New method of calculating water balance for the Castle Hill, Buda

Géza Hajnal
Technical University, Budapest
Department of Building Materials and Engineering Geology

Abstract

In the previous centuries, a lot of energies were expended on the scientific knowledge of the Castle Hill, Buda, declared a part of the World Heritage, however only few scientist carried out researches on the hydrogeology of the Hill and out of them only the results of Kessler's studies survived in a systematized form. The author has been dealing with the hydrologic and hydrogeologic investigation of the Castle Hill nearly for ten years. The present paper is a part of his PhD thesis in preparation on the water balance model of the whole of the Hill.

Key words: water balance calculation, hydrogeology, recharge, infiltration, public-utility loss

Introduction

Outstanding representatives of several professions have worked and work in order "to put the Castle Hill in good repair", however the hydrologic and hydrogeologic description of the territory occurs only as parts of certain studies. Still, preservation, renovation and maintenance of deep cellar and cave systems, supporting walls, castle wall systems, buildings and public utilities, closely related from the points of view of underground building are not possible (or at least extremely difficult) without the results of the hydrologic basic research. Such researches, however, were carried out only at the beginning of the '70-ies and are carried out nowadays, respectively. A stage of high importance of these researches was the elaboration of an entirely new water balance calculation method. The water balance gives answer to the important questions on the amount of the dynamic water resources of the Castle Hill from precipitation and network loss, which outcrop to the surface in the form of springs and filtrations at the margin of the Castle Hill, since in excess they are a threat to the security of engineering facilities.

Water types of the Castle Hill are summarized in Table 1. This arrangement was made not according to the classic hydrologic system (surface, subsurface, ground, confined, etc. waters), but on the basis of the simplest sorting of the available data. Origin of certain water types may partly or totally correspond.

Table 1: Water types of Castle Hill, Buda

Water types	Data types
Precipitation (P)	30 years monthly time series (Kitaibel Pál Street measuring station), 18 months time series (Táncsics Mihály Street measuring station)
Evaporation (E)	estimated and calculated values
Infiltration (I)	calculated values
Draining (D)	estimated and calculated values
Water of drains (W_{od})	hydrochemistry
Water of ground-water level observation wells (W_{gw})	30 years measured water level time series, hydrochemistry
Water overflows (W_o)	temperature and output data, hydrochemistry
Water of boreholes (W_b)	water level, hydrochemistry (in a single period, only!)
Cellar water (W_c)	hydrochemistry
Lukewarm water (W_l)	references in literature, assumptions
Water of cave wells (W_{cw})	water level time series, temperature and output data, current measurements
Dripping water (W_d)	intensity (output) data, hydrochemistry
Public-utility loss:	
Water-mains (W_m)	measured and calculated values, hydrochemistry
District heating (D_h)	values calculated from measurement loss
Conduit pipe (C_p)	values estimated from precipitation and Wm, Dh

The previous calculations

So far, water balance has been drawn up four times for the plateau or slopes of the Castle Hill, or for both of them simultaneously. The first one was made in order to determine the causes of the sliding in the Logodi Street (Horusitzky, 1937), the later ones to measure out the water structures (conduit pipes, drains – FŐMTERV, 1988, 1993), as well as to determine the amount of water, getting down into the caves (Kessler, 1971).

The results – which were aimed mainly to determine the degree of infiltration – showed significant divergences. It was due not only to the differences of the calculation methods but also to the different survey of basic data (extent of the catchment area, annual average of precipitation). The starting data and the resulted infiltration values are presented in Table 2.

Table 2: Comparison of the results of the previous water balance calculations

	Area (m^2)	Precipitation (mm/year)	Draining (m^3/y) [draining factor]	Evaporation (m^3/year)	Infiltration (m^3/year)
Plateau					
Kessler (1971) I.	400,000	610	[0.7] 170,800	48,800	24,400
Kessler (1971) II.	400,000	365*	–	–	146,000
FŐMTERV (1988)	394,000	610	[0.7] 168,238	–	72,102
FŐMTERV (1993)	–	580	[0.7] 165,214	52,964	15,473
Slope					
Horusitzky (1937)	445,000	564	321,970	241,477	241,477
FŐMTERV (1988)	750,000	610	[0.8] 366,000	–	91,500
unknown origin	750,000	610	[0.9] 137,000 [0.8]122,000 [0.16] 25,000	10,000 20,000 70,000	66,000

*This value corresponds to the already infiltrated amount.

