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Geothermal Budapest

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ABSTRACT

Hungary is known for its good geothermal potential and Budapest, its capital, is especially well provided for in this regard. Thermal water has been used there since ancient times and even now its famous spas are a major source of Budapest's popularity among tourists. Until recently, however, there was no accurate yet practical publication to comprehensively and graphically describe the geothermal resources of Hungary and its capital. This was remedied in 2016 with the publication of the Geothermal Atlas of Hungary, which was followed by a similar geothermal atlas for Budapest in 2019. Both atlases were commissioned by the Hungarian Energy and Public Utility Regulatory Authority (HEA). The Budapest geothermal atlas aimed to comprehensively analyze the city's geothermal energy potential while suggesting possible ways to satisfy Budapest's heating and cooling demands. The scale of this ambitious and difficult project required specialized contributions from a range of professionals, including geologists, hydrogeologists, civil engineers, architects, and city planners.

1. INTRODUCTION

Hungary's thermal-water resources are world-class in terms of their quantity, quality and usability. Furthermore, no capital city in the developed world has as many working and historically significant thermal baths as Budapest. It may be fairly said that enjoying the city's many historic baths is among the most cherished and popular experiences for Budapest's visitors, whether foreign or domestic. As with most cities blessed with abundant thermal-water, that resource's geothermal energy is used mostly to heat spa pools. In many cases, therapeutic value is attributed to the spas' mineral-rich water, often bottled and sold separately for that purpose. Such is the case at the famous Gellért baths.

Although the relative location and height of Hungary's hydrothermal sources have changed since their distant origin, the hydrogeological processes that created them have not changed. This has ensured the continued existence of these geothermal phenomena. Over the last half-century, Hungarian geologists and geographers have done important work researching the origins of the many thermal water sources found along the Danube. Although Budapest's thermal water is not of volcanic origin, this tempting hypothesis could not be disproved until many 'dry-land' and riverbed drilling samples had undergone extensive hydrological and tectonic testing. Meanwhile, the effect of human construction has become ever more significant, especially intense in larger urban agglomerations such as Budapest. Such construction and excavation has led to significant changes in thermal water flow not only at the surface, but also among the deeper storage rocks.

2. HISTORICAL USE OF THERMAL WATER IN BUDAPEST

Hungary's warm and lukewarm springs came about during the Tertiary, i.e., during the late Pliocene period. When trapped during the ice ages, large tropical animals such as hippopotamuses found their last refuge in the hot springs of the Pannonian Basin. In a melancholy echo of these last oversized survivors, almost equally adipose humans find refuge in those same baths, but as an escape from what many consider human-induced global warming.

In Buda and Obuda, along the shores of the Danube, readily available thermal water has been used since pre-historic times. On the Danube's western shore and on nearby islands, one sees evidence of the Roman era's Aquincum baths, such as the still active Thermae Majores near the Árpád bridge (Horvath, 1986). That spa's flow system still operates largely as designed by the original Roman engineers. Near what is now the Lukács spa, a cloister and spa was established in the 12th Century to treat the sick, first under the aegis of the Knights of St. John, then by the Knights of Rhodes and Malta. In the renaissance era the 15th Century Hungarian king Matthias Corvinus founded the Rác spa, still functioning and delivering 40 ^{o}C water.

During the Turkish occupation which followed in the 16th Century, many additional spas were developed: the Király (King's) spa by Pasha Arslan; the Rudas spa by Pasha Mustafa Sokoli; and the Császár (Imperial) spa by Bey Veli. Notably, the Turks also used the thermal water's energy to mill grain and produce gunpowder. From 1868 to 1877, geologist Vilmos Zsigmondy directed the drilling of what was then Europe's deepest well (971 m) in the Városliget (Budapest's largest city park). More importantly, in practical terms, Zsigmondy's drilling project brought forth 74˚ C medicinal water. In 1938 this became the source of the world-famous Széchenyi spa, whose waters heat the spa's extensive building complex as well as a nearby zoo.

At present, Budapest has 19 thermal baths, 13 of which are officially 'therapeutic,' i.e., containing water with a mineral content officially certified as therapeutic. Over the years, Budapest's spas and their 32 km. of distribution pipes have of course required continual maintenance and modernization, quite apart from the idea of deriving additional benefit from their combined heat energy.

Modern Budapest only began using its thermal-water energy more efficiently in the 1930s, when thermal water was piped from beneath the Margit bridge to the Pest (eastern) side of the Danube, to provide heating for Pest's largest apartment building. The devastation of WWII unfortunately put an end to these promising experiments. It wasn't until 1949 that the new Communist government began various similar projects, successfully using left-over thermal water from free-flowing wells to pipe the water directly to buildings' heating systems. These projects have all occurred in an ad hoc manner, with no attempt to more efficiently organize them into a more rational district-heating network. This is still true in 2020, even as there are ever more examples of Budapest using its thermal water to provide residents with hot water for bathing, for space heating as circulating hot water, or for heating/cooling in conjunction with heat pumps.

