HYDROGEOLOGICAL STUDY OF THE CAVE SYSTEM OF THE CASTLE HILL IN BUDAPEST

Géza Hajnal[1]

ABSTRACT:

The Castle Hill of Buda is a Word Heritage Site and is located in Budapest capital of Hungary. The hill is mainly composed of Eocene marls, Oligocene clays and covering fluvial sediments and travertine. In this area an extended three-level cellar system is found. The upper two cellar levels are artificial ones while the lowest one is an artificially extended dissolutional cave system. The natural caves were formed within the travertine or in the basal beds of travertine in the terrace gravels. The most extended cellar system is approx. 4.4 km long .

The available hydrological data sources are very limited. The most useful information on the hydrogeology is provided by the analyses of wells in the cellars.

The studies demonstrated that the water level of wells did not change in the last year despite of the extremely high precipitation rate. Some of the wells are polluted with sodium chloride.

The chemical analyses and water dyeing showed that there is no direct connection between the individual wells of the cave system although there are individual wells where a NW-SE flow was recorded. This water seepage can cause severe stability problems (retaining walls, house foundations, etc.).

RÉSUMÉ:

La colline du château de Buda fait partie du patrimoine mondial et se situe ŕ Budapest, la capitale de la Hongrie. La colline est consistée surtout aux marnes éoccčnes, aux argiles oligoccčnes et elle est couverte du sédiment fluvial et du travertin. Un réseau étendu ŕ trois niveaux de cavernes se trouve sur ce terrain. Les deux niveaux supérieurs de cavernes sont artificiels, tandis que celui ŕ l'inférieur est un réseau de grottes artificiellement étendu, en état menacé. Les cavernes naturelles se sont formées au sein du travertin ou dans la couche de base du travertin, sur la terrasse de gravier. Le réseau de grottes le plus étendu fait ŕ peu prčs 4.4 km de long.

Les sources de données hydrologiques disponibles sont trčs limitées. Ce sont les analyses des puits dans les caves, qui fournissent les renseignements les plus utiles pour l'hydrogéologie.

Les études ont démontré que le niveau d'eau des puits est en dépression. (2 m en moyenne). Quelques puits sont pollués du sodium et du chlorure.

Les analyses chimiques et la coloration d'eau ont démontré qu'il n'y a pas de communication directe entre les puits du réseau de caves, bien que pour certains puits un flux dirigé du nord vers le sud soit indiqué. Cette fuite d'eau peut causer de sérieux problčmes de stabilité (murs de soutčnement, fondations des maisons etc.).

INTRODUCTION

The Buda Castle Hill is located in Budapest, Hungary and is a very important sight of the Hungarian capital.

Water has had a double role in the formation of the Buda Castle Hill: on one hand, the water contributed to the formation of the Castle Hill itself, together with the travertine caves inside the hill; while it is also the basic reason for the engineering problems of the hill and the town, which is part of the World Heritage Site. This is also the reason for the importance of collecting and synthesizing all the information and data relating to the water, observed and recorded by representatives of overlapping sciences (mapping, geology,

---

[1] Géza Hajnal, Technical University of Budapest, Department of Construction Materials and Engineering Geology, H-1521. Budapest, , Hungary, phone: (36-1)-463-2079, fax: (36-1)-463-2017, E-mail: hajnalok@eik.bme.hu

hydrology, engineering, architecture, archaeology, mining, speleology). But this activity is also very important in order to provide future architects and investors of the cave system with the necessary information for a proper approach of this very complex technical problem.

Between 1993 and 2000 we have examined the following aspects of the wells, including the measurements of the water flow and water quality of the wells by carrying out field investigations and laboratory tests:

- water table
- discharge of wells
- temperature of the water
- water flow conditions
- chemical parameters of the water

GEOLOGICAL OVERVIEW

The majority of the Castle Hill is formed of Eocene Buda Marl which, from the point of view of our study, has two important characteristic features:
a., the compressive strength of the marl decreases to a significant extent with water saturation, to one-third/one-fourth
b., the marl beds mainly dip to the South and south-west, which plays a major role in the movement of subsurface waters
The marl is covered by Oligocene clay on which there is an alluvial sediment cover. The top of the hill is covered by fresh-water limestone with an average thickness of 8 m which was formed by hot springs. Within and at the bottom of this formation a unique travertine cave system had formed.