The figures between brackets before the draining data are the draining factors, taken into account at the calculations.

In the survey of the calculating parameters, the following differences occurred: The degree of evaporation was totally ignored, or assumed as one-third or two-thirds of the entire precipitation. At the survey of the draining factor, proportions of the extent of the green area were different; thus calculations were made with 10, 15, 20 and 30 percent green area ratio. Areal proportions of the roofs and paved streets were determined similarly as one-third, and the values between brackets were formed on this basis. The degree of infiltration was surveyed as one-third and 25 percent of the entire precipitation, respectively.

Besides these differences, the most striking divergence between the water balances, drawn up so far, is that only Horusitzky took into account the factors of urbanization, the subsequent calculations ignored them totally. Though Kessler compared his “reversed” calculations, based on

the measurements in caves, with the results arising from the conceptual model, he did not try to determine all the parameters. He established correctly that the losses, resulting from the faults of public utilities, are determinant in the water balance of the hill, but later their proportions were published wrongly in several expert reports (FŐMTERV, 1984, 1993 – 95% water from water-mains and 5% meteoric water mixed with waste water).
Further on, individual elements of water balance, taking into consideration also the effects of urbanization, will be discussed.

Natural recharge

The oldest precipitation measuring station of Buda has been operating in the territory of the Hungarian Meteorological Service (HMS), in the Kitaibel Pál Street, at the foot of the Rózsa Hill (Rózsadomb) since 1841. Differences in the data series of the measuring stations of Budapest were observed already in the 19th century, and it was established that distribution of precipitation is varying by areas. This might give the reason for the setting up of a new measuring point in the territory of the castle garden, some hundred air meters from the HMS station. The annual average of precipitation, measured by the two stations in the first half of the last century, was published (Karakas, 1967). Accordingly, between 1901 and 1950 the annual precipitation average at the castle garden station was 579 mm, while at the HMS station annually 617 mm precipitation was measured in average for the same period.

Areal differences in precipitation distribution as well as ceasing of precipitation measurement in the Castle made necessary to carry out new measurements here. The author measured the precipitation in the Táncsics Mihály Street for 18 months. As compared to the data series of the precipitation measuring station in the territory of the HMS, some 500 air meters away, for the same period (October 1993–March 1995), precipitation values of 13 months are in accordance basically, measurement data of two months were destroyed and only the values of three months show significant differences (Fig. 1). These differences, however, resulted from the conditions of observation (due to the absence of the observer the registration did not occur on several days), thus on the basis of the data, measured in the Táncsics Mihály Street, it can be stated that the data series of the HMS can be interpreted for the area of the Castle Hill. Accordingly, a 30 years precipitation data series is available, which is sufficient, as among the other water data there were no values comparable with precipitation from the previous study period. This makes the statistical–hydrological investigation of the time series and the calculation of new average values, respectively, possible.

The annual precipitation average depends on the number of studied years. The different water balances, made for the territory of the Castle Hill, take into account essentially different annual precipitation averages (Horusitzky, 1937; Kessler, 1971; FŐMTERV, 1988, 1993), most of the studies 610 mm per year. This value is nearly identical with the average values of two 5-years periods (1965–1970, 1975–1980), as well as the annual averages of the first half of the century, that is it can be interpreted for these periods. From 1970, annual precipitation has exceeded 800 mm 4 times in Buda, at the Szabadság Hill station. Maximum value (841.2 mm) at the HMS station was measured in 1999. At the same time, it is worth mentioning that the annual minimum (326.5 mm) of 30 years appeared in 1997. These data also show that a drier period began at the end of the last millennium as compared to the first 50 years of the last century.

