# Quantitative drip water measurements in the Buda Castle Cave with classical and modern measurement methods

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**Abstract**
The study of cave waters is important for the preservation of the Castle Cave, which lies underneath the Buda Castle Hill. The objectives of this research were to carry out quantitative measurements of drip water and to identify the changes from previous observations. This study also aimed to investigate the relationship between drip water locations and drip water and precipitation data. The present study employed self-made tipping bucket gauges and ad hoc drip water measurements. Correlation analysis was carried out on the values measured at the two drip locations and on the drip water and precipitation time series. Annual drip water volumes were calculated, and the results were compared with past measurements. The results indicate that there is a strong correlation between the two drip locations, and both have a weak connection to precipitation. The annual drip water volume has possibly increased compared with past data, based on the study period. Further research with longer measured data and water chemistry tests is needed to determine the origin of the cave waters.

**Keywords**
Buda Castle Cave, drip water, monitoring, precipitation, correlation analyses.

# A budai Várbarlang csepegővizeinek mennyiségi mérése klasszikus és modern mérési módszerekkel

**Kivonat**
A budai Várhegy alatt húzódó Várbarlang állagmegőrzése szempontjából fontos a barlangi vizek vizsgálata. A kutatás fő céljai a csepegővíz mennyiségi mérése és a korábbi megfigyelésekhez képest bekövetkezett változások feltárása voltak. A célok közé tartozott továbbá a csepegővíz mérési helyek, valamint a csepegővíz- és csapadékadatok közötti kapcsolat vizsgálata. A méréseket saját készítésű billenőedényes mérőműszerekkel és ad hoc helyszíni mérésekkel végeztük. Korrelációvizsgálatot hajtottunk végre a két helyszínen mért csepegővíz értékeken és a csepegővíz és csapadék idősorokon. Az éves csepegővízmennyiségeket kiszámítottuk, és az eredményeket összehasonlítottuk a korábbi mérésekkel. Az eredmények azt mutatták, hogy a két csepegőhely közt erős, azonban a csapadékkal csak gyenge lineáris kapcsolat van. Az éves csepegővízmennyiség a korábbi adatokhoz képest a vizsgált időszak alapján valószínűleg nőtt. A barlangi vizek eredetének megállapításához további kutatások szükségesek hosszabb mérési adatokkal és vízkémiai vizsgálatokkal.

**Kulcsszavak**
Budai Várbarlang, csepegővíz, monitoring, csapadék, korrelációvizsgálat.

## INTRODUCTION

The problems of stability and wetness in the Buda Castle Cave have been mentioned in a wide range of literature (*Szontagh 1908, Horusitzky 1937, Scheuer 1986, Hajnal 2003, Hajnal and Farkas 2011*) over the last century, and scholars at the Budapest University of Technology and Economics have been actively researching the Castle Cave for the past 40 years. Consisting of natural limestone formations and artificial corridor systems, the cave system is located underneath the Buda Castle Hill in Budapest, Hungary (*Figure 1*). The area above the Castle Cave is an area of great administrative, economic, cultural and touristic importance, furthermore this landscape is part of the UNESCO World Heritage Sites. In recent years, there have been several projects in the area – such as the development of the government quarter – making it even more important to study and monitor the underground areas, which are particularly important for the preservation of the surface. Despite this, there were very few measurements available until recently.

The hydrology of the Castle Cave was first researched in the 1970s by *Kessler (1971)*. The investigations continued in the 1990s, and a comprehensive study of the hydrogeology of the Castle Hill was accomplished by *Hajnal (2003)*. The latest measurements were carried out between 2008 and 2010 when water levels in the wells were investigated, pumping tests were performed, and water quality parameters were studied (*Hajnal and Farkas 2011*). Since then, the measurements have been suspended. However, recently, in the area of the Great Labyrinth (in Hungarian: "Nagy Labirintus"), the amount of water seeping into the cave appears to have reached an unprecedented level during the studied period. The infiltrating water caused some weathering and rock fall – mostly at the roof of the cave – that has recently become more common. It can be concluded that a detailed investigation of the water conditions in the cave is necessary for the preservation of the Castle Cave. To achieve this goal, cave waters, including drip waters need to be measured to determine if they are increasing and to discover the reasons for these changes. Accordingly, the study introduced in this paper had three primary aims: (1) to install and operate instruments suitable for cave conditions, that measure drip water at several locations with high temporal resolution, (2) to compare the drip water intensity time series at two locations, (3) to correlate precipitation time series and drip water intensities, and (4) to investigate the changes since the previous measurements.

