could determine the sedimentation rate in the following way.

The suspended material content of $A_1$ suspension (on the basis of 10 cm depth) decreases exponentially. While to the same measuring point, the degree of decrease can be determined by calculating the difference of the original concentration and the instantaneous concentration. These values have a saturation curve in the function of time. We also applied this process at the 5.0 and 7.5 cm water depth.

We are going to get half (1 g) of the starting concentration (2 g) if we read the value of axis *y* of the curves' intersection. The intersection of value on axis *x* is suitable for the time that is necessary that in the given experiment the concentration

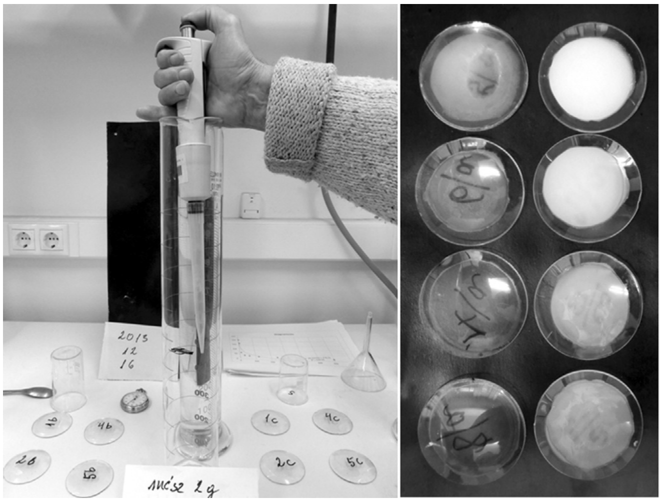

**Fig. 2.** The pipette method and dry matter content.

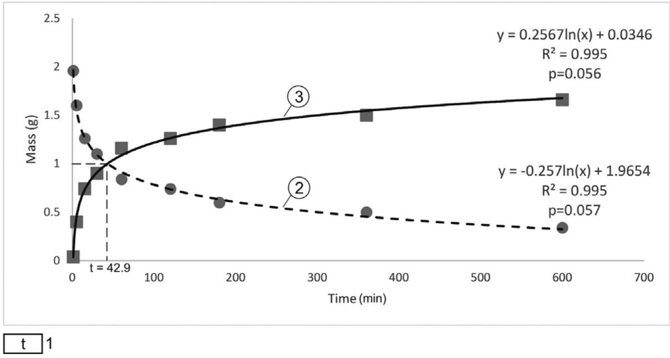

**Fig. 3.** The change of the measured and calculated concentration of the suspension in the function of time. (1) Half-life of the concentration, (2) the suspension concentration on the sampling point in the function of time, (3) the difference between the original concentration and the suspension concentration at the given time in the measurement point in the function of time.

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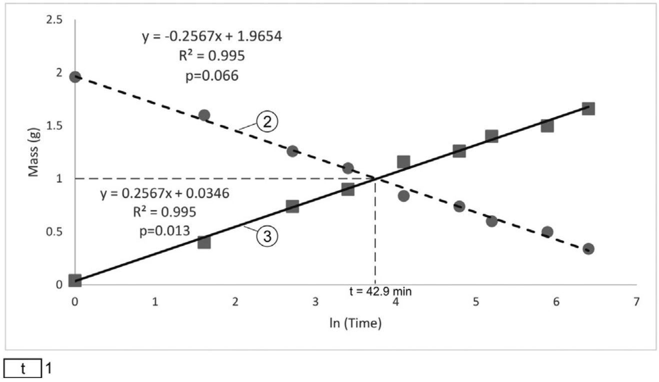

**Fig. 4.** The change of the measured and calculated concentration of the suspension in the natural logarithm function of time. (1) Half-life of the concentration, (2) the suspension concentration on the sampling point in the logarithm function of time, (3) the difference between the original concentration and the suspension concentration at the given time in the measurement point in the logarithm function of time.