At water balance calculations and other water investigations, respectively, the 30 years average (which almost corresponds to the average of the last five years), the 5-years averages of the last

30 years and the monthly precipitation values of 1970–1971 and 1998–1999 were taken into account (Table 3).

Table 3: Averages of the data of the precipitation measuring station in the territory of the HMS

Period	Precipitation (mm)
1971–1975	528
1976–1980	610
1981–1985	500
1986–1990	517
1991–1995	504
1996–2000	532
1971–2000	539

For the regimen of the ground-water level and cave wells as well as the hydrochemical changes in water overflows, average values of greater units than months (years, several years) cannot be taken into account. Use of the calculated values, customary in the special field of hydrogeology (e.g. standard precipitation percentage – Kessler, 1954; Maucha, 1990) is not reasonable due to the urbanized environment, however they will be produced for the water balances in order to make the comparisons.

It is important to stress that the values derived from precipitation (evaporation, draining, infiltration) are much more complex in the Castle Hill than in the natural karst areas. Due to the roofs and pavements, the draining factor $\alpha = 0.8$, at the same time a great part of the draining water gets into the unified system of canalization. From there, however, there is a significant filtration into the rocks and cavities, thus waters of precipitation origin nourish a significant part of waters, occurring and measurable in the area, after all.

Recharge from public-utility loss

Water supply

Experts define differently the concept of system loss. On the Castle Hill, only that amount of water is regarded lost which is not used for useful purposes, as opposed to the more precise sales balance, which is the difference of the annually fed and sold water.

At burstings of pipes, a relatively great amount of water increases the loss with high intensity but for a short time.

As opposed to burstings of pipes, the defect sites of small size cause the filtration of small amount of water but due to their great number and constancy they may represent 40–60% of sales balance. The resulting loss in the system of Budapest may reach 15 millions m^3.

In order to avoid the system loss due to the defects of the system two kinds of procedures are in force: periodical and continuous system inspection. In the Castle, periodical system inspections are carried out by means of water loss analyzing survey vans.

The Waterworks of Budapest Co. Ltd. (WBC) began the regular measuring activity on the Castle Hill in 1985 because of the endangerment of the area.

Table 4: Results of water loss analysis in the Castle district (on the basis of the data supplied by the Waterworks of Budapest Company)

Survey area	Length [m]	Measured loss [m³/h]	Specific loss [m³/h/km]	No. [pcs]	Defect site types [pcs/m³/h]					
					Water pipe	Junction	Curb cock	Latch	Fire cock	Internal damage
Castle dist. 1985	1,600	4.2	2.62	3		2 / 3.6	1 / 0.6			
Castle dist. 1987	4,800	6.1	1.27	5	1 / 1.8	2 / 2.3	1 / 0.8			
Castle dist. 1989	4,800	12.9	2.69	15	2 / 8.6	10 / 7.7	2 / 0.6	2 / 0.4	1 / 0.1	19 / 13.5
Castle dist. 1990	14,200	7.7	0.54	13	1 / 2.0	3 / 2.9		2 / 0.4	1 / 0.6	6 / 1.8
Castle zone 1992	28,200	74.9	2.66	90	1 / 5.0	6 / 5.9	6 / 6.0		4 / 1.1	73 / 56.9

Certainly, the survey areas shown in Table 4 (Castle district and Castle zone) do not cover the areas delineated by the author (Plateau, Slope), since the WBC determines the important areal units on the basis of the water-feeding units. It can also be observed from the Table that most of the defect sites occur at the junctions and due to internal damages. When comparing age, specific loss and number of defect sites of water-mains of several survey areas, data of the year 1990 were taken as a basis.

Diameters of water-mains in the Castle range from 100 to 300 mm. Their predominant part was laid down in the ‘60-ies, thus they are not considered old (particularly in relation to the age of the water-mains of Budapest).

