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Water balance calculation method for urban areas examples from Hungary

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A new water balance calculation has been worked out that considers the effect of urbanization. This calculation method was applied to evaluate the water balance of the historic center of Budapest, the Buda Castle Hill, where an intensive network of cellars is found. The method, a combination of hydrogeologic tests and field measurements, was also tested in other Hungarian cities where underground structures are common, such as Eger, Pécs and Veszprém.

The calculation considers both natural and anthropogenic water sources. Beside the commonly-used natural factors such as precipitation, evaporation, runoff, infiltration, etc. it also employs input parameters such as broken pipelines and sewer systems. The water losses of these waterworks significantly influence the natural water balance and provide additional and very often significant water input into the water system. The new method is of great importance in designing and planning remedial actions for historic cities, where the built environment, cellars and natural caves are endangered by infiltrating water. Another feedback of the method is the application of the results in the long-term planning strategy of public works supplying or using water (water works, sewer system and energy sector).

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

Introduction

The classical method of water balance calculations considers precipitation on the input side and runoff, evaporation and infiltration on the output one. This method, however, does not provide satisfactory results in settlements, due to the

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fact that the effects of urbanization – primarily those of public utilities – may significantly change the water system. Below are published the results of calculations carried out in Hungarian cities, using the method (Hajnal 2002, 2003) that was elaborated for the Castle Hill, Buda.

Groups of water types

The first step of the water balance calculation method that takes into account the effects of urbanization is to collect and structure all possible water data. These fall into the domain of geology, geotechnology, meteorology and (the development of) public utilities.

In a given settlement the following water types of natural sources may occur:

– precipitation,
– runoff,
– evaporation,
– infiltration.

Anthropogenic water types are the losses by public utilities:

– water pipelines,
– sewage,
– district heating systems.

The form of appearance of both types of water can be very diverse:

– springs and water overflows,
– water in boreholes for geotechnical purposes,
– cellar water (regular and constant flooding),
– water of drilled and dug wells,
– water of ground-water level observation wells (Fig. 1),
– water of draining-channels.

It is notable that these groups are not based on the classic hydrologic system (surface, subsurface, ground, confined, etc. waters), but are set up according to the simplest groups of measurable and observable data. The origins of certain water types may be partially or totally correlatable. For example, water of a natural spring in a city hillside might be joined by that from public utility losses; it can also occur in the opposite fashion at a water overflow, whereby water deriving from a long unobserved break in the pipeline system can mix with water coming from infiltration of precipitation (Fig. 2).

The importance of water losses by public utilities

The measurements and calculations carried out during this study proved that the water system of a given settlement, or that of a city quarter that can be distinguished from others from a morphological and geologic point of view, is basically influenced by the losses by public utilities.

Before presenting the essentials of this method, a few examples that justify this statement are presented:

– Examining the data series of ground-water level observation wells (Budapest, Pécs and Eger) it can be stated that the water level diagram never mimics changes of annual precipitation (not even with any delay; Hajnal 2005).

– The annual total amount of changes in water level in individual wells significantly exceeds the annual amount of precipitation.

– In Hungarian settlements it is hardly possible to find any ground-water level observation wells, which can be considered as having a free flow regime, when examined with the hydrologic-statistic method (examinations of consistency and homogeneity; Réthái 1974).

Fig. 1
Measuring water level, temperature and pH value of the ground-level observation well in Pécs

Fig. 2
Periodic water outflow in a retaining wall (Veszprém)

In water supply, that amount of water is regarded as lost, which is not usefully employed (e.g. flushing of the pipeline network). A spectacular but small proportion of this loss is generated by pipe ruptures, whereby a large amount of water increases water loss with great intensity but for a short period of time. Compared to these losses, smaller-sized defective sites (connections to houses, defects at junctions) cause the filtration of small amounts of water, but because there are so many of them and they go unnoticed for a long time (possibly even over several years), this may correspond to 60% of the sales balance. As an example, at a defective site with a diameter of 5 mm, water leakage amounts to 25 l/min, and such anomalies can occur at one or two places within a 1 km-stretch of pipeline. When not measuring the loss in a given area, the Hungarian waterworks companies apply a rule of thumb, which determines the loss as 10% of the water amount piped into (pipelines) or drained away (drains) from the area (Hajnal 2002, 2003; there are areas though which this proportion might be as high as 50%.)

Water balance calculation

This calculation method was elaborated for the Castle Hill quarter of Buda. The extent of the catchment territory of the Castle Hill totals 920,000 m^2; of this, the area of the Plateau is 400,000 m^2 and that of the Castle Slope 520,000 m^2. The calculation takes into account the pipeline input proportional to area. The area of the continuous cave system below the Plateau is 18,000 m^2 and the area of individual cavities can reach up to 4.000 m^2.