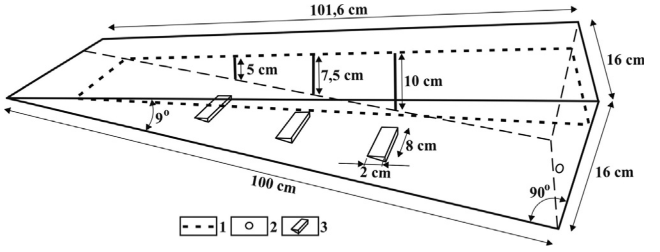

**Fig. 5.** A theoretical figure of the sediment basin. (1) Original water level, (2) place of water outflow, (3) microscope slide.

decreases to half. The halving time of the concentration can be determined more accurately if the concentration changes are described in the natural logarithm of measuring dates (Fig. 4). If we divide the measured distances (5.0, 7.5, 10.0 cm) from the surface of the stage to the sampling points by the halving time of the concentration, we get the sedimentation speed referring to the measuring points.

We measured the quantity of the deposited sediments from the suspension by the given speed of water level sinking in the settling pool (the water level sinking was ensured by the drainage at the bottom of the pool). The speed of water outflow in the settling pool can be determined and controlled (Deák et al., 2013). We marked the water level determined by the water of 10 dm$^3$ in the pool. Compared to this water level we put microscopic slides suitable for trapping the sediments in depth of 5.0, 7.5, and 10 cm (Fig. 5) Next we filled the pool with 10 dm$^3$ suspension marked A$_1$ and we did two types of water level sinking: first slow and second time quick outflow. We determined the quantity of the deposited material on the slides put in the given depth. We knew the sedimentation speed, since we had already determined it from the data of the measuring cylinder as we mentioned above. These measuring series were also repeated by vegetable residue containing suspension.

Applying the two methods together it can be proved whether there is sedimentation or not in case of given water level sinking, given suspension in case of known granulometric fractions with given deposition speed.

## 4. Results

The half-life of the determined concentration of suspensions A$_1$ and A$_2$ in the water depth of 5.0, 7.5, and 10.0 cm and the sedimentation speed were summed up in Table 1. The data from the mass of the depositing sediments, from the 10 dm$^3$ volume suspensions marked A$_1$ and A$_2$ in the case of the different water level sinking in the depth of 5.0, 7.5, and 10 cm, were summed up in Tables 3 and 4. Based on the data of the tables the following can be stated.

While the speed of the water level sinking changes between the values of $5.6 \times 10^{-2}$ and $1.1 \times 10^{-1}$ cm/min and the sedimentation speed of the suspension was $0.33 \times 10^{-2}$ cm/min at the most, we did not observe deposited material in none of the sampling points (Table 3). So sediment did not deposit when the speed of the sedimentation was smaller than the speed of the water level sinking.

**Table 3**
Sedimentation from samples A$_1$ and A$_2$ in different depths at high velocity of water table decline.

| Sample | | Sample A$_1$ | | | Sample A$_2$ | | |
|---|---|---|---|---|---|---|---|
| Composition of the suspension | | 1 dm$^3$ + clay ≈ 0.2 m/m % | | | 1 dm$^3$ + clay ≈ 0.2 m/m % + veg.waste ≈ 0.05 m/m % | | |
| Investigated depth (cm) | | 5.0 | 7.5 | 10.0 | 5.0 | 7.5 | 10.0 |
| Half-life time of the sedimentation (min) | | 23.9 | 39.9 | 42.9 | 15.7 | 21.1 | 27.6 |
| Sedimentation rate (cm/min) | | 0.209 | 0.187 | 0.233 | 0.318 | 0.355 | 0.362 |
| The velocity of water table decline is high | Velocity of water table decline (cm/min) | $5.6 \times 10^{-2}$ | $6.2 \times 10^{-2}$ | $1.1 \times 10^{-1}$ | $5.2 \times 10^{-2}$ | $6.9 \times 10^{-2}$ | $8.9 \times 10^{-2}$ |
| | Time of reduction of water table (h, min, s) | 1 min 29 s | 2 min 9 s | 2 min 31 s | 1 min 35 s | 2 min 11 s | 2 min 39 s |
| | Quantity of deposited material (mg/cm$^2$) | None | None | None | 6.4 | 2.4 | 8.3 |