In the last ten years, the WBC has significantly renovated the water pipe system of the Castle district: only according to the most recent data in 1999 850 m pipes were replaced in the territory of the Plateau and in 2000 renovation works were carried out in the Hunfalvy, Szabó Ilonka and Donáti Streets, on the Castle slope. However, one can still find water pipes from 1886 in the area. Nevertheless, the data from 1990 may be taken as a basis even today when calculating loss, since only the water-mains and appliances running in publicly owned land are under the supervision of the WBC. (The same holds true for the other public utility companies, as well!)

Calculating with a loss of 7.7 m^3/h, the annual loss in the Castle district is 67,452 m^3. When not measuring the loss in a given area, the Waterworks Company applies a rule of thumb, which determines the loss as 10% of the water amount, fed to the area. (In sense of the data on the previously mentioned loss, it seems to be correct.) From the water-feeding data of the Krisztina station, annual averages were formed for the periods between 1992–1995 and 1996–2000, respectively. (There were no detailed data series for these two periods, as no computerized records of the amount of water-feeding had been kept before.) Annual average of the latter period is less by 15% than that of the former one. As to the water-feeding, a more serious decrease took place between the end of the ‘80-ies and the beginning of the ‘90-ies due to the appearance of the new water-charges of market approach. On this period, data of the production volume for the system of the area of Budapest were available.

Compared to the beginning of the ‘70-ies, the amount of water-feeding has decreased only in a smaller degree till today. The loss for the area of the Castle Hill was calculated on the basis of the proportion of house connections in the whole area. (A detailed public-utility map was made available by the Waterworks Company, indicating all the house connections.) The number of house connections of the whole zone is nearly 2,700, out of them some 440 belong to the area of the Castle Hill. After modifying the feeding quantities by this proportion, the water-feeding data for the given year or period in the Castle Hill were obtained, and from them – by means of the 10% rule of thumb – the loss. The water balance calculations were carried out with the following water-feeding data (Table 5):

Table 5: Water-feeding in the Castle zone

Period	Feeding (m^3/year)
1971–1975	1,447,116
1986–1990	1,963,614
1992–1995	1,543,864
1996–2000	1,308,136
1971–2000	1,565,682

Loss of the two latest periods corresponds to 168 mm/year and 142 mm/year infiltrating precipitations in respect of the Plateau, which is a striking value with the knowledge of the annual precipitation quantities.

Conduit

The oldest conduit pipes of Budapest could be found in the territory of the Castle Hill. The oldest one, made at the end of the 18th century from red marble, was exposed in the Donáti Street. The most significant conduit pipes of the Plateau were built in 1822 in the Szentháromság Square and Úri Street, in 1835 in the Dísz Square, in 1842 in the Országház Street.

Most of the conduit pipes in the Castle have been aged, in the ‘90-ies the oldest one run under Tóth Árpád Walkway and was built in 1877.

During World War II, the system of canalization was damaged and silted up, respectively at several places. In the ‘50-ies, renovation and extension of the system began, simultaneously with the continuous monitoring, repairing and cleaning of the existing canalization facilities.

The present-day canalization network has a unified system, which conveys water from the plateau to the conduit pipes of the area in six separate systems. On the plateau, 3,736.6 linear meters of conduit pipes of small profile and 411.9 linear meters of conduit pipes of large profile can be found. Due to the water intrusion in the cave cellars, the Budapest Municipal Sewerage Co. Ltd. (BMSC) surveyed the condition of the conduit pipes in November 1992.

Conduit pipes of Polgárváros (Bourgeois Town) are oversized, thus their transmissibility is suitable, their hydraulic features are good, however from the point of view of statics and impermeability the system is generally of bad condition. Great damages took place also due to land motions.

Erosion of filtrating waters and collapse of cellars might cause the ground subsidence, landslide and formation of cavities in the environs of conduit pipes, which resulted in the disjunction or even bursting of pipe elements at the junctions (FŐMTERV 1993).

Vertical movements also took place. Here, jumpers came into being, due to which the conduit pipes got into an operating condition under pressure. Around the junctions in the gully-holes, cavities have been formed. Materials of the structures (mainly the manholes), connected to the conduit pipes, have also been used up; cracks and collapses have been found at a lot of places. The gully-holes do not meet the requirements of impermeability, their ladders have been corroded. In several cases, binding of the eaves gutters as well as the courtyard drains in the system is not solved.