3. BUDAPEST'S CURRENT ENERGY DEMAND AND SUPPLY

In 2019 the Hungarian Energy and Public Utility Regulatory Authority (HEA) commissioned a thorough study of greater Budapest's geological and geothermal conditions. The aim was to determine how to best use Budapest's geothermal energy resources, for the purpose of providing clean and affordable district heating to the capital's private, business and institutional consumers.

84% of Budapest's energy use is currently derived from fossil fuels. More specifically, 38.8% of the city's electricity production and 95% of its district heating comes from oil or natural-gas combustion. 40-50% of the city's total energy is consumed by individual households. In 2016, Budapest's total primary energy consumption was 142.78 PJ, with a per capita primary energy consumption of 81.15 GJ.

Budapest has four combined heat-and-power plants, in Csepel, Kelenföld, Kispest and Újpest. The city's heat demand is met by both district heating and by natural gas supplied directly to residences. The increase in district-heating supply began in the late 1950s, with the construction of many large apartment complexes.

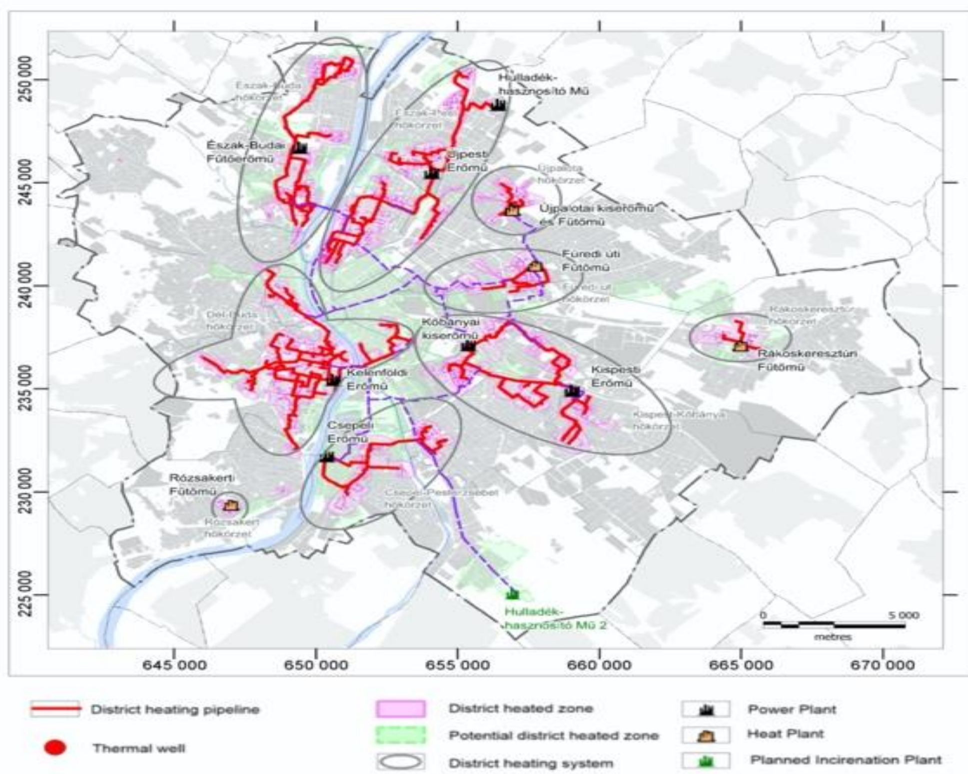

Figure 1: District heating system locations in Budapest

The salient features of Budapest's district heating system are:

- The provision of several hydraulically independent district heating zones, each based on one dominant heat source;
- Significant reserves of heat production capacity, even after much intense development;
- A significant percentage of the heat supply from highly energy-efficient cogeneration, i.e., power *and* heat generating plants, an environmentally friendly solution (most of these burn natural gas, unfortunately, but one is a bio-fuels plant);
- Waste combustion, which contributes 0.632 PJ to the heating grid;

– A district heating system which was developed parallel to and independently of the natural gas grid, and therefore bears the additional cost of a parallel infrastructure.