**Table 4**
Sedimentation from samples A$_1$ and A$_2$ in different depths at a low velocity of water table decline.

| Sample | | Sample A$_1$ | | | Sample A$_2$ | | |
|---|---|---|---|---|---|---|---|
| Composition of the suspension | | 1 dm$^3$ + clay ≈ 0.2 m/m % | | | 1 dm$^3$ + clay ≈ 0.2 m/m % + veg.waste ≈ 0.05 m/m % | | |
| Depth (cm) | | 5.0 | 7.5 | 10.0 | 5.0 | 7.5 | 10.0 |
| Half-life time of the sedimentation (min) | | 23.9 | 39.9 | 42.9 | 15.7 | 21.1 | 27.6 |
| Sedimentation rate (cm/min) | | 0.209 | 0.187 | 0.233 | 0.318 | 0.355 | 0.362 |
| The velocity of water table decline is small | Velocity of water table decline (cm/min) | $1.4 \times 10^{-5}$ | $2.4 \times 10^{-4}$ | $2.8 \times 10^{-4}$ | $2.0 \times 10^{-4}$ | $3.6 \times 10^{-4}$ | $3.9 \times 10^{-4}$ |
| | Time of reduction of water table (h, min, s) | 9 h 40 min | 12 h 25 min | 14 h 54 min | 6 h 54 min | 8 h 53 min | 10 h 38 min |
| | Quantity of deposited material (mg/cm$^2$) | 3.1 | 7.5 | 12.8 | 10.0 | 13.0 | 51.2 |

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In contrast, sedimentation was identified from the suspension marked $A_2$, containing also vegetable residue at nearly similar water table decline (from $5.2 \times 10^{-2}$ cm/min to $8.9 \times 10^{-2}$ cm/min). This can be attributed to the increasing sedimentation speed caused by the vegetable residue (from $0.318 \times 10^{-1}$ cm/min to $0.355 \times 10^{-1}$ cm/min). The quantity of sediment calculated on 1 $cm^2$ changed between 2.4 and 8.3 mg (Table 3).

If we decreased considerably the speed of the water level sinking ($2 \times 10^{-4}$–$3.9 \times 10^{-4}$ cm/min), and so we increased the time of sinking (between 6 h 54 min and 14 h 54 min), sediments were deposited in every sampling, moreover from the suspension which does not contain vegetable residue, too.

So, when the sedimentation speed exceeded the water level sinking speed sedimentation occurred. This has happened because the sedimentation rate increased because of vegetable residue or because the velocity of water table decline decreased. The deposited material quantity on 1 $cm^2$ in both suspensions increased with the increasing of the depth and sinking time (Table 4). While, in case of suspension $A_2$, the quantity of deposited material increased directly with the increase of depth, in case of suspension $A_1$ it did not happen. The deposited material quantity was the greatest at 7.5 cm. However, the quantity of the deposited material calculated on 1 $cm^2$ in the suspension containing also vegetable residue exceeded the measured values of the suspension containing sediment only on each sampling places at same depth of sampling.

## 5. Discussion

Our experiments contain results concerning sedimentation speed, and relation between sedimentation rate and the velocity of water table sinking. On the basis of sedimentation speed measurements it can be stated that the suspension, the components and concentration of which are known, the half-life of the concentration is determined at a given water depth and this is typical of the given suspension. The measurement can be repeated with the same result. The sedimentation speed at a given point (cm/min or cm/s) is expressed by the quotient of the examined water depth and the half-life of concentration. The sedimentation speed is greater in the suspension containing vegetable residue than the only sedimentation containing suspension at same water depth because the colloidal sized sediments are adsorbed on threadlike surface. The adsorbed material and the vegetable residue deposit together to the sediment.