Waste waters feed on precipitation and water from water-mains equally. No data are available on the amount of loss of waste water; the BMS Company does not measure its loss. Thus, the 10% rule of thumb is applied again. According to the experiences, it can be regarded as a "benevolent" approach in the area of the Plateau, taking into account the intensity of dripping in the caves.

In the estimation of the author, the precipitation getting down into the conduit amounts to the 90% of all the running down water, while from the water-mains all the water gets into the conduit with the exception of the loss of the fed quantity, in principle. According to the calculations, the amount of waste water loss from the water-mains is 4–6 times higher than that from precipitation. Taking into account the data of the second half of the '90-ies, the loss of waste water from the water-mains corresponds to ca. 130 mm/year of infiltrating precipitation, while the loss of waste water from precipitation corresponds to ca. 30 mm/year on the Plateau. (Altogether, the loss of water-mains and conduit pipes corresponds to 300 mm! of infiltrating precipitation annually, which is more than half of the yearly precipitation.)

District heating

District heating has been supplied from 1969 in the Castle. Reconstruction as well as rebuilding of the pipe network were carried out at the end of the '90-ies. Order of size of loss was estimated from the measurements of extra water demand in December, 2000.

Daily average of extra water demand is 25 m^3. This means 9,125 m^3 annually. According to the experts of the Budapest District Heating Works Co. Ltd., about half of this amount may be loss.

This amounts to 4,560 m^3 annually, which means in respect of the Plateau little more than 12 mm/year of infiltrating precipitation, thus the loss from district heating is negligible as compared to that of other public utilities.

Determination of average water discharge of springs and filtrations on the slopes of the Castle Hill, Buda and in the Tunnel:

Only some of the several dozens of permanent and temporary overflow sites at the margin of the Castle Hill have been observed several times (Csollány, 1955), the springs in the Logodi Street were measured by the author. Their discharge is small, their temperature varies independently of the air temperature (Table 6).

Table 6: Results of measurements of spring-like overflows

Name, locality of the spring	Water discharge (l/m)	Water temperature (°C)	Air temperature (°C)	Measurement date
Unnamed, 24 Donáti Str.	filtrating	17.1	26	1971.01.14.
	3–4	12.3	18	1974.05.10.
	35.0–40.0	12.5	5	1986.11.11.
Crystal, 2 Hunfalvy Str.	1.9	10.0		1953.11.02.
	2.1	8.5		1954.03.11.
	2.2	9.0		1955.02.06.
	1.2	10.9		1968.05.02.
	0.8	10.4		1969.06.17.
	1.0	9.0	25	1971.05.07.
	1.0–2.0	11.2	14	1971.10.08.
	1.2	12.7	18	1973.10.09.
	5.0–6.0	10.9	5	1986.11.11.
Hunyadi János Road	1.8	10.0		1953.11.02.
	2.0	8.5		1954.03.11.
	3.6	6.5		1955.02.06.
Unnamed, 1 Lovas Str.	73.0	17.0		1968.10.11.
	2.0–3.0	12.8	25	1971.06.14.
	10.0–12.0	14.6	5	1971.11.29.
	4.0–5.0			1974.05.10.
	dried up			1986.11.11.
5–7 Logodi Str.	5.0	14.0	6	1995.10.11.
	2.2	13.5	11	1996.04.05.
9 Logodi Str.	1.0–1.5	14.0	6	1995.10.11.
	0.2	12.5	11	1996.04.05.

Sum of the water discharge calculated for 50 years is 165.5 l/minute = 238.3 m^3/d = 86,980 m^3/year. (Table 6 contains the discharge measured at least once of all the springs and filtrations at the margin of the Castle between 1950 and 2000.)

The most important filtrating network of the Castle Hill is the adit system, working as a giant drain pipe, which was established for dewatering the Tunnel. It drains the confined waters and fissure waters filtrating from north – mainly through the cracks of the Buda Marl. Infiltration of a significant amount of water was observed in the passages also in the drier periods, however their discharge has never been measured. Estimated amount of water getting into the Tunnel is: 30,000 m^3/year.