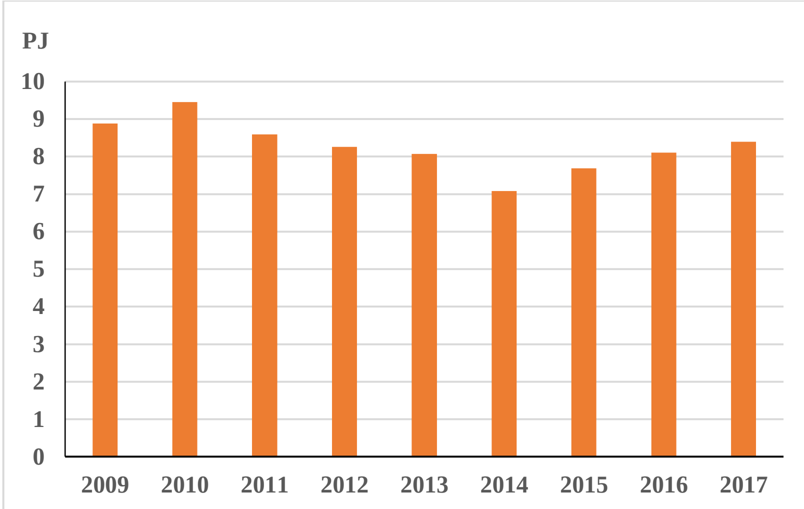

Figure 2: Total residential district heating in Budapest

4. THE GEOLOGICAL STRUCTURE AND HYDROGEOLOGY OF BUDAPEST

Budapest overlaps several distinct geographical regions. For geothermal purposes, the city can be divided into three major areas, each distinguishable by its particular geography, topography (height), human population density, and man-made changes to natural conditions.

The three main "geothermal recovery regimes" in Greater Budapest are:

1. The Buda Hills, which are geothermally fairly weak;
2. Lowland and hilly areas in Pest and on islands in the Danube such as Csepel, generally characterized by above-average geothermal features;
3. Everywhere else, including an upland zone with extremely variable geothermal conditions, from weakest to strongest.

Figure 3 is a geological/geothermal cross section which shows two 100-meter deep geothermal holes. one on the Buda side (West) and the other on the Pest side (East). Most of the holes drilled in Pest went through easily penetrated, almost horizontal clay tertiary layers. In the hillier areas of Pilis and the Buda Hills, however, there was only hard-rock drilling. In such conditions, where the drill can unexpectedly encounter faults and caverns, there is naturally a much greater risk in terms of higher economic costs, ambiguous results and even accidentally-induced environmental hazards.

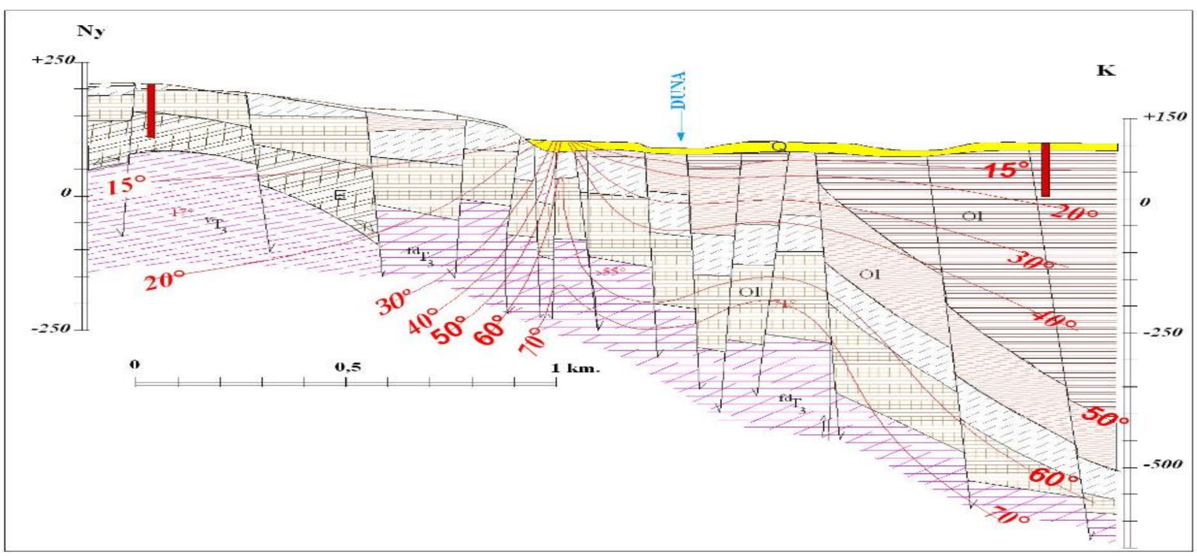

Figure 3: Typical rock temperatures and layers from the Buda Mountains to the Pest Plain (Lorberer and Toth, 2017)

(purple = Triassic, light brown = Eocene, dark brown = Oligocene, yellow = Quaternary)

Budapest's geology is characterized by 5 major rock types:

1. The main karst reservoir of the middle and upper Triassic level, which is very thick and constitutes the most significant part of the Transdanubian Mountains;

2. The Eocene (55-35 million years old) limestones and marls;

3. The Oligocene (35-25 million years old), a water-impermeable clay-marlstone and sandstone formation which effectively separates the near-surface cold-water aquifer from the thermal main karst water reservoir – very important from the geothermal point of view;

4. The Miocene and Pliocene, mixed sediments with Pest-specific Neogene overlays and containing varying amounts of volcanic tuff;

5. The Quaternary, the youngest, made up of loose sand-pebble river sediments, run-off sand, and loess deposited on the elevated parts -- and forming near-surface layers where it is buried under manmade earth and waste dumps.