## STUDY AREA

The plateau of the Castle Hill is estimated to be about 405 000 m$^2$. The total area of its sides and slopes is approximately 750 000 m$^2$. The longitudinal axis of the plateau is 1 500 m, the total length of the hill is 2 000 m. The width of the plateau varies between 450 m and 120 m. The eastern and south-eastern parts of it are bordered by the steep valley side of the Danube, while the western, south-western and southern sides are bordered by the Ördögárok (*Krolopp et al. 1976, Scheuer 1986*). The average height of this erosion terrace-island, which has been transformed by sliding and degradation, is 154-159 m, with a maximum height of 169 m a. s. l. The plateau gradually decreases towards the south with levels of 149, 144-134, 119-114 m a. s. l. (*Scheuer 1986*). (All of the altitude units are in meters above the Baltic Sea level.)


*Figure 1. The location of the Buda Castle Cave in Budapest, Hungary (Map data: Open Street Map, Google Satellite)*
*1. ábra. A budai Várhegy elhelyezkedése Budapesten, Magyarországon (Térképadatok: Open Street Map, Google Satellite)*

### Stratigraphy, tectonics, cave formation

To this day, the Várkert thermal, installed in 1938 at the south-east end of the hill, provides the most information about the stratigraphy and geology of the mountain (*Figure 2)* (*Horusitzky 1938*). On Castle Hill, the Triassic dolomite bedrock is covered by Upper Eocene–Lower Oligocene Buda marl (*Horusitzky 1938*). The next geological unit is the Oligocene Tardi Clay Formation, which is followed in the stratigraphic sequence by the Oligocene Kiscelli Clay Formation (*Scheuer 1986*). There are no traces of young rocks from the Tertiary period in the area, probably due to the erosion of the Miocene and Pannonian layers (Scheuer 1986). In the Polgárváros area, the next layer is an approximately 0.5-1.5 m thick fluvial alluvium, consisting of cobble gravel, sandy gravel, and clayey gravel, deposited by the Ördögárok stream (*Krolopp et al. 1976, Scheuer 1986*). Above the sediment layer, or where it is absent, there is a valley bottom layer, typically consisting of silt and clay. Hot springs, which had a significant lime ($CaCO_3$) content, emerged in the Buda Hills in the Upper Pliocene, forming freshwater limestone deposits at the site of the Castle Hill. In some places, loess settled on the limestone, but most commonly, the limestone is covered by anthropogenic fill (*Hajnal 2003*).

Until the Pleistocene, the area of Castle Hill was similar to its surroundings: the Triassic carbonates were covered by young Tertiary sediments. The present form of the Castle Hill was formed thanks to the freshwater limestone deposits and the incision of the Danube and the Ördögárok. Although the Ördögárok valley is of tectonic origin, there is no evidence of a fault on the other (eastern) side (nor has there been any vertical movement along the fault in the Ördögárok valley), so the Castle Hill cannot be considered a faulted mountain. The surface formation was primarily influenced by the limestone cover, which is significantly harder than the Buda marl. The limestone withstood erosion and denudation, protecting the layers below it, and thus the Castle Hill gradually rised above its surroundings (*Leél-Őssy et al. 2011*).

There are several theories about how the caves in Castle Hill formed. According to *Cholnoky (1936)*, the Castle Hill was directly connected to the Szabadság Hill during the Oligocene epoch and the streams rushing down from there carved out the cavities under the freshwater limestone. Others believed that the warm spring water could no longer rise through its own sediment – freshwater limestone – so it sought a path at the surface of the Buda marl, where it abraded the lower layers of limestone and the looser layers beneath the limestone (*Horusitzky 1938, Kerekes 1940*). The presence of corrosion marks on the walls of the caves also supports this theory. Another theory (*Kadič 1942*) suggests that surface water from precipitation dissolved the cavities through cracks and gaps in the limestone.

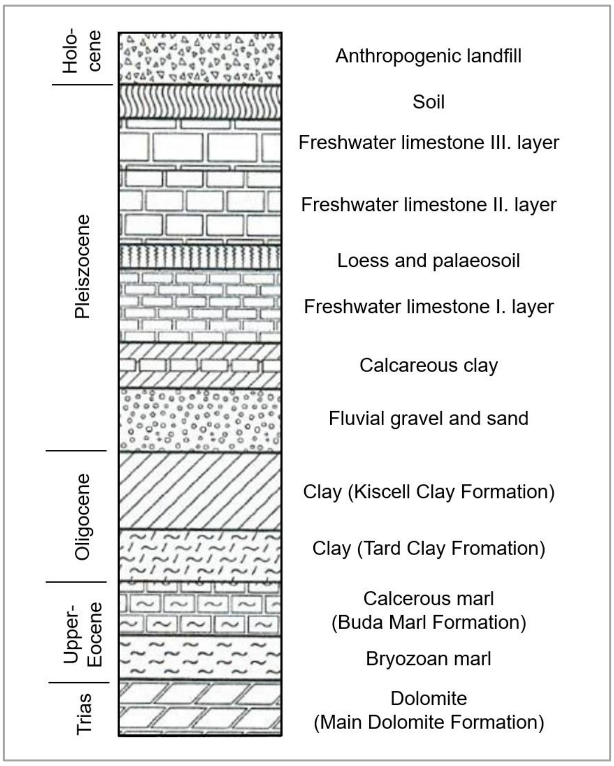


*Figure 2. The stratigraphy of the Buda Castle Hill (Hajnal 2003, after Horusitzky 1938)*
*2. ábra. A budai Várhegy rétegsora (Hajnal 2003, Horusitzky 1938 alapján)*