The schematic cross-section of the Plateau is shown in Fig. 3 and the flowchart of the calculation is presented in Fig. 4.

Calculation steps

Draining was calculated with a weighted draining factor $\alpha = 0.8$.
Precipitation on the area: P (m^3/year) = A_p (m^2) × P (mm/year);
The following initial losses from P are by: evaporation [$E = 1/3 \times P$]; drainage [$D = \alpha \times (P–E)$]; if $\alpha = 0.8$, $D = 8/15 \times P$;
Therefore, infiltration of precipitation is [$I_p = P–E–D$] or $I_p = 2/15 \times P$.
Loss by water-mains in the Plateau/(Plateau + Slope) area ratio:
$I_{wm} = (40/92 \times W)/10$ or $I_{wm} = W/23$;
Amount of water infiltrating from the loss of district heating: $I_{wdh} = 2/3 \times W_{dh}$;
Waste water loss from precipitation: $I_{pcp} = (0.9 \times D)/10$, $I_{pcp} = 0.048 \times P$;
Waste water loss from the water-mains:
$I_{wmcp} = (40/92 \times W–I_{wm})/10$, $I_{wmcp} = 9/230 \times W$;
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: $I_{pol} = 31/40 \times I_p$;

Fig. 3
Schematic figure of the water balance for the Castle Hill Plateau, Budapest

C – precipitation
P – evaporation
Be – infiltration
L – drainage
V_v – water conduit
V_{ta} – district-heasting water
V_{csa} – channell
V_{cse} – dripping waters
V_{bk} – cave wells
V_{ki} – water outlets

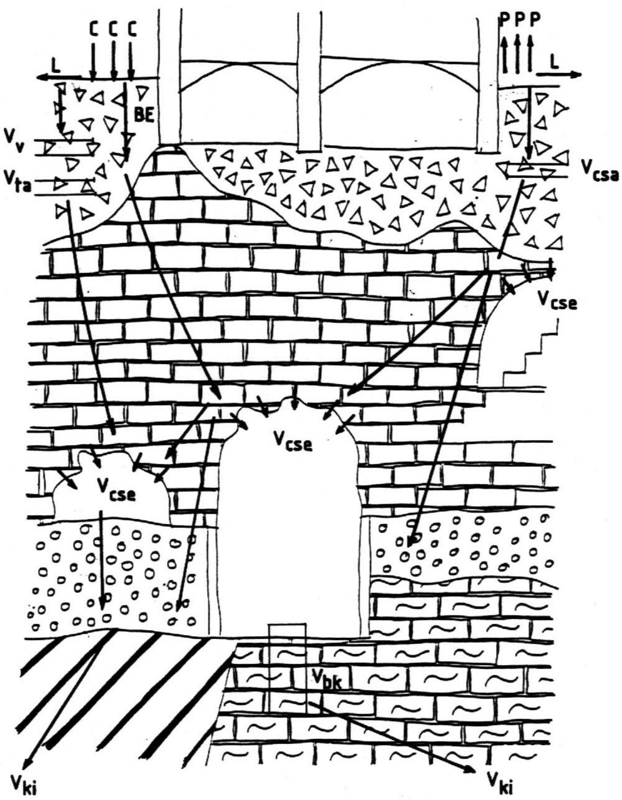
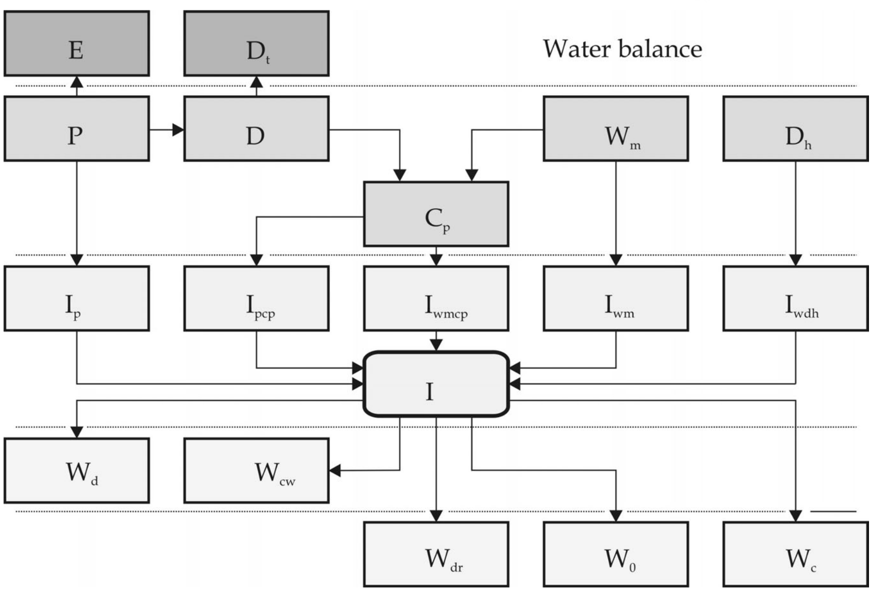