In the last decades, several studies have been made on the wetter and wetter cellars of the slopes of the Castle and the condition of the drains. The yearly amount of water can only be estimated again: water quantity of the regular cellar inundations is 50,000 m^3/year and 70,000 m^3/year water may leave the drains of poor condition.

Algorithm of calculations:

Legend

A_p	Area of the Plateau
A_s	Area of the Slope
P	Precipitation
E	Evaporation
D	Draining
W_{wm}	Water of water-mains
W_{dh}	Water of district heating
I_p	Infiltration from precipitation
I_{wm}	Infiltration from water-mains
I_{wdh}	Infiltration from water of district heating
I_{pcp}	Infiltration of precipitation origin from conduit pipe
I_{wmcp}	Infiltration of water-mains origin from conduit pipe
I_{cp}	Infiltration from conduit pipe
I_p	Infiltration into the Plateau
I_{pol}	Infiltration into Polgárváros
I_{dc}	Infiltration into deep cellars
I_{gl}	Infiltration into the Great Labyrinth
I_{sc}	Infiltration into separate cavities

Basic data

Statements on the annual average of precipitation were presented before. The evaporation has been taken into account as one third of the whole precipitation, all through.

Draining was calculated with a weighted draining factor $\alpha = 0.8$.

Losses, resulting from the faults of public utilities, were presented before.

The Plateau

The schematic figure and the legend of the water balance for the Plateau are shown on Fig. 2.

Extent of the catchment territory is 400,000 m^2, altogether. Out of this, the area of Polgárváros is 310,000 m^2, while the area of the Palace is 90,000 m^2. Division of the territory into two parts is justified by the fact that the cavity system, which modifies considerably the conditions of water balance, runs under Polgárváros, while in the section under the Palace there are no cavities in all probability. The area of the Great Labyrinth is 18,000 m^2 and the areas of the separate cavities amount to 4,000 m^2.

Precipitation on the area:

$P\ (m^3/year) = A_p\ (m^2) \cdot P\ (mm/year);$

Out of this evaporates:

$E = 1/3 \cdot P;$

drains:

$D = \alpha \cdot (P - E)$, if $\alpha = 0.8$, $D = 8/15 \cdot P;$

infiltrates:

$I_p = P - E - D$, $I_p = 2/15 \cdot P$;

Loss of water-mains in the area ratio Plateau/(Plateau + Slope):

$I_{wm} = (40/92 \cdot W)/10$, $I_{wm} = W/23$;

Amount of water infiltrating from the loss of district heating:

$I_{wdh} = 2/3 \cdot W_{dh}$;

Waste water loss from precipitation:

$I_{pcp} = (0.9 \cdot D)/10$, $I_{pcp} = 0.048 \cdot P$;

Waste water loss from the water-mains:

$I_{wmcp} = (40/92 \cdot W - I_{wm})/10$, $I_{wmcp} = 9/230 \cdot W$;

Loss from all the waste water:

$I_{cp} = I_{pcp} + I_{wmcp}$;

All the infiltration into the Plateau:

$\Sigma I_p = I_p + I_{wm} + I_{wdh} + I_{cp}$;

Infiltration into Polgárváros in the ratio of the areas:

$I_{pol} = 31/40 \cdot I_p$;

All the water amount getting into the cavities:

$I_{dc} = 22/310 \cdot I_{pol}$;

Out of this, infiltration into the Great Labyrinth:

$I_{gl} = 9/11 \cdot I_{dc}$;

Water amount getting into the separate cavities:

$I_{sc} = I_{dc} - I_{gl}$;

The Castle Slope

The schematic figure and the legend of the water balance for the Slope are shown on Fig. 3. The area of the Slope is 520,000 m^2.

The method of calculation is the same as in the case of the Plateau, the values vary only in the function of the area ratio Slope/(Slope + Plateau).

P (m^3/year) = A_s (m^2) • P (mm/year); according to the sense all the values result from the amount of precipitation referred to the area of the Slope.