CAVES, SOLUTION CAVITIES, CELLARS

In their original evolution the travertine cavities in the Buda Castle Hill were random and low formations and people in the course of history have tried to adjust them for their own benefit and usage. If the limestone was too hard, they hollowed the bottom surface; if it was loose enough, they extended the caves in the direction of the roof and the side walls. The walls at many places were built up while the roof was supported with pillars (Kadič, 1942). Wells were dug to collect water flowing into the natural cavities and people often made air holes between the roof and the ground surface to provide easy access to these wells.

As a result of all these developments several expressions have become widely used by now regarding subsurface openings. We call them caves, cavities, cellars, deep cellars, cave cellars, Turkish cellars, rock cellars. To clarify these expressions it might be helpful to group the different types of cavities of the Castle Hill. The most common method of grouping is on the basis of vertical arrangements (Figure 1.).

1. On the top there are the cellars of buildings at a depth of 2 to 3 meters below the ground level. These cellars are all artificial.
2. The middle level of cellars is located at a depth of 3 to 8 meters below the buildings. Most of them were natural cavities in the limestone that were later enlarged by the dwellers.
3. On the third level there are individual and connected cellars, a part of these connected cellars is called the Big Labyrinth. Cavities at this level had originally been formed as a result of the hot spring cave formation, but the majority of their current form is owing to the above-mentioned transformations. The main passages are parallel to the fracture system of the formations.

The total area of the connected cave cellars is approx. 18.000 sqm, while that of the individual cellars is 4.000 sqm (Figure 2.).

WELL DATA

The number of wells that can be found and identified in the Castle Hill have continuously been decreasing in the course of time. In the middle of the 17th century there were 75 wells registered (Zolnay, 1961), in 1908 there were 28 (Szontagh, 1908), in 1938 only 13 of them were examined (Horusitzky, 1939), and maps dated in 1951 marked 26 wells. This current research focuses on a total of 20 wells. Some of the wells cited by Kessler (1971) cannot be identified anymore.

Water-table

Measuring the water-table of the wells in the caves so far has been carried out regularly in three different periods. The first period was between 6th September, 1970 and 30th May, 1971 (Kessler, 1971). During these nine months 12 wells were observed on a weekly basis. The second period started at the beginning of April in 1994 and lasted for about a year during which 7 wells ("No. 7", "No. 8", "No. 9", "No. 11", "No. 12", "No. 13"and "No. 15") were equipped with water-level recorders. The equipment in theory was able to provide continuous recording (Hajnal 1995).

In the third period (June 1998 - January 2000) we recorded the water-table once a month in 10 different wells. After having analysed the data recorded in the first period, in the second period we decided to locate the water-level recorders. This equipment, due to its structural construction, has a 5-cm longitudinal play because of the tensile strain of the nylon line, however, data recorded by H. Kessler in many cases showed a water-table fluctuation rate higher than that. The shortest weekly fluctuation was 33 mm (Well "No. 13"), while the highest was 170 cm recorded at the well called "No. 3". Despite of these facts of the first period, in the second one the equipment recorded continuous levels of water only, therefore after a period of one year we removed the recorders.

Several interesting findings on the water-table of wells can be summarized on the basis of this one examination.

1. During the observation periods, the water-table of the wells "No. 13" and "No. 12" had the same fluctuation rates. Both of them had an almost equal draw-down rate of 2.6 m, from which we can conclude that most probably the water-table fluctuation rates were the same in-between observation periods as well. The only exception is the data recorded in June 1999. (Figure 3.).

Figure 3. Water table of two wells

2. The following "pairs" of wells: "No. 13" and "No. 11", and "No. 8" and "No. 9" provided the same reactions as regards water-table during this period when one of the highest monthly precipitation rates of the century was recorded.