Fig. 4 ↓
Flow sheet of the water balance calculation that takes into consideration the effects of urbanization



All the water amount getting into the cavities: $I_{dc} = 22/310 \times I_{pol}$;
Out of this, infiltration into the Great Labyrinth: $I_{gl} = 9/11 \times I_{dc}$;
Water amount getting into the separate cavities: $I_{sc} = I_{dc} – I_{gl}$;

Results

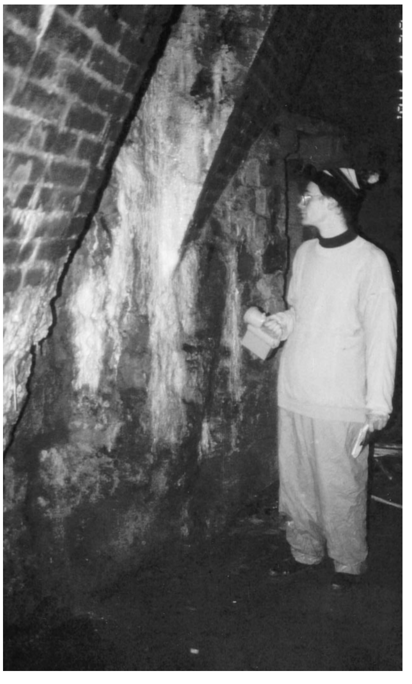
Each city has its own special character which modifies the flowchart. Significant differences can depend on whether the drainage system is unified or separated (Fig. 4 shows an example of a unified, and Fig. 5 of a separated system) and also on other parameters, which either increase or decrease water infiltration. An increasing parameter can, for instance, be a karst spring with high discharge (Fig. 6) or a system of cavities with public utilities (Fig. 7), while examples of decreasing parameters can be a system of tunnels with drainage (Buda), as well as backfilled cellars (Eger and Buda).

Retaining walls, drainage systems and pavements on the slopes also basically influence the water system conditions (Figs 8, 9).

The method elaborated for Castle Hill of Buda has been expanded to apply to some additional Hungarian settlements. The most important initial data and the rates connected to infiltration are shown in Table 1.

Fig. 5
Precipitation drainage ditch (Pécs)

Fig. 6
Karst spring "Tettye" in Pécs



There are large differences between the urban areas in terms of being researched, mapped and the recording of data; therefore the initial data of our calculations are not always exact, but the order of magnitude can be considered correct (for example, when determining the size of an area, the precision of the maps is of capital importance, especially in the case of caves and caverns. Similarly the public utility parameters such as transport distance and quantity of water delivered are not entirely exact values; therefore the results deriving from these data cannot be either. Water-supply data are much more reliable than those of sewerage.)

Fig. 7
The cave system of Castle Hill of Buda; water inflow deriving from defective public utilities

Fig. 8
Soaked retaining walls in the castle of Veszprém

Fig. 9
Wet narrow passage in Veszprém

Table 1
Calculation results for seven areas

Examined area / Data	Castle Hill of Buda		Rózsadomb		Budafok	Kőbánya	Eger Hajdú-hegy	Pécs		Szentendre Szamár-hegy
	Plateau	Slope	József Hill	Csatárka				Forrásvölgy	Tettye-völgy	
Rock	Travertine	Buda Marl	Travertine, Buda Marl, Kiscell Clay		Limestone	Limestone	Rhyolitic tuff	Travertine, Limestone, Marl		Andezit, Rhyolitic tuff
Area (m^2)	400,000	520,000	1,652,900	2,518,035	8,760,000	1,770,000	4,500,000	145,910	573,200	672,000
Cavern, cellar (m^2)	22,000	-	58,500	134,880	420,000	195,000	12,000	500		47,000
Precipitation (mm/years)	540		513		525	552	647	688		751
Water input (m^3/years)	568.755	739.381	1.190.203	2.506.222	3.550.333	1.067.012	1.683.394	58.688	151.709	300.425
Water input/Area	1.42	1.42	0.72	0.99	0.40	0.60	0.37	0.40	0.26	0.45
Infiltration (m^3/years)	150.270	192.920	400.656	709.730	1.207.213	385.113	685.725	32.100	93.389	117.977
Cavern, cellar	8265	-	14.180	38.017	57.880	42.427	1828	223		8251
Infiltration/Water input	0.264	0.371	0.337	0.283	0.340	0.361	0.407	0.547	0.615	0.392
Infiltration/Area (mm/years)	376	371	242	281	137	216	152	220	163	175
Infiltration/ Precipitation (%)	70	69	47	55	26	39	23	32	24	23
Length of water pipeline (m)	4.000	4.375	18.418	25.750	98.740	17.420	80.475	3.470	8.970	3.600
Length of water pipeline /Area	0.010	0.008	0.011	0.010	0.011	0.010	0.017	0.023	0.015	0.005
Specific loss	1.62	1.93	0.81	1.11	0.38	0.70	0.24	0.19	0.19	0.95
Calculation/Measured (m^3/h/km)	*0.54*		*1.05* *0.69*						*0.58*	
Years	1996–2000		1992–2001		1999–2004	1999–2005	1995–1999	1994–2003		2005