Loss of water-mains:

$I_{wms} = V/10 - I_{wm}$;

Amount of water from the loss of district heating is one third of all the district heating loss:

$I_{wdhs} = 1/3 \cdot W_{dh}$;

Waste water loss from the water-mains is as follows:

$I_{wmcps} = 117/2300 \cdot W$;

Results of water balance calculation

The calculations were made for the water-feeding periods of known amount as well as for the years of extreme precipitation conditions (Table 7).

Table 7: Results of water balance calculation for the area of the Plateau

Period	Precipitation (mm/year)	Water-feeding on the Castle Hill (m^3/year)	Draining (m^3/year)	Evaporation (m^3/year)	Infiltration (m^3/year)
1971–1975	530	1,447,116	113,066	70,666	161,026
1986–1990	520	1,963,614	110,933	69,933	202,968
1992–1995	540	1,543,864	115,200	72,000	169,744
1996–2000	540	1,308,136	115,200	72,000	150,270
1997	326	1,402,805	130,400	43,466	142,568
1999	841	1,133,610	336,400	112,133	157,685

Infiltration data for the last two years, calculating with a water-feeding average of five years, are 154,221 m^3 and 191,576 m^3, respectively. Consequently, an increase in precipitation of more than 60% results in increase in infiltration of only 20% in case of the same amount of feeding from water-mains.

Table 8: Structure of infiltration into the Plateau according to the origin of waters

Period	Infiltration from precipitation (I_p)	Infiltration from water-mains (I_{wm})	Infiltration from conduit pipe (I_{pcp})	Infiltration from conduit pipe (I_{wmcp})
	(m^3/year)			
1971–1975	28,266	62,918	10,176	56,626
1986–1990	27,733	85,374	9,984	76,837
1992–1995	28,800	67,124	10,368	60,412
1996–2000	28,800	56,875	10,368	51,188
1997	17,386	60,991	6,259	54,892
1999	44,853	49,287	16,147	44,358

The infiltration of precipitation origin is 30–40% of the infiltration of water-mains origin. The assumed 95% : 5% ratio was incorrect.

The infiltration value calculated for the first period comes nearest Kessler's reverse value of 1971. The difference in annual quantity can hardly be detected already in case of the Great Labyrinth. Kessler determined the amount of water getting down into the Great Labyrinth as 20,000 l/day, which corresponds to 7,300 m^3/year. On the basis of the summarizing calculations of the author, this value is 7,246 m^3/year. This proves the correctness of the method of calculations as well as the accuracy of Kessler's measurements and the justness of the drawn conclusions.

For the 30 years period between 1971 and 2000, the following results arise by averaging the values of Tables 7 and 8 (Table 9).

Table 9: 30 years average water balance of the Castle Plateau for the period 1971–2000

Precipitation			Draining			Evaporation			Infiltration		
mm	m^3/year	%	mm	m^3/year	%	mm	m^3/year	%	mm	m^3/year	%
530	212,000	100	283	113,600	54	178	71,149	33	71	28,399	13
	1,565,682								*427*	*171,002*	*80*

The values in italic mark the quantity of water-feeding and the calculated degree of infiltration.

It can be stated that the roughly 70% draining, 20% evaporation, 10% infiltration ratio is modified by the decrease in the amount of draining (escaping from conduit pipe) and the increase in infiltration due to public-utility loss. 9% of all the fed water quantity escapes into the soil.

It is worth studying the changes in infiltration between the periods 1971–1975 and 1996–2000 in case of the Great Labyrinth. The difference between the two values is 484 m^3/year. It corresponds to 1,326 l/day. A part of this quantity feeds the cave wells and this amount is "missing" from the wells. (During the hydrologic investigation of the wells of the caves in the Castle, an average depression of 2 m was demonstrated. Assuming a fictive well of 2 m diameter, more than 6,000 l water run out from the well in between the two periods.)

It can be stated that the water level of the cave wells subsided in the first place due to the decreasing water-feeding, in the second place due to the less precipitation in recent periods.