The calcareous tuff caverns of the Castle Cave were originally irregular, low-lying formations, which people have historically sought to shape for their own benefit. If the limestone was hard, it was hollowed out at the bottom. If it could be carved, they were extended towards the roof and the sides. The latter were often walled up and the roof was supported by pillars (*Kadič 1942*). Wells were dug to collect water that seeped into the cavities, often with air shafts from the roof to the surface. To the best of our present knowledge, caves of natural origin are found only under the Polgárváros. The total floor area of the connected cave cellars is about 18 000 m$^2$, and the total area of the individual caves is about 4 000 m$^2$ (*Hajnal 2005*). Part of the connected cellar system is called the Great Labyrinth. At present, the Great Labyrinth can be divided into three parts based on the operator. The southern part is rented by an entrepreneur, the northern part is operated by the Danube-Ipoly National Park Directorate (DINPI) and the third part consists of the Hospital in the Rock. This study was carried out in collaboration with the Duna-Ipoly National Park Directorate on the northern area of the Great Labyrinth (see the study area on *Figure 3*).

**Hydrogeology**

According to the classical hydrogeological classification, there is no contiguous body of groundwater on the plateau of the Castle Hill. In the travertine beneath the anthropogenic fill, karst water flows through fractures. Since this layer is on average 5-8 m thick, it is not karst water in the classical sense. Because of the variability of the limestone and its various structural appearance, it can also be present in varying quantities, for example, in capillary networks but also in cavities of a few cubic metres. The water that runs down into the one- to two-metre-thick fluvial alluvium beds beneath the limestone also does not form a contiguous water body. The wells in the labyrinth are fed by water collected in separate, small sumps (*Hajnal 2003*). These are recharged by rainfall and by the losses from utilities. This could be proven by stable isotope measurements (*Czuppon et al. 2022*) but so far this was proven with other methods. The calculations of *Hajnal (2003)* revealed that water from utility losses plays a dominant role compared to precipitation in terms of the amount of water that seeps in.

**Previous measurements**

Historical data on drip waters is highly scattered in time and space, so few conclusions can be drawn from them, as indicated by *Hajnal (2003)*. At the time of the 1 885 surveys, only the drip sites were determined, no other measurements were made (*Rétiné 1994*). The identification of drip sites was a very difficult task based on the past descriptions, as street names and house numbering changed several times over the span of more than 100 years, and several inaccuracies were noted in the texts (*Hajnal 2003*). The study performed for the Tunnel drainage also identified several drip sites (*Szontagh 1908*). A thorough, more detailed study was only carried out in the 1970s (*Kessler 1971*). At that time, six measurement points were recorded, but today it is only possible to clearly identify five of them (*Hajnal 2003*). The method of these measurements was the following: one m$^2$ plastic sheet was placed under the drip points and the drip rate was measured through an opening in the middle of the sheet once a week from February to May 1971. By analysing the measured values, it was found that the individual measuring points responded differently to precipitation (*Kessler 1971*).

## METHODS

In this study, the drip water in the Castle Cave was measured continuously using tipping bucket gauges at two locations, but additional ad hoc measurements were also carried out. The measurement locations are indicated on the map in *Figure 3*. This map was based on the laser scanning survey by the BURKEN Ltd. The methodology of these measurements is described in the following chapters.