Water input data was provided by the waterworks of the cities. The examined areas did not overlap with the input ones (zones), so the quantity of water in our areas has been determined by scaling (in all cases proportional to the area size, except for Pécs, where the length of the pipeline was used).

Table 1 shows that the ratio of input divided by the area is highest on Castle Hill (1.42) and on Rose Hill (0.72, 0.99), while the lowest is in the Tettye Valley (0.26). This figure (input/input area) basically depends on the conditions of the built-up environment. It is interesting to compare the input/input area figures with the length of pipelines/area quotients; these are quite similar in the different areas. In percentage terms we can say that the length of pipelines covers 1% of the built-up areas (in summary: water must be delivered everywhere, but in different quantities.)

Correlating total infiltration to water input has been found to be important, due to the fact that water input is of the highest importance among all the input data; this is because it basically determines pipelines losses as well as wastewater losses. Infiltration/water input values are very close to each other; generally they are around 0.3 and 0.4. The distinct value in Veszprém might have been caused by inexact initial data, while in Pécs the special location of the area and the operation of the karst spring might be the reason behind the high figure. It is also shown that when the water input/area value is high, then the infiltration/water input is low and *vice versa*: if the former value is low, the latter is high. This has a simple computational reason: in both quotients there is water input, first in the numerator, then in the denominator.

Specific losses are measured by specialized companies; therefore, where such data was available they were compared with our calculations. This figure reflects the condition of the pipeline (thus only infiltration coming from the water losses is taken into consideration); therefore a possible repair job can significantly change the situation. In the period of our examinations the pipelines in worst condition were on Castle Hill, on Rose Hill, and in Szentendre; there have been major reconstruction works performed in the Castle area since then, so today much better results would be obtained.

The table also shows total infiltration (mm/year) divided by precipitation. This ratio expresses to what extent urbanization (public utilities) influences infiltration conditions, and consequently water balance. The urban character of the settlement does not cause significant changes in Kőbánya, Budafok and Pécs, while in the case of Castle and Rose Hills, as well as in Veszprém Castle, the amount of infiltration could double. In Szentendre and in Eger the value is specifically low.

Due to the increasing building density and area of pavements it is necessary to take higher runoff factors into account, which reduce direct infiltration; simultaneously, however, public utilities are also being expanded, the losses of which increase infiltration. The joint rate of the two influences is expressed in the percentage ratio.

The significance of the types of rocks in the areas would be much higher without road surfaces, but in small areas, in the case of damaged buildings and movements of supporting walls, it might still be important to be aware of the perviousness, structure and the fracturing network of the rocks.

Summary

The water system of a given settlement is basically determined by the losses of the public utilities. Anthropogenic waters endanger the built-up environment, the monuments, as well as the natural values of a city. A water calculation method that takes into consideration the effects of urbanization can provide useful data for the necessary regional planning, environmental protection actions and the establishment of a monitoring system.

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References

Hajnal, G. 2002: New method of calculating water balance for the Castle Hill, Buda. – Acta Geologica Hungarica, 45/4, pp. 385–402.

Hajnal, G. 2003: A budai Várhegy hidrogeológiája (Hidrogeology of the Castle Hill, Budapest). – Akadémiai Kiadó, Budapest, 129 p.

Hajnal, G. 2005: Talajvíz és közmű, Természetes és mesterséges hatások a talajvízjárásra Budapest területén (Groundwater and public utilities, Natural and artifical influences on ground water level in Budapest). – Mélyépítés, 3, pp. 16–21.

Hajnal, G. 2006: Water balance calculation method for urban areas, examples from Hungary. – IAEG 2006.

Réthári, L. 1974: Talajvíz a mélyépítésben (Ground water in civil engineering). – Akadémiai Kiadó, Budapest.