By changing the initial data, several comparative calculations were made. One of the changed parameter was the annual amount of precipitation, which is usually given in average of Budapest as 610 mm. It could be stated that the significance of precipitation is secondary as compared to the public-utility loss regarding the order of size of infiltration.

The other changed parameter was the area of the Slope, which has an effect on the infiltration data of the Plateau due to the area ratios. The infiltration quantities received this way are 8–10% less than those in the Tables, accordingly the exact determination of the area is a more important factor than the registration of the correct precipitation values.

Instead of taking into account the features of the terrain, frequently emphasized when making classical calculations, this method uses weighted draining factor. It is justified by the fact that the amount of infiltrating water is determined basically by the public-utility loss, while the degree of direct infiltration is insignificant as compared to it. Thus, calculations with the cover of the surface would complicate senselessly the drawing of the annual water balance. For determining the hydrological cycle of certain part-areas, however, the local conditions, including the cover of the surface, have to be known exactly.

The 50 years average water balance of the Castle for the period 1951–2000 alters to some extent with knowledge of the hydrologic data (Table 10) as compared to the 30 years average water balance. And this is due not only to the slight increase in precipitation average, but also to the smaller average evaporation value of many years. The latter can be well approximated from the pan evaporation data, measured at the Jósvafő Research Station for a long time (Nováky, 1984). The evaporation value of many years is 656 mm/year, which has to be reduced by the number of rainy days of the year. Thus, the period of evaporation from the surface can be regarded as 70 days yearly. This is 19% of the 365 days, which determines the annual evaporation as 125 mm.

Table 10: The 50 years average water balance of the Castle Plateau for the period 1951–2000

Precipitation			Draining			Evaporation			Infiltration		
mm	m^3/year	%	mm	m^3/year	%	mm	m^3/year	%	mm	m^3/year	%
565	226,000	100	367	146,800	65	125	50,000	22	73	29,200	13
	1,565,682								*427*	*171,002*	*80*

Kessler's method applied for the Castle Hill

As an experiment, the annual water discharge of springs of the Castle Hill was calculated taking into account the extreme precipitation values of the last decades, presuming that there were no urbanization effects on the hill, at all (that is if the Castle Hill stood in a "natural state" on the riverside of Danube, relieved of the constructed buildings, pavements, public utilities). For this, Kessler's method was used. The catchment area of the Castle Hill was regarded as 920,000 m^2. The results are presented in Table 11.

Table 11: Results of calculations by Kessler's method for the Castle Hill, Buda

Hydrologic parameters	1997	1999
Precipitation (mm)	326.0	841.00
Standard precipitation percentage (%)	24.5	5.93
Corrected standard precipitation percentage (%)	39.5	15.93
Infiltration percentage (%)	50.0	25.00
Total spring discharge (m^3/year)	150,190.0	193,476.00

Afterwards, it turned out that the so-called “infiltration curve” of Kessler’s original method should not be used, as he had taken over wrongly the catchment area of the Tettye Spring from a former study. Thus, the corrected standard precipitation percentage may be regarded the right value of the infiltration. Calculating this way the infiltration of the two extreme years, 118,468 and 123,253 m^3/year are derived.

Comparing these results with the results of the above Tables, it can be stated that the due to the urbanization effects 30% increase in water load appears on the Castle Hill.

Summary

During the last twenty years, several expert reports and scientific publications have informed on the water intrusion in the cave system of the Buda Castle. However, the detailed hydrologic and hydrogeologic investigations seemed to prove its contrary, that is the drying process of the system. By means of the water balance calculating model, taking into consideration the public-utility loss, as well, the drying process could be proved, since a determinant input factor of the system is the water-feeding (and not the precipitation!), which has been drastically diminished recently in the whole area of Budapest. At the same time, it was stated that the hydrological cycle of the Castle Hill is greater by 30% than it would be under natural conditions even in the present situation.

In the future, the complex water balance calculations of other settlements, possibly districts of a town in Hungary and abroad, with a geomorphology similar to that of the Castle Hill, Buda, are proposed to be made.

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