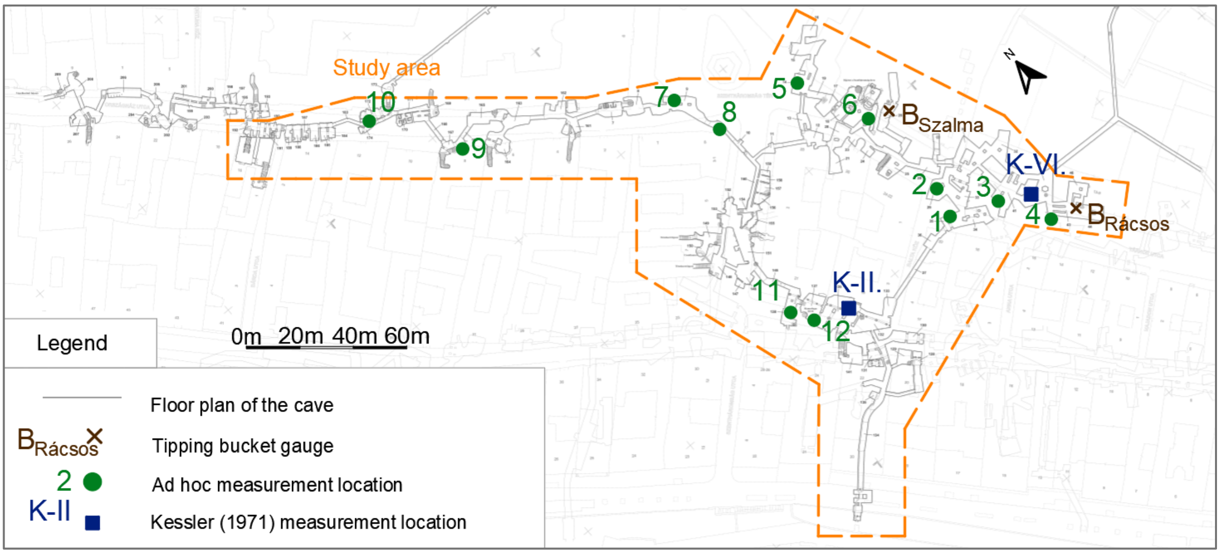


*Figure 3. Measurement locations in the Great Labyrinth (base map by Havasi (2011) based on Burken Ltd. survey (2010); measurement points added by the author)*

*3. ábra Mérési helyszínek a Nagy Labirintusban (Havasi (2011) által készített áttekintő térkép a Burken Kft. (2010) felmérése alapján, saját mérési pontokkal kiegészítve)*

### Tipping bucket gauge measurements

The drip water measurements required an instrument that was low power, as access to the cave required prior arrangement and it was only possible on a monthly basis and the devices were left unattended for the time interval between the readings. In addition, it was necessary to obtain high resolution data. Therefore, a version of the drip water measuring instrument, which is currently under development, was built and adapted to the conditions of the cave. The device is based on the designs of *Tóth (2016)* and *Nagy (2021)* in their diploma theses, but it has been modified to enable self-powered operation. The assembled measurement device is based on a tipping bucket rain gauge, consisting of a funnel, a two-armed tipping bucket and a Reed-relay. The funnel directs the precipitation into one half of the tipping bucket, and when the tipping bucket is filled up, the device tilts over, closing the circuit momentarily. The hardware consists of an Arduino Pro Mini microcontroller, a DS3232 clock and an SD card reader module located on the motherboard. The power supply is secured by an 18650 1600 mAh lithium iron phosphate battery. As for the operation principle, the instrument is asleep by default. When the circuit is closed (tipping occurs), the Arduino microcontroller detects an interrupt on one leg, wakes up and increases the tipping count. If more than 10 minutes have elapsed since the previous recording, it writes the number to the SD card, then resets the count to zero and returns to sleep. The instrument was calibrated, using a burette. Based on the calibration measurements of the tipping bucket gauge, the average volume of the tipping bucket was found to be 4.6 $cm^3$, but the range of the measurements was relatively large, from 4.3 to 4.9 $cm^3$. Considering the observations of *Nagy (2021)*, this was probably owing to some waterdrops remaining in the buckets after the last tipping. Based on this assumption, the calibrated value was accepted, as this could also happen to the device after installation.

The instruments were installed in the Castle Cave after a visual inspection of the cave and an assessment of the drip water intensities. When considering the placements, the previous measurement locations and the securement of uninterrupted operation were also taken into account. After selecting the locations, a tarpaulin was placed over the funnel of the tipping bucket gauges, which collected water from a larger area into the instruments. Two measurement devices were placed in the Buda Castle Cave on the 8$^{th}$ of January 2024 on the “Szalmacseppköves” and “Rácsos kút” drip locations (*Figure 4*).

*Figure 4. "Szalmacseppköves" and "Rácsos kút" drip water measurement location in the Buda Castle Cave*
*4. ábra. "Szalmacseppköves" és "Rácsos kút" csepegővíz mérési helyek a budai Várbarlangban*

As the data was processed, the measurement times were rounded to the nearest minute and the tipping count was converted to water volume by multiplying it by the calibrated volume and dividing it by the area of the tarpaulin. The time passed from the (n-1)th to the nth measurement was calculated and the volume was divided by the elapsed time (in minutes). The resulting value was assigned for each minute between the (n-1)th and nth measurement according to *Eq. 1*.

$$i_{t_{n-1}+1} = i_{t_{n-1}+2} = \cdots = i_{t_n} = \frac{V_{t_n}}{(t_n - t_{n-1}) \cdot A} \tag{1}$$

Where:

- $i_{t_{n-1}+1} \left[\frac{ml}{s \cdot m^2}\right]$ – is the intensity value (or specific drip yield) one minute after the time of the (n-1)th measurement,
- $V_{t_n}[cm^3]$ – is the water volume calculated as $V_{t_n} = c_{t_n} \cdot V_{cal}$, where $c_{t_n}$ $[-]$ is the tipping value at the nth measurement and $V_{cal}$ $[cm^3]$ is the calibrated volume of the tipping bucket,
- $t_n$ $[s]$ – time at the nth measurement,
- $A$ $[cm^2]$ – is the area of the tarpaulin.