3. In the first observation period the water-table of wells "No. 10" and "No. 9" had shown an extremely high increase as a result of the relatively large amount of winter precipitation and probably human actions as well.

4. During the new observation period wells "No. 9" and "No. 8" had almost the same hydrological behaviour.

5. With the exception of well "No. 6" the average water-table of all the wells has significantly decreased, between 0.8 m and 2.6 m. The major difference in these figures excludes any errors deriving from inaccurate levelling data.

6. The shallowest water level had been observed in the well "No. 4" (it might be due to the cleaning of the bottom!), while "No. 8" provided the highest water column that several times was higher than 3 meters.

7. During the first observation period wells “No. 13”, “No. 12” and “No. 4” had only a slight reaction to precipitation, while “No. 11” had a reverse reaction.

Temperature

At the beginning of the last century the temperature of the water in the wells was measured a couple of times, most of them had a temperature of 12 °C (Szontagh 1908).

We also have a few more data recorded in 1938 (Horusitzky 1938), when temperature of the water of 13 wells was recorded. Results varied between 10.5 and 13.85 °C. In this measuring period the temperature of the air in the cavities was between 8 and 11°C.

The first significant data line (after a long measuring period) was provided in 1970-71 (Kessler 1971). At that time the temperature of the water of wells varied between 10.6 and 15.8 °C, and the temperature of the water more or less followed the changes in that of the air. The latest measurements we carried out in 1998, with an approximate frequency of once a month (Table 1.).

Table 1. Temperature of well-waters of the caves

	1970 - 1971		1998 - 1999	
Wells	min. °C	max. °C	min. °C	max. °C
“No. 3”	13	14	13.7	16.0
“No. 4”	14	15	14.3	18.0
“No. 5”	13	14	16.2	17.6
“No. 6”	12	13	15.3	17.2
“No. 8”	14	15	12.0	14.0
“No. 9”	15	16 (15.8)	10.0	14.5
“No. 10”	12	14	11.5	14.0
“No. 11”	13	14	12.0	14.3
“No. 12”	13	14	13.0	14.8
“No. 13”	11 (10.6)	13	14.1	16.0

The lowest temperature was recorded in well “No. 9” (10 °C) and the highest in “No. 4” (18 °C). The lowest results were with no exception recorded on January 4th, 1999, while the highest ones in the summer months and early autumn. Data of the first series of measurements were a lot more balanced than those of the second. Difference between the minimum data of the wells was 4 °C, and 3 °C between the highest results, while in case of the new data line the difference was 6.2 °C and 4 °C, respectively. This can be explained by the fact that this part of the caves together with this well has a direct connection to the ground level via an open vent in the roof.

The lowest figures of the two data series were basically the same: 10.6 and 10 °C, while highest temperature data have shown an increase by 2 °C. The unbalanced character of the second data series provides a tendency whereby at the southern parts of the Labyrinth, which was in use at the time of our observations, thus some parts were heated, we recorded by an average of 2 °C higher temperature data than at the wells of the northern part of the Labyrinth. The only exception to this tendency was well “No. 13”.

Discharge of wells

The discharge of wells in the caves was first tested in 1970 (Kessler, 1971), then in the middle of the 1990-ies (Debreceni Búvárklub 1994a, 1994b, 1996) (Table 2).

Table 2. Discharge of wells in the caves

Years	1971.	1993.	1994.	1996.
Wells		(litre/day)		
“No. 1”	-	-	480.00	1,008

“No. 2”	3.9	-	3.84	-
“No. 3”	16.0	-	14.40	-
“No. 6”	43.0	-	-	-
“No. 7”	-	1,296	744.00	720
“No. 8”	-	-	43.20	-
“No. 12”	-	744	480.00	-
“No. 13”	-	552	38.40	-
“No. 14”	9.3	-	-	-
“No. 15”	-	-	89.12	528
“No. 16”	-	-	5,400.00	7,200
“No. 17”	-	-	10,080.00	12,000
“No. 18”	-	-	13,000.00	12,000
“No. 19”	-	-	1,440.00	1,440

As the table shows, we have very few data available, and the tests were carried out once and lasted for a very short period of time. Discharge of wells were calculated on the basis of pumping tests. When pumping test is applied it is very true that data obtained after one test only are not well justified. Unfortunately we do not have any data available on the discharge of wells called “No. 4” and “No. 9” which is a disadvantage from the point of view of comparing the tested parameters.