According to the measurements made in the settling pool, if the sedimentation speed is smaller than the velocity of water table sinking, there is not any sedimentation formed at the bottom of the pool. In case of suspension with vegetable residue, if the sedimentation speed and the velocity of water table sinking are almost the same, then the sedimentation speed increases because of adsorption between vegetable residue and sediments, for this reason sedimentation can form in the pool. If the velocity of water table sinking is smaller than the sedimentation rate of the grains, the sedimentation happens in every sampling place of the pool. The quantity (mg) of the deposited material calculated on 1 $cm^2$ grows in proportion to the water column. The existence of vegetable waste takes large amount of material away from the liquid stage by adsorption, and it grows the quantity of deposited material.

The reason for the formation of the intermittent lakes of subsidence dolines can be both the reduced water conducting capacity (sediment is accumulated in the passages) and the intensive recharge process (intensive rainfall and/or snow melt) or the rise of karst water level too (Sweeting, 1973; Zhang, 1980). According to Veress (Veress, 1987a, 2000), the flood lakes of subsidence dolines can be grouped by their period of existence, as: ephemeral, moderate-duration and enduring lakes. The ephemeral lakes only exist during a single active period (active period is when the dolines get water from their environment). The moderate-duration lakes remain after an active period, as they collect more water again before draining as a consequence of repeated recharge. Because of the repeated inflow of water, the water level of such lakes can fluctuate or be interrupted with rest water levels. Moderate-duration lakes are presented in Figs. 6 and 7. The enduring lakes remain for more days or weeks after the end of a meteorological event (weather front). The ephemeral and the moderate-duration lakes lose their water because the water drains to the karst through the passages. In contrast, the water of enduring lakes is lowered by evaporation.

Dissolved and suspended materials are carried in different grain sizes to the lake via overland flow or via the superficial deposits and bedrock. Surface water delivers organic matter, which originates from the flora of the environment, to the lake. The solid state dispersed material and the liquid state together form suspension. The volume of the developing suspension depends on:

- the size of the catchment area,
- the intensity of recharge,
- duration of recharge

The character of the suspension (concentration, grain size of the suspended material) is affected by the quality, state of weathering of the superficial deposits and the bedrock. The density of vegetation in the catchment areas also affects the quality. The transported material can be suspended in the water as grains or colloids and organic matter. The suspended grains deposit, while the colloid and vegetable waste adhere to the bottom of the depression (Figs. 6 and 8) and to the objects in the depression. The colloids can also adhere to the grains and to the vegetable waste and with it they increase the velocity of settlement. Sediments, which were formed from the ephemeral lake of the subsidence doline, are shown in Figs. 6 and 9.

The naturally originated suspension contains quickly, slowly, very slowly and not settling material. The sediment with a large grain size (125–250 μm) settles quickly or very quickly. Because of quick settling, the time of deposition is hardly measurable or is not measurable at all. The settling rate of the grains of 63–125 μm is slower because of smaller diameter and thus it is well-measurable. The settling rate of grains smaller than 3.9–63 μm is slower because their diameter is even smaller. Grains smaller than 1 μm and also grains of 1–3.9 μm do not settle since they have charge (Pais, 1981; Rohrsetzer, 1991) provided that they do not coagulate, but they adhere to the different surfaces.

The intermittent lakes of subsidence dolines and the sediments of dolines were investigated in the Bakony Mountains (Transdanubian Middle Mts, Hungary). The studies were carried out with the help of exploration pits (Veress, 1986, 1987b, 1995) and with VES measurements (Veress, 2009). The sedimentation of flood lakes of several subsidence dolines was also observed (Veress, 1987a).

The covered karsts of the mountains developed in various patches (Veress, 2000). The superficial deposit of the karst is mainly loess and its clayey, sandy varieties and varieties with limestone debris and the redeposited materials of the Csatka Gravel Formation which is clay and gravel (Veress, 2005, 2006, 2009). Silt, plant waste and laminite series (laminae of colloid and silt matter alternate) were demonstrated in the sediment fill of several dolines (Veress and Futó, 1990). The above-mentioned sediment types developing following the emptying of intermittent lakes could be identified on the floor of depressions.