5. GEOTHERMAL RESERVOIRS IN THE AREA OF BUDAPEST

There is a well explored and equally well documented Triassic karst reservoir location along the Danube near Buda, at a depth of 1100 to1600m. The Triassic sediments' cap rock is Eocene marl or limestone, usually part of the fractured karstic reservoir. Here, drilling sometimes finds a good geothermal source at relatively shallow depths. Figure 4 shows the estimated cap rock level of the Triassic main karstic aquifer; Figure 5 shows the cap rock level of the Eocene layers. Although as yet unproven, it is assumed that there is a sufficiently thick intermediate water barrier between the Triassic and Eocene aquifers (the Kosdi Formation).

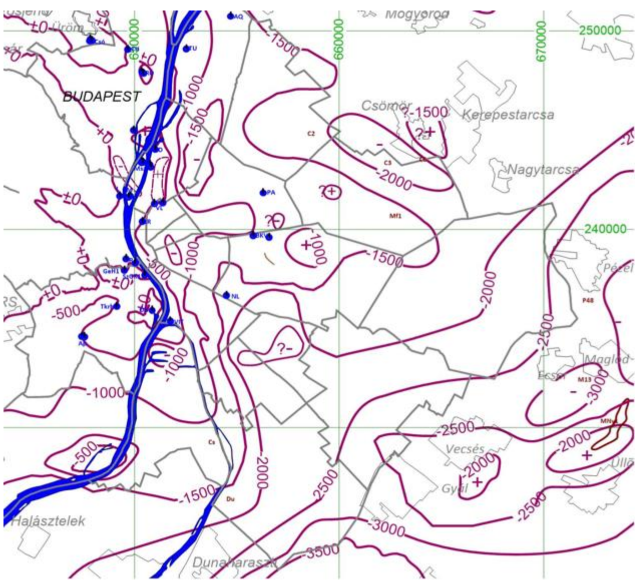

Figure 4: Triassic karst reservoir's cap rock level

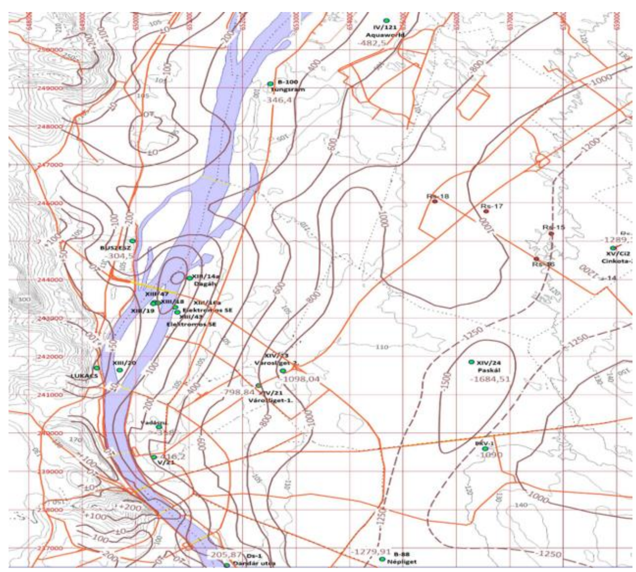

Figure 5: Eocene karst in north Pest

The karstic reservoir's temperature distribution can be estimated from the temperature profiles measured during well-drilling and again later, based on production water outflow temperature. The temperature distribution in southern Budapest is narrower, since most wells there produce little or no thermal water. No thermal wells have been established in the eastern deep basin. In the northern half of Budapest, however, there are wells producing thermal water from natural springs (e.g., City Park, Dagály).