After the intensities were calculated in such way for each minute, the hourly values were also calculated from them.

This measurement provided data with high temporal resolution. However, as groups of tourists regularly visit the Castle Cave, it was not possible to establish an extensive, continuously operating drip water monitoring network. Therefore, ad hoc measurements were essential to obtain information on drip water intensity over a larger cave area and determine the amount of drip water over the whole study area.

**Ad hoc field measurements**

The ad hoc field measurements were carried out in September 2024. On the first occasion, on 18 September, the dripping from the roof of the cave was observed and measuring buckets were placed at high-intensity points. The measurement locations were marked in *Figure 3* and numbered 1-12. The classical, most simple measurement method was used, where the drip water was collected in a bucket for a set time. During the field measurements, the time was recorded after placing the measuring buckets. At the next site visit, the volume of water collected in the measuring buckets was measured and the elapsed time was recorded. The drip water yield was calculated as the water volume divided by the elapsed time. At first, the measurements were carried out for one and a half to two hours, then the subsequent three measurement lasted for one week. The reason behind this is that it was not easy to schedule and perform the measurements at once, as it required more time (two hours), and the weekly measurements allowed for the measurement of the mean value over time. Due to the measuring containers overflowing in many places in a week, another short measurement of approximately one hour was conducted on the 8th of October. Overall, this resulted in a total of five drip water yield values per measurement location.

During the measurement process, the wet or dripping areas were identified on the roof of the cave and similar areas (based on dripping intensity) were delineated around each measurement location. These areas were later used for the annual drip volume estimation (*Table 2.*).

**Correlation analysis**

A simple correlation analysis was performed on the hourly data from the two drip locations using linear regression, to examine the similarities in drip water behaviour across the cave. Another one of the study's objectives was to investigate the origin of drip water by comparing it with precipitation data and searching for connections between them. The ten-minute automated weather station data from the Meteorological Data Repository of *HungaroMet Nonprofit Zrt. (2024)* was used. The Station Number 44121, in District II in Budapest, lies the closest to the Castle Cave, and according to *Hajnal (2003)*, the precipitation on the Castle Hill correlates well with the measurements of this station. The connection between the precipitation and drip water intensities was studied using linear correlation. The temporal resolution was decreased as it can be more difficult to explore the relation between time series with high temporal resolution and they also may be subject to larger bias and errors. Therefore, the analysis was executed on the daily precipitation sums and the daily average drip water intensities. The precipitation data was shifted by 1,2, … n days (maximum of five months), and the correlation coefficients were determined for each data pair using linear regression. The highest correlation coefficients and the shifted day value belonging to them were determined.

## RESULTS

The tipping bucket gauge measurements resulted in a 10-minute temporal resolution drip water intensity data. The two time series were correlated to each other and also with precipitation. The ad hoc measurements were used to calculate an estimate of annual drip water volume. These are introduced in the following sub-chapters.

### Measured drip waters

The result of the tipping bucket gauge measurements can be seen in *Figure 5.* The dotted line indicates that there was a gap in the measurements. From April to August, the devices needed to be repaired. At the "Rácsos kút" drip location, the specific drip water yield was around 140 ml/h $m^2$ at the beginning of the measurements in January 2024, but it has decreased to 50 ml/h $m^2$ by the end of March. In the middle of August, it was approximately 70 ml/h $m^2$ and it has been decreasing since, although it has less steepness than that of the time series at the beginning of the year. At the last reading, it was around 40 ml/h $m^2$. The „Szalmacseppköves" measurement location had a much lower drip water intensity of about 18 ml/h $m^2$ in January and 4.7 ml/h $m^2$ in October, about 1/8 of those at the „Rácsos kút".