However, we can still come to a few important conclusions on the basis of the existing results. Discharges of wells in the northern part of the Castle Hill are two or three orders of magnitude larger than those in the southern part. The only exception is the well below the house at 15, Dísz square. According to the discharge of wells the Castle Hill is divided into four areas (Debreceni Búvárklub 1994) which, based on such a limited amount of tests, might not be a well-justified statement, so further tests are needed to prove it. In my view there are two main areas surely. One is the area including the wells “No. 2”, “No. 3”, “No. 6”, “No. 8” and possibly “No. 9”, the other area is bordered by the streets Táncsics Mihály, Fortuna and the northern part of Országház Street (including the wells “No. 12”, “No. 13”, “No. 15”, “No. 16”, “No. 17” “No. 18” and “No. 19”).

In case of wells “No. 2” and “No. 3” we can notice that in spite of the long period in time in-between the two pumping tests, in both cases the results showed almost the same rate of discharge. The difference in the data gained in 1993 and 1994 can be observed in case of 3 wells: discharge of “No. 7” and “No. 12” decreased almost to its half, while that of “No. 13” by one order of magnitude . Although the reports do not include the exact date and time of the tests, on the basis of the dates on the documents, backfilled water was measured at the end of 1993 and in January 1994. Therefore in case of the above-mentioned three wells the significant decrease in the discharge can be in part explained by the changes in the amount of precipitation. In October 1993 the amount of precipitation was 134.9 mm, which is regarded as extremely high rate, while in the following months it was 82.3, 53.1 and 43.7 mm. So we can assume that at the time of the first measurements, as a result of the large amount of precipitation, a lot more water has accumulated in the formations than later. According to H. Kessler the wells get backfilled not directly by the precipitation but the passive water reserve in the formations. This conclusion he has drawn from the increase in temperature measured at the time of backfilling (Kessler, 1971).

The discharge of the well “No. 7” recorded in 1996 did not change compared to the data from 1994. Both wells of Táncsics Mihály Street (No. 17 and No. 18) each time had a discharge higher than 10,000 liters a day.

The cellars at 9-11, Országház Street, NW part of the hill, have a very significant role in the northern part of the Castle Hill. There used to be a diving pump which has been replaced by the experts of the DBK by an automatic turbine pump. Into the pump-sump are connected the canals of the labyrinth, as well as spouts from outside the walls. It is probable that the refilling of water in this well derives from a larger area than in case of other wells.

Water chemistry

Results of the chemical tests have been published in several studies (Szontagh 1908, Horusitzky 1938).

In the course of the comprehensive tests in 1970, chemical analyses were carried out at the laboratory of FŐMTERV (Civil Engineering Consultancy) Corporation. Tests in 1994 were carried out at the laboratory of the Department of Water Supply and Canalization, Technical University of Budapest, while from 1998 again at FŐMTERV Corporation. Facilities of the two laboratories are serving different types of measurements, therefore their data cannot always be compared. The most important results are summarized here.

pH The pH value of the water samples varied between 7 and 8.5, no significant changes were recorded at individual wells.

Mg^{2+} The presence of magnesium was only analysed in the latest water samples. Mg^{2+} can derive from the dissolution of rocks (e.g. mineral water of the Gellért Hill), but not from sewage. Therefore the significant changes experienced at tests carried out a few months later is very surprising. From among the 11 wells tested, the water of 6 did not show any major changes, while in case of the other 5 the magnesium content has multiplied by several times, or on the contrary, has decreased. Research activity carried out at the karst area in Aggtelek, Northern Hungary proved that during dry periods magnesium ions in the water can be found in larger quantity than what could be expected based on the ratio of limestone and dolomite in the catchment area (Maucha 1998).