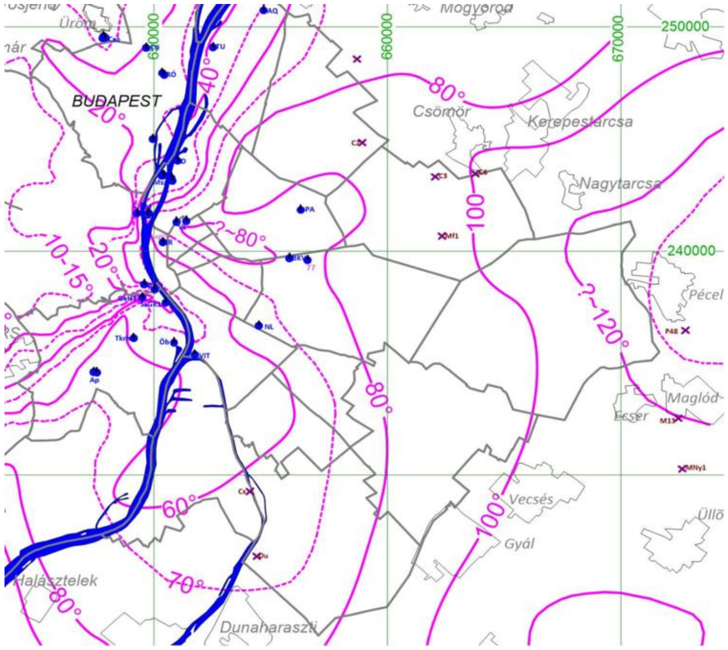

Figure 6:. Estimated heat distribution in the karstic reservoir, showing temperature gradients (Lorberer and Lorberer, 2006)

6. EXISTING GEOTHERMAL WELLS IN GREATER BUDAPEST

85 geothermal wells are registered in Pest county, which includes Budapest. 59 of the 85 are in Budapest alone. Figure 6 shows Pest county, and Figure 7 shows only Budapest. Budapest's geothermal wells have a temperature range of 30 to 76 ° C, and depths ranging from 2.2 m. to 2 km. District 11 has the shallowest well, which flows freely from a depth of only 2.2m and has a water temperature of 42 ° C. District 22 has the deepest well, which is slightly deeper than 2000 m and has an outflowing water temperature of 52 ° C. The wells producing the hottest water temperature (76 ° C) are in District 24, with a depth of 900 to 1200m. Looking at where Budapest's thermal wells are located, it's hard to see a generally valid geothermal gradient distribution.