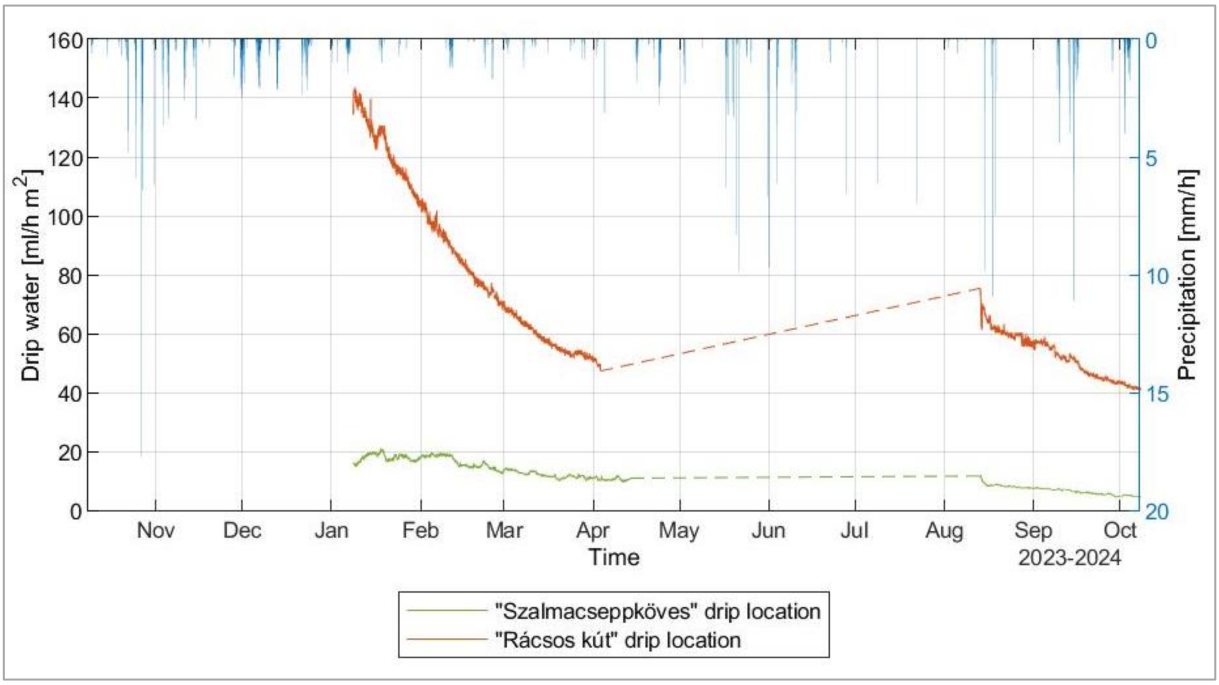


*Figure 5. The drip water measurement data from the two tipping bucket gauges in the Castle Cave*
*5. ábra. A Várbarlangban lévő két billenőedényes mérőműszerrel mért csepegővíz intenzitás adatok*

The calculated drip water yield for each ad hoc measurement point is shown in *Figure 6*, where the change in values over time can also be observed in the consecutive columns for each location. The measurements, when the measuring bucket overflowed, are marked with "+" in the figure. This means that there was a higher drip water yield than these values during the measurement interval, but there is no information on how high it was. In some cases, the measuring bucket may have been moved at some point during the measurement interval, as it was not in its original location at the time of measurement. These were not included in *Figure 6* and these 'displaced' values also with the 'overflowed' ones, were not considered in the following calculations introduced in the next chapter.

### Correlation analyses on drip water intensities and precipitation

The correlation analysis was conducted on the time series data of drip water intensities and precipitation presented in *Figure 5.* The data from the two drip water locations correlates well, with a correlation coefficient of 0.87 (*Figure 7*).

The resulting maximal correlation coefficients and the shifted day (lag) values belonging to them are shown in *Table 1.*

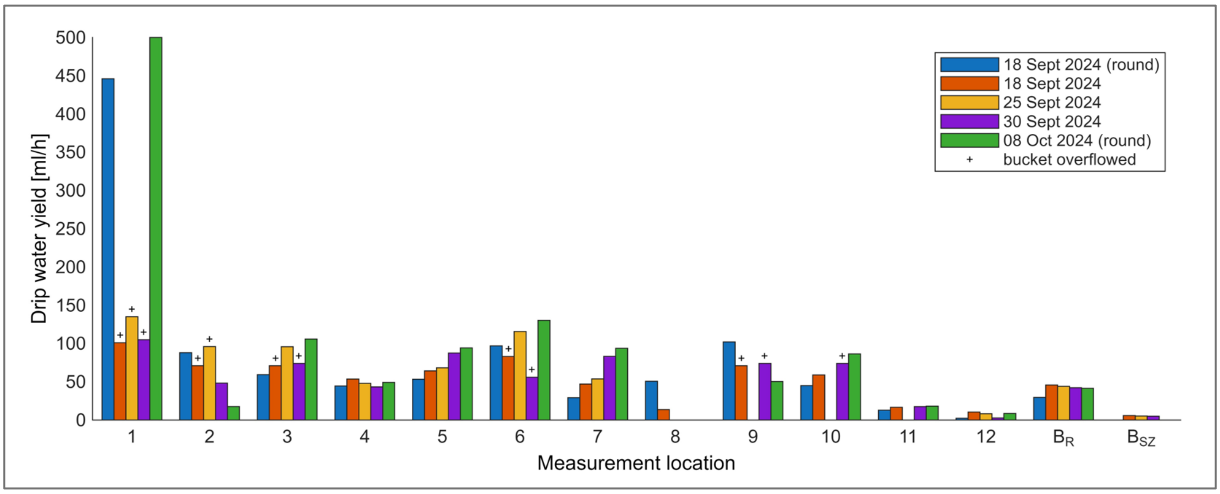


*Figure 6. Drip water yields from the ad hoc (Nr. 1-12) and tipping bucket gauge ($B_R$ and $B_{SZ}$) measurement locations*
*6. ábra. Az ad hoc és a billenőedényes mérésekből származó csepegéshozamok az egyes mérési helyeken*