The surface of the catchment area of the studied dolines has a small dipping mainly. Therefore no rain furrows, gullies and creeks developed or only very rarely. Thus, there were no features like this

**Fig. 6.** Occurrence of the intermittent lakes and dolines presented in the figures. (1) Intermittent lake in the ponor of Zsófia plain, (2) intermittent lake of the Cerknisko polje, (3) dropout doline marked Gy-12.

**Fig. 7.** Intermittent lake in the ponor of Zsófia plain (Mountain Kab, Hungary). (1) Cave entrance.

connecting to the dolines. However, a significant fill could be observed in these dolines. In some dolines, a sediment fill with a depth of some tens of centimetres or some metres developed within some decades (Veress, 1987b, 2000) which refers to intensive inward material transport and to an intensive denudation on the catchment area. Because of the lack of the above-mentioned linear erosional features, the intensive denudation did not happen by linear erosion but by sheet erosion, the efficiency of which was promoted by the fact that arable lands were created on the catchment area of the dolines.

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**Fig. 8.** Part of suspended vegetable residue zone (1) above the edge of the evolved lake (13 October 2013) of the katavothron of the Cerknisko polje (Slovenia) (the vegetable waste stuck to the bottom by adhesion).

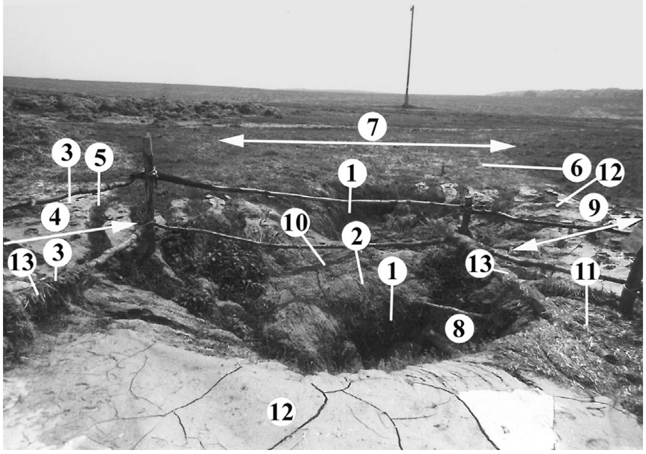

**Fig. 9.** Sediments of an ephemeral flood lake in dropout doline Gy-12 (following the activity of 9 May 1980) (Hárskút basin, Bakony Mts., Hungary). (1) Partial depressions, (2) sill, dividing wall, (3) coarser sediment or plant waste created by intensive water inflow, (4) zone of intensive surface water inflow, (5) rills created in sediment, (6) discolouring of colloidal origin on vegetation, attesting to slow surface water inflow, (7) zone of surface water inflow, (8) ephemeral section of the former lake (intensive water flow and conduction), (9) moderate-duration section of the former lake (limited water flow and conduction), (10) plant waste deposited on the sill because of shallow water depth, (11) plant waste accumulation attesting to overflow, (12) sediment created by overflow, (13) plant waste stuck on an object.

By sheet erosion mainly the soil denuded and also the loess where the soil had denuded earlier (possibly the redeposited material of the Csatka Gravel Formation). There was a possibility for the denudation of the cover under soil at such places only where the gullies cut through the soil. Therefore following the spread of the cultivation of arable lands, mainly soil and clay minerals of soil and residues of arable vegetation were transported into the dolines. Because of this, first of all, colloid (with a diameter smaller than 1 μm) and material of colloidal nature (with a diameter of 1–3.9 μm) were transported into the flood lakes. However, silt (with a diameter of 3.9–63 μm) and fine sand (with a diameter of 63–125 μm) could also get into the lakes from the soil as well as from the superficial deposit under soil. These materials were transported either into the karst through the passages of the depressions (if the rate of their sedimentation was lower than the rate of water level sinking of the lake) or they settled (if their sedimentation rate was larger). The grain size of the deposited sediment could be various since the grain size of the inward transported material was different (depending on the denudation of the soil or superficial deposit or on the intensity of the wash) and because of the various rates of water level sinking of the lake.