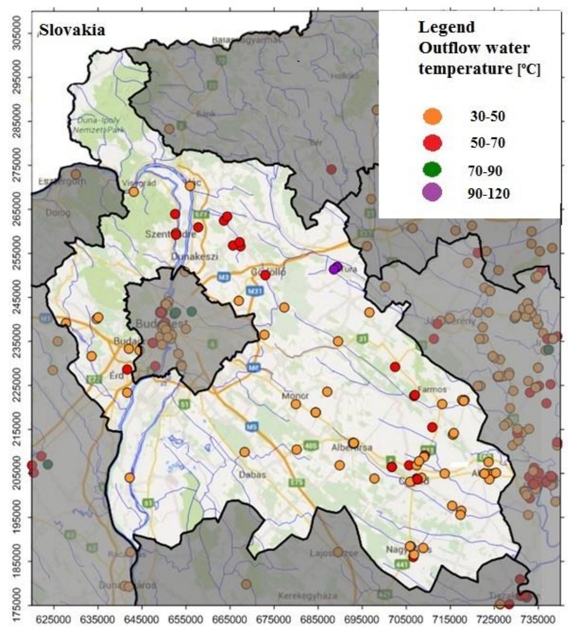

Figure 7: Registered thermal wells in Pest County

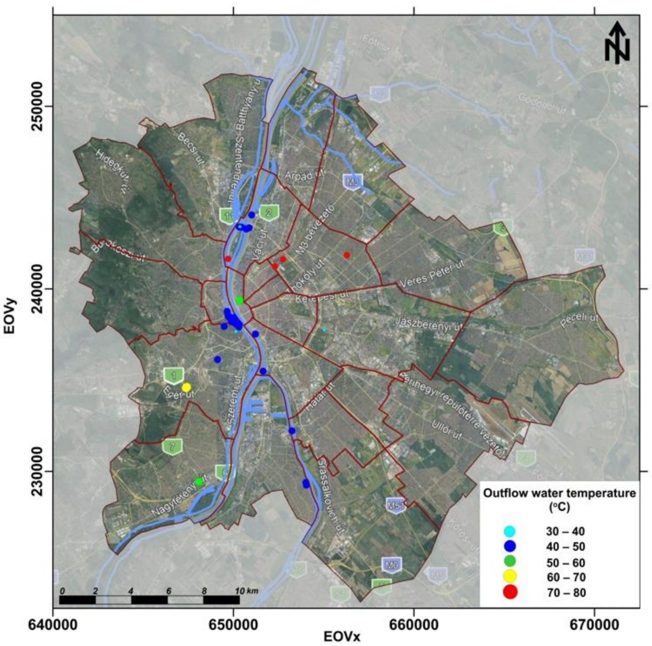

Figure 8: Registered thermal wells in Budapest

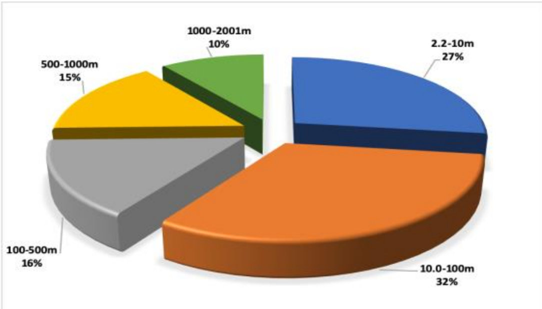

Figure 9: Depth of Budapest's thermal wells

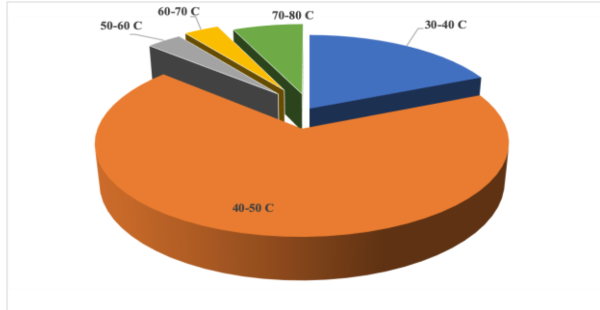

Figure 10: Thermal-well temperature distribution

Apart from the 85 wells noted above, there are another 113 wells yielding water 30 ^{o}C or colder, from a depth of 2 to 120 m. Although these wells do not produce thermal water -- strictly speaking -- they might still be geothermally useful, possibly in ground source heat pump applications.

7. GEOTHERMAL DEVELOPMENT OPPORTUNITIES IN BUDAPEST

7.1 Procedures for minimizing drilling, production and re-injection risks

There are significant risks -- geological, hydrogeological and economic -- involved in drilling through Budapest's main karst-reservoir system to develop geothermal applications. Over the last thirty years much has been published about these risks and about potentially adverse effects in connection with the numerous different investment plans, reports and studies that have been proposed regarding geothermal development. Unfortunately, despite warnings from professionals, there are still too few laws regulating geothermal development in Hungary, and too little enforcement of existing laws. It is still not automatic, for example, that geothermal projects invest in the reinjection required to preserve their geothermal reservoirs' longevity.

7.2 Opportunities for the geothermal exploitation of Budapest's main karst reservoir

Contrary to long-held beliefs, wells drilled into Hungary's karstic reservoirs seem to yield better results and better flow rates than those drilled into porous systems, such as the older wells in Szeged or Szentes. The successful example of the Veresegyháza well shows that the karst water's gas content and salt content (TDS: 1250-1450 mg/l) is within acceptable levels, allowing produced water to be used safely and profitably.

Depending on geothermal conditions and local regulations, there are three main methods for the main karst water reservoir for geothermal applications:

1. Using the heat pumps to recover heat from water that has already heated spas – a method already being used in several Hungarian spas

2. Drilling production and injection doublets – a system currently in use in Örs Vezer Square.

3. Capturing more of the thermal upflow from the Danube's riverbed, to bring the thermal water on shore as is being done at Gellert Hill or Óbuda Island; or to concentrate the warm water already flowing into the Danube into a confined area of the river, where it could be used as a winter river-bathing resort – the last does not yet exist, but has been unofficially suggested by Mr. Attilla Nyikos of the Hungarian National Energy Authority.

Another interesting geothermal opportunity involves the possibility of helping cool businesses and residences around the Buda Hills. There, 8-26 ^{o}C karst water can be produced constantly, which could significantly help air-conditioning in an area where, like many cities in Europe, builders have not yet adapted to >40 ^{o}C summer temperatures. Theoretically, if such a system could be shut down every spring and autumn (when there is no cooling demand), a cold-water well and a deep hot water well near the Buda Hills could be used as an alternate production/injection system for cooling in Budaörs.

In downtown Budapest, the main technical barrier for any large-scale geothermal project is the sheer urban density and physical complexity of an area divided by streets, squares, underground garages and subway tunnels. This means that designing and building a network of insulated, high pressure pipelines connecting production and injection wells could be a difficult, risky and expensive proposition. Construction costs would be vastly greater than well-drilling costs – which is itself a significant expense. Any such deep-geothermal project would also have to deal with the reluctance of landowners to cooperate. Generally, it would be logical to place a doublet's production well and the injection well on two widely separated sites, but that would require a continuous, long-term working relationship between what are likely to be two different owners, possibly separated by additional property owners. In these cases, experience has shown that cooperation is an unlikely prospect.

7.3 Maximizing the chances of a successful thermal-water exploration, based on the projected amount of geothermal water

In utilizing Budapest's main karst water reservoir for geothermal, the challenge is twofold:

1. To find and successfully develop geothermal wells which produce warm enough water at a high enough flow rate.

2. To profitably maintain the reservoir, the well, the well-head and its distribution system over the long term.

Luckily, the vast majority of Budapest's karst wells have been successful, and in most cases are capable of producing even greater quantities of water. The expected flow rate from a Budapest karst well is at least 500 l/min, but maximum tested flow rates at the Dagály Bath in Buda and the Paskál Fountain in Pest (Figure 8) have reached 6000 l/min. Their average flow rate is about 1500 l/min.