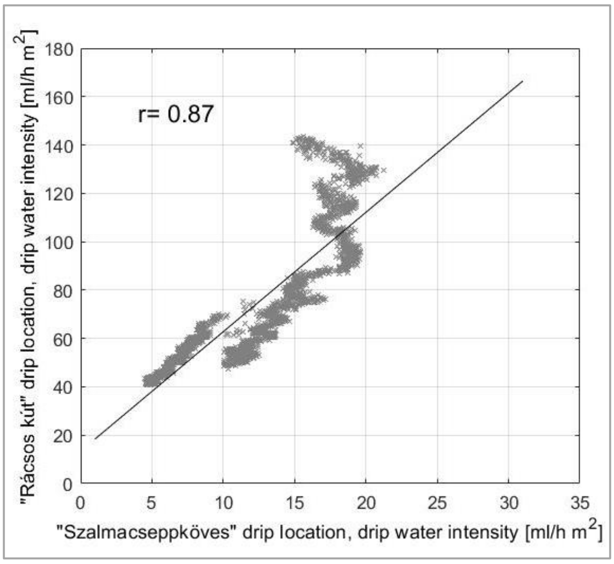


*Figure 7. Correlation between the drip water intensities at the two tipping bucket gauge measurement locations*
*7. ábra A két billenőedényes mérési hely csepegés intenzitás adatsorai közti korreláció*

*Table 1. Correlation coefficients between the drip water intensities and precipitation*
*1. táblázat. A csepegővíz intenzitások és a csapadék közötti korrelációs együtthatók értékei*

| Drip location | Szalmacseppköves Jan 2024 - Apr 2024 | Szalmacseppköves Aug 2024 - Okt 2024 | Rácsos kút Jan 2024 - Apr 2024 | Rácsos kút Aug 2024 - Okt 2024 |
|---|---|---|---|---|
| R [-] | 0.34 | 0.35 | 0.40 | 0.36 |
| Lag [days] | 48 | 88 | 41 | 88 |

Due to the good correlation, the "Szalmacseppköves" and "Rácsos kút" drip locations in the Castle Cave have very similar correlation coefficient values to the same shifted precipitations for the interval since August, and they also have a lot of similarities before April.

The correlation analysis with precipitation revealed only weak connections. Since the correlation analysis could only be performed on data from two locations, these findings are less generalizable to the entire study area. While this study did not confirm the origin of cave waters, it partially contributed to our understanding of their relation to precipitation. It can be assumed, that there is no strong linear correlation between the drip waters and precipitation. In karstic areas this is to be expected, as there does not need to be a connection between daily precipitation and infiltration. After all, the relationship between precipitation and infiltration is not linear, it is much more complex, even in non-urbanised areas. Since the methods usually applied to karst areas are not relevant in the Castle Cave due to the urbanisation of the area, further studies could be conducted with other methods capable of exploring non-linear relationships.

**Estimation of annual drip water amount in the study area**

As the measured intensities ranged across several magnitudes and the spatial variety of the drip waters was considerable, a minimum and maximum estimate of the drip water for the whole study area (3 700 m$^2$) was calculated. First, the minimum value was estimated directly from the measured drip water yield ($Q_n$ [ml/h]). It was assumed that the measuring buckets collected most of the drip water in a one $m^2$ area. Thus, during the calculation of the lower estimate, the measured value was considered as a specific drip water yield defined for a unit area of one $m^2$. Next, the maximum estimate was also calculated using specific drip water yields, but these were acquired from the measured drip water yields using a different empirical ratio ($r_{emp}$ [-]) for each area. The ratios were determined based on the visual inspection of the wet areas and considering the spatial distribution of drip water around each measuring bucket. The area of a measuring bucket was 0.07 $m^2$, which is approximately 1/14 of the unit area, therefore these empirical ratios ranged between 1 and 14. The minimum and maximum specific drip water yields and the empirical ratios for each area can be found in *Table 2*. The minimum and maximum specific drip water yields were multiplied by the area assigned for each measurement location ($A_n$ [$m^2$]) and the annual drip water quantity (V [$m^3$/year]) was calculated. This evaluation method is summarized in *Eq. 2* and *Eq. 3*.

$$V_{min,annual} = \sum_{n=13}^{n=1} Q_n \cdot 10^{-6} \cdot 365 \cdot 24 \cdot A_n \qquad (2)$$

$$V_{max,annual} = \sum_{n=13}^{n=1} Q_n \cdot r_{emp} \cdot 10^{-6} \cdot 365 \cdot 24 \cdot A_n \qquad (3)$$