Na^{2+} It is suggested by chemists that the majority of sodium in this area derives from salting. Therefore it is very interesting to see the difference in magnitude of values between the individual wells, especially that the tests were carried out in the summer.

NH_4^+ The presence of ammonium in the water of wells is an obvious sign of pollution. On the basis of the results we can say that none of the wells has a constant connection with the sewer system, but some of the wells have a few times been infected by significant pollution.

NO_3^- The presence of NO_3^- also indicates that waste water got into the wells. An extremely high figure we have found in case of water samples from the wells “No. 12” and “No. 9”. A decreasing tendency can be observed at each of the wells as time passes by which is partly owing to the elimination of the problems of the canal system, and also to the fact that water coming both from precipitation and the pipes dissolve NO_3^-.

NO_2^- To examine the presence of NO_2^- fewer tests were carried out as compared with the previously mentioned parameter, but we still can conclude that the amount of NO_2^- in the water samples from all wells by several times exceeded the upper limit of 0.1 mg/l.

Cl^- The high rate of chlorine reflects an active connection with the ground level, as it can derive from salting, and to a smaller extent, from pipeline water. Most of the water samples have significantly exceeded the upper limit of the chlorine contents of the water in dug wells, i.e. 30 mg/l.

SO_4^{2-} Sulphate may dissolve from rocks, concrete and plaster. Water from several wells (“No. 5”, “No. 8”, “No. 7”, “No. 16”, “No. 9”) have not reached the limit of 300 mg/l at any of the tests.

δ^{18} O tests

Water from 8 wells was tested with the δ^{18} O method at the Nuclear Research Institute of the Hungarian Academy of Sciences in Debrecen, Hungary, in order to demonstrate the ratio of pipeline water within the well water (Divers Club of Debrecen, 1996.).

The results are listed below and well data are given from the South to the North. (Table 3).

Table 3. The ratio of pipeline water within the well water in the caves of the Castle Hill (Divers Club of Debrecen, 1996.).

Wells	Ratio of pipeline water (%)
“No. 1”	61,9
“No. 7”	9,9
“No. 9”	0,0
“No. 15”	0,0
“No. 17”	75,0

“No. 16”	71,6
“No. 18”	78,6
“No. 19”	55,9

Flow conditions

In the framework of the research work carried out in 1970, flow conditions were determined on the basis of changes in the water-table (Kessler 1971). In order to examine the connections in-between wells, simultaneous pumping tests and water dying were applied (Divers Club of Debrecen, 1994). Current directions assumed on the basis of water-table of the wells were not confirmed, but in some cases were disproved by applying water dye (wells “No. 9” and “No. 8”)

Pumping tests in 1994 provided the following results:

The well under building at 15, Dísz tér was drawn down to which the water in the well “No. 4” had a slight response only (2 cm).

The draw-down of the well “No. 15” resulted in a sensitive reaction by the water in the well “No. 16” (15 cm), however, in reverse case (when this latter was drawn down) there was no response by the water in “No. 15”.

None of the neighbouring wells (“No. 9”, “No. 11”) had a reaction to the draw-down of the well “No. 10”.

As regards water colouring tests, an important result was recorded in case of the well “No. 18”, i.e. the fluorescent water appeared on the Castle Hill bent, besides Kagyló stairs.

SUMMARY OF WELL DATA

Below I am providing a summary of the most important results of well-water measurements carried out in 1998-1999.