For heating purposes, best practices generally require at least 3000 l/min of thermal water. Luckily, two of Budapest's karstic wells meet this requirement. In Veresegyház, about 30km from Budapest, the associated injection well can absorb the total water of three production wells with a flow rate of more than 3800 l/min.

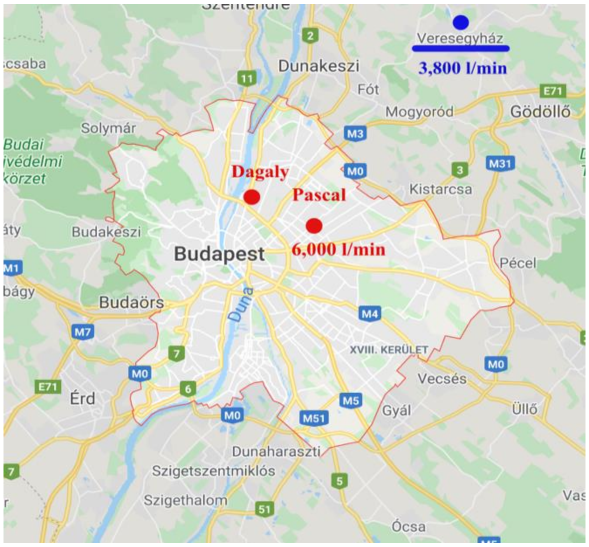

Figure 11: Springs with high flow rates in Budapest

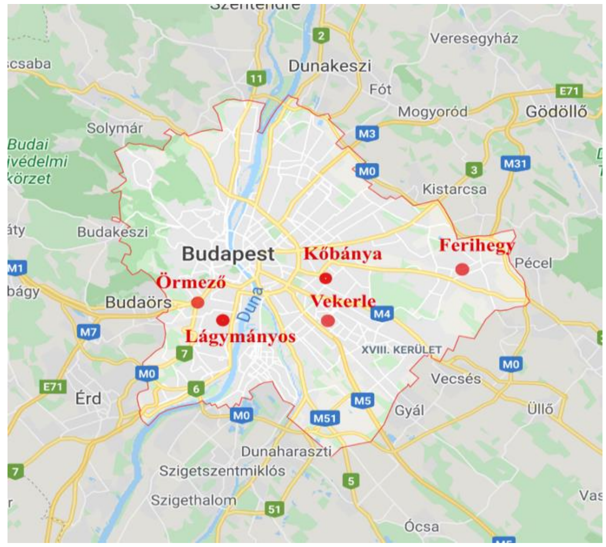

Figure 12: Sites of potential sources and consumers

7.4 Recommended geothermal investments in Budapest

Although the thermal-water reservoir lies near the surface in and around Budapest, and along the Danube, these areas already have many thermal spas, often very close to one another. Production from these wells continues to influence the natural water flow. To keep from interrupting their supply, and to prevent further damage to the reservoir – for which there is still no coherent and reliable reservoir model – responsible geothermal investment requires special care.

From the purely economic point of view, potential investors and consumers must take into account not just water temperature and drilling depth, but several other factors as well. These are all shown in the Table 1 below, and are applied to some of the Budapest area's most promising geothermal sites.

Location	Őrmező	Lágymányos	Vekerle-telep	Kőbánya-Kispest	Ferihegy
Type of Facility	Housing complex	Housing complex	Housing complex	Factory complex	Airport
Karst water production	Good	Excellent	Poor	Uncertain	Good
Geological risk	Minimum	Minimum	High	High	Average
Expected temperature	~60 ^{0}C	~45 ^{0}C	50-70 ^{0}C	70-80 ^{0}C	90-105 ^{0}C
Expected drilling depth	700-1000 m	~200 m	~900-1300 m	~2000 m	~2500 m
Population	High	Average	High	High	Low
Heat demand	Significant	Significant	Significant	Significant	Moderate

Table 1: Promising geothermal sites in Budapest

7.5 Unique and Unconventional geothermal-use possibilities in Budapest

7.5.1 Large-scale geothermal storage in unused Sarmatian-epoch limestone cavities

In SE Pest the area of Kőbánya (quarry) contains an extensive and often interconnected network of caverns and cellar systems, more than 32 km. in total length. They were used for storage by the Dreher beer company from 1862-1892 because of their constant temperature and coolness, but are nowadays flooded with ground water (see Figure 14). They remain abandoned and unused, except for some enterprising individuals who lead tours there. This enormous water-filled cavity could be a great opportunity to create one or more geothermal systems. In conjunction with a series of heat pump systems, a geothermal development here could exploit the inherently great heat transfer potential, while at the same time mitigating the area's chronic flooding – a big problem for local residents, and compounded by the recurring flood danger posed by the Danube. A project of this magnitude would of course require a thorough assessment of current conditions, followed by careful impact assessment and modeling of the different geothermal-project possibilities.