The following cases of lacustrine sedimentation in depressions could occur based on our measurement results, according to which only that material is able to settle, the grains of which sink quicker than the water level. In case of a quick water level sinking (ephemeral lakes) only the fine sand with a grain size of 63–125 μm settles from the lakes, the sedimentation of which is very fast from lakes (not from flowing water) (1–2 s) both literary data (Pais, 1981; Hiemenz, 1986; Rohrsetzer, 1991) and our measurements, but because of its small grain size, the sheet water is able to transport this fine sand (Fig. 9). From lakes with slower water level sinking rate (moderate-duration lakes) even silt can settle. A colloidal coating (with a grain size smaller than 1 μm) develops on the trunk of the trees of depressions, on their leaves and on other objects (Fig. 9). The substance with a grain size of 1–3.9 μm can also form a coating, but following its coagulation it can also settle with the silt together. Since the plant waste increases the rate of sedimentation in depressions which get a lot of plant waste, in case of the same water level sinking, the material of finer grain size can also settle which results in the increase of the amount of the settled matter and thus the greater fill of the depression. A chance for this is great mainly in case of depressions with arable land catchment area. In case of stagnant water levels or if the water level sinking is slower than the above mentioned, the plant waste is able to settle independently and separately (Fig. 8) or it sticks on the floor. In another cases, becoming loaded with the sediment of the lake, as it has been presented in our laboratory experiments, it settles on the floor. Plant waste accumulated on the floors could be observed in many depressions (Veress, 1987a, 2000). Finally, lakes with non-decreasing water level (enduring lakes) lose their water by evaporation and from such lakes all inward transported sediment

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settles. If there is silt in the transported sediment, laminite will develop. First the silt settles (this constitutes the lower plate of the laminite), then colloid remains from the lake water that loses its water by evaporation (this constitutes the upper plate of the laminite). Laminites show a significant similarity with the evolution and development) of varves (Zolitschka, 2007). However, the development environment of the seven sediment types is completely different.

The sediment fills of the lakes of the studied subsidence dolines can alternate with sediments of other origin (aeolian and fluvial) or sedimentation can even cease. The lacustrine sediment formation is replaced by fluvial sedimentation if a passage develops in the doline and a water course develops on the catchment area. An aeolian sedimentation occurs if there is no significant precipitation inflow from the catchment area. It may occur if the doline gets into an elevated position because of the denudation of its environs or its newer dolines develop in large numbers on the catchment area of the doline and by this the catchment area of the doline significantly decreases or ceases. A rapid evolution of subsidence dolines is a common phenomenon. An example for this is the valley of the Flint River, where 312 dolines developed within 48 h in 1994 (Hyatt and Jacobs, 1996). In the Minnesota covered karst 48 newer dolines developed within 10 years (Kemmerly and Towe, 1978). In Florida a newer doline develops each week (Beck and Sinclair, 1986).

## 6. Conclusions

Our laboratory experiments refer to the fact that the velocity of water table sinking of the lakes of the subsidence dolines determines what grain size the sediment has which deposits from their water. A slower velocity of water table sinking can generate a fine grained sediment deposition. This phenomenon is fortified by the vegetable residue which gets to the lake. For this reason the clogging of the dolines is a self-generating process. The subtler sediment (and vegetable residue) increases the possibility for the clogging of the doline. Therefore the velocity of water table sinking of the lakes formed in dolines decreases and thus their lifetime grows. However, this causes the deposition of subtler (and therefore more) sediments which causes the forming of lakes with even longer lifetime. The result of the two processes (sedimentation speed and velocity of water table sinking) is the complete clogging of the doline, then filling and destruction. According to our field observations, the chance for the filling of subsidence dolines is increased by the small dip angle of the catchment area, the lack of vegetation and the presence of plant waste.

Further investigations to be carried out would be useful in two directions. On the one hand, sedimentation in case of water level sinking should be modelled under laboratory circumstances, on the other hand, a study for the distribution of grain size of the sediment fill of depressions is necessary to study. A conclusion to the grain size of sediment source or the water level sinking of lakes of depressions can be drawn from the distribution of grain size.

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