*Table 2. Calculation of annual drip water volume from ad hoc measurements*
*2. táblázat Az éves csepegővíz mennyiség kiszámítása az ad hoc mérésekből*

| Measurement location | $A$ | $q_{min}$ | $r_{emp}$ | $q_{max}$ | $V_{min,annual}$ | $V_{max,annual}$ |
|---|---|---|---|---|---|---|
| | $[m^2]$ | $[ml/h \cdot m^2]$ | $[-]$ | $[ml/h \cdot m^2]$ | $[m^3/year]$ | $[m^3/year]$ |
| 1 | 103 | 473 | 3 | 1 419 | 427 | 1 280 |
| 2 | 256 | 51 | 5 | 257 | 115 | 575 |
| 3 | 283 | 65 | 1 | 65 | 162 | 162 |
| 4 | 161 | 48 | 1 | 48 | 67 | 67 |
| 5 | 45 | 74 | 2 | 147 | 29 | 58 |
| 6 | 66 | 114 | 4 | 457 | 66 | 264 |
| 7 | 111 | 61 | 1 | 61 | 60 | 60 |
| 8 | 40 | 13 | 1 | 13 | 5 | 5 |
| 9 | 157 | 51 | 1 | 51 | 70 | 70 |
| 10 | 45 | 52 | 2 | 104 | 21 | 41 |
| 11 | 63 | 14 | 1 | 14 | 8 | 8 |
| 12 | 360 | 6 | 7 | 45 | 20 | 143 |
| 13. (entrance) | 31 | 6 | 1 | 6 | 2 | 2 |
| | | | | $\sum$ | **1 051** | **2 735** |

The calculation resulted in a total of 1051 $m^3$/year minimum and 2 735 $m^3$/year maximum drip water for the studied 3700 $m^2$ area of the Great Labyrinth. This can be compared to *Kessler's (1971)* and *Hajnal's (2003)* calculations, as they calculated the amount of water infiltrating to the Great Labyrinth (GL). *Kessler (1971)* calculated based on drip water measurements in 1971, *Hajnal (2003)* determined the infiltration based on water balance calculations, proportional to each area on the Castle Hill, for several intervals between 1971-2000 (although some years were missing). For the comparison, the average of his calculations was used. To be able to compare the exact values, the results of *Kessler (1971)* and *Hajnal (2003)* were divided proportional to the total area of the current measurements $V_{annual,GL\text{-}part}$. As they both examined all 18 000 $m^2$ of the Great Labyrinth, their calculated drip water volumes for a year were divided by 18 000/3 700=4.86, as the currently measured area is about 1/5 of their study area. Their results are compared with the current calculations in *Table 3*. The past calculations of *Kessler (1971)* and *Hajnal (2003)* are between the current minimum and maximum estimates, showing good agreement. As they are closer to the minimum estimate, the drip water volume per year has probably increased. It should be noted that a source of weakness in this study which could have affected the annual drip water volume estimates is that although the ad hoc measurements covered the study area, they were limited to a few occasions.

*Table 3. Comparing calculated annual drip water volumes to previous studies*
*3. táblázat. A korábbi tanulmányokban található éves csepegővíz mennyiség összehasonlítása a számított értékekkel*

| Study | Time interval | $A\ [m^2]$ | $V_{annual,total}$ $[m^3/year]$ | $V_{annual,GL-part}$ $[m^3/year]$ |
|---|---|---|---|---|
| *Kessler (1971)* | 1971 | 18 000 | 7 300 | **1 504** |
| *Hajnal (2003)* | 1971-2000 | 18 000 | 7 382 | **1 517** |
| Current Min. | 2024 | 3 700 | 1 051 | **1 051** |
| Current Max. | 2024 | 3 700 | 2 735 | **2 735** |

## SUMMARY

This study was carried out with the primary objective of the preservation of the priceless historical and cultural assets of the Buda Castle District, by assessing the water conditions in the underlying Castle Cave. Drip water measurements with tipping bucket gauges and ad hoc field tests were performed. Two self-made, low-cost and low-power tipping bucket gauges were placed in the Castle Cave. The measured drip water intensity ranged from 4.7 to 140 ml/h $m^2$. The drip water intensity at the two locations were analysed using linear regression and a strong connection (R=0.87) was found. Both drip locations have a weak connection to precipitation, so other impacts (such as losses from utilities) should also be examined. The ad hoc field measurements resulted in highly varying drip water intensities, and the spatial distribution was also variable. Thus, minimum and maximum estimates were calculated for the annual drip water volumes. According to the estimates, the drip water volume in the studied area is at least 1 051 $m^3$/year and it can be up to 2 735 $m^3$/year. The previous calculations of annual drip water volumes of *Hajnal (2003)* and *Kessler (1971)* were proportionally calculated for this part of the Great Labyrinth and those values also fall into this range, with 1 517 and 1 504 $m^3$/year. Consequently, it can be assumed that the drip water volumes during the study period have increased since the past measurements. In the future, longer measurement data would be helpful to analyse the factors affecting the drip waters so that more assured conclusions could be drawn about the changes since the past measurements. In addition, water chemistry tests would be essential to ascertain the origin of the cave waters.



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*Wet area from drip water near measurement location Nr. 12 (Photo by Fanni GAZDA)*
*Vizesedés a 12. mérési helyszín környezetében (Gazda Fanni fotója)*