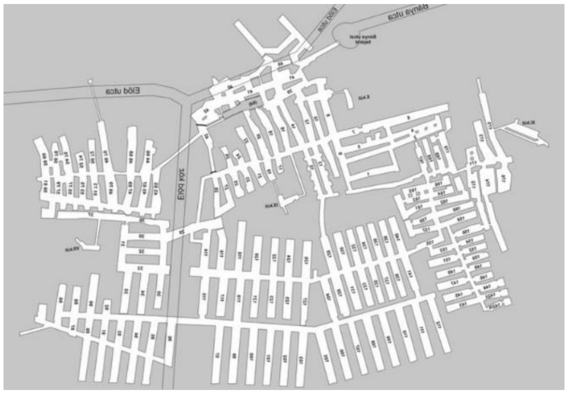

Figure 13: Cellar system in Kőbánya [1]

Figure 14: Flooded cellar in Kőbánya district [1]

7.5.2 An overlooked karst spring in the Danube riverbed

In 1974, a small, uninhabited island (known only as Fürdösziget or Bath Island) in the Danube was dredged out of existence to ease shipping. This island just northeast of Margitsziget (Margaret Island) had a valuable natural thermal spring, which after the island's destruction has simply emptied into the Danube unused for the last 45 years. Redeveloping this abandoned geothermal resource would have the following advantages:

1. It is almost on the surface, only 110 meters from the shore of Pest.
2. It flows freely, so producing the artesian water it discharges requires little investment.
3. As the used, cooled thermal water can be sent back into the river, there is no need for reinjection, and the Danube's water quality would not be affected.
4. The production water's temperature can be adjusted by water drawn at the same time from the Danube, thus optimizing heat-pump temperature in both winter and summer. The energy efficiency factor (COP) of such a "warm" hot-water system can be very high, between 6 and 10.
5. A thorough underwater investigation of the site was undertaken in 2016, including a seismic test of the rock beneath the hidden spring, as shown in Figure 16.

Figure 15: Hidden spring in the Danube riverbed

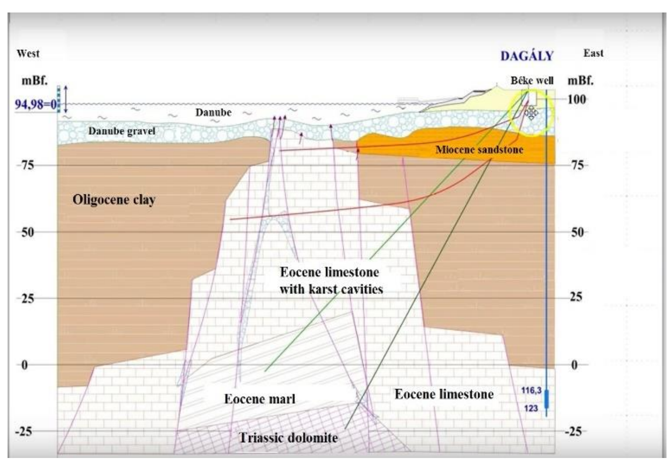

Figure 16: Rock type under the hidden spring (Lorberer, 2017)

8. CONCLUSION

Budapest's many geothermal wells vary greatly in terms of their efficiency, water amount and water temperature. Similarly, the conditions for ground, pond or river heat-pump usage vary significantly from place to place, depending on the particular geology and urban conditions. Nonetheless, it can be said that Budapest has exceptionally good geothermal properties on the whole.

Why then has geothermal production and development lagged behind expectations? There are several reasons: 1/ the country's economy; 2/ although Hungary's geothermal wells can only produce insignificant amounts of very expensive electricity (given the current state of technology), the lure of cheap geothermal electricity has sometimes led to poor geothermal development choices; 3/ Hungary does not have a systematic approach to helping spa operators derive maximum economic benefit from their wasted spa-water energy; 4/ until the 2019 publication of the Budapest Geothermal Atlas, the lack of an accurate, reliable, and comprehensive map of Budapest's geothermal resources has denied city leaders the information they needed to start drawing up a consensual agreement about how to develop Budapest's geothermal resources.

To ensure the responsible development of the city's geothermal patrimony, especially along the Danube, it is vital that a uniform protection area be created for Budapest's existing thermal springs. This would also require a complex risk assessment of the city's geothermal aquifers, for which the necessary research expertise and experience is fortunately available. After having fulfilled those conditions, many of the geothermal development projects proposed in this article would have a much better chance of succeeding.

ACKNOWLEDGEMENTS

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