Table 4. Summary of results of well-water measurements

Well	Response to precipitation	Temperature of water	Discharge of wells	Communication with public utilities	Flow
“No. 1”	-	-	average	pipeline water	From the direction of well “No. 4”
“No. 2”	strong	-	small	-	to the South
“No. 3”	strong	high	small	-	-
“No. 4”	average	high	-	sewage	to the South
“No. 5”	weak	high	-	-	-
“No. 6”	average	high	small	-	-
“No. 7”	-	-	average	-	-
“No. 8”	average	changes according to air temperature	small	-	-
“No. 9”	strong	very actively changing according to air temperature	-	sewage	no communication
“No. 10”	weak	changes according to air temperature	-	-	no communication
“No. 11”	average	changes according to air temperature	-	sewage	-
“No. 12”	average	changes according to air	average	sewage	-

		temperature			
“No. 13”	average	high	average	sewage	-
“No. 14”	-	-	small	sewage	-
“No. 15”	-	-	average	-	from North
“No. 16”	-	-	big	pipeline water	from North
“No. 17”	-	-	big	pipeline water	-
“No. 18”	-	-	big	pipeline water	to the North
“No. 19”	-	-	average	pipeline water	-

CONCLUSIONS

1. Water chemistry tests have proved that none of the wells have water of drinking-water quality.
2. On the basis of the results provided by the water-table tests in relation to precipitation; chemical parameters and pumping tests it can be stated that communication in-between the wells is not as active as it was assumed by Kessler (1971).
3. From the point of view of the discharge of wells the area can be divided into two precisely distinct areas: the northern and the southern one. In the northern area the discharge of wells is approximately 10,000 liters per day, while in the southern area it is changing between 10 and 1,000 liters per day.
4. The temperature of the water in the wells has a close relation to air temperature.
5. Each of the wells have faced a significant draw-down, the average depression was 2 meters between the two measurement periods (between 1970 and 1998).

I suggest that a monitoring system should be established that would enable us to carry out additional, simultaneous tests. If we had a sufficient amount of data available, we would be able to model the system in such depth that would also contribute to a quick remedy of events such as road collapse, burst in a water pipe, landslides, etc.

ACKNOWLEDGEMENTS

I wish to take this opportunity to express my thanks to my scientific supervisor, Dr. Béla Kleb (Budapest University of Technology and Economics) for providing professional guidelines; to Mr. László Sásdi (Ariadne Caving Club) and Mr. László Czakó (Divers Club of Debrecen) for their continued assistance they have lent at the measurements in the caves; and also to Mrs. Géza Olasz (FŐMTERV Rt.) and Ágnes Perényi (Budapest University of Technology and Economics) for the chemical analysis of water samples.

REFERENCES

Hajnal, G. (1995): A budai Várbarlangok hidrológiája, Karszt- és Barlangkutatás, 10. pp. 211-223.
Horusitzky, H. (1939): Budapest Duna - jobbparti részének geológiai viszonyai. Hidrológiai Közlöny, 18 (1938). p. 404.
Kadic, O. (1942): A budavári barlangpincék, a várhegyi barlang és a Barlangtani Gyűjtemény ismertetése. Barlangvilág, 12 (3-4). pp. 49-75.
Kessler, H. (1971): A budai Várbarlangban végzett hidrológiai mérések értékelése. Kézirat (FŐMTERV 30.891)
Maucha, L. (1989): A karsztvizek jelentősége és kutatása hazánkban. Karszt és Barlang, 1989 (1-2). pp. 67-76.
Szontagh, T. (1908): A budai várhegyi Alagút hidrogeológiai viszonyai - Jelentés a Várhegyi Alagút vizesedésének okairól. Bp., p. 23.
Zolnay, L. (1961): Buda középkori vízművei. Történelmi Szemle, pp. 16-55.

Reports by the Divers Club of Debrecen:
Összefoglaló jelentés a budai Várbarlang 1993. máj. 29. - 1994. jan. 28. között vizsgált és tisztított kútjainak hidrogeológiai megfigyeléseiről (kézirat, 1994.)

Jelentés a Táncsics u. 15. sz. kút állapotfelméréséről, összefüggésvizsgálatáról és próbaszivattyúzásáról (kézirat, 1994.)
Jelentés a budai Várnegyed 8 kútjának és 2 forrásának vizsgálatáról, melynek célja a vizek hálózati részarányának meghatározása (kézirat, 1996.)