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**RESEARCH ARTICLE**

# Evaluating climate change impacts on water safety: A case study of the Danube in Budapest

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***Abstract*** **-** The study examines the impact of climate change on the example of the Danube as a drinking water base in the Budapest area. The drinking water supply provided by river bank filtration systems is exposed to more frequent water level fluctuations and temperature changes in the connected surface waters. Our goal was to identify the most critical periods within the year by evaluating the daily water level and water temperature data between 1943-2021 and 1947-2021, respectively.
It is important to understand the severity and frequency of climatic changes influencing drinking water safety. This aim can be achieved by evaluating the identified risks. Furthermore, as these risks affecting drinking water safety change significantly within a year, attention is drawn to the important role of both residential and industrial water use patterns. The minimum level of water safety determined for the period of increased load is of indicative value, based on which it becomes necessary to develop appropriate action plans.
Based on statistical methods, it has been previously identified that the average water level of the Danube showed a decreasing trend in addition to an increase in water temperature. In this paper, we demonstrate that the water level fluctuations and the temperature changes follow an annual pattern. By superposing these patterns in an additive risk matrix, critical periods can be determined and, therefore, play a significant role in the time planning of larger maintenance or investment tasks. The study did not aim to evaluate in detail the investigation of other ecological, economic, and social effects of climate change related to drinking water safety for reasons of scope.

***Keywords*** – drought and flood events, riverbank filtration, threats on drinking water safety, water temperature

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## 1. INTRODUCTION

Water occurs in many forms on our Earth (Jaganmohan, n.a.). Oceans and seas make up more than two-thirds of the surface. 96.5% of the total water resources are found in seas and oceans, whereas only 2.5% is fresh water. About 2/3 of this freshwater is locked in glaciers and ice caps of the poles, making it virtually inaccessible. The easiest and most economical way to use water for human purposes is groundwater, water from lakes and rivers, and a part of atmospheric moisture.

In other words, even though water is one of the most common compounds on Earth, drinking water is appallingly scarce. With the development of our society, as well as with the development of technology and the growth of the human population, albeit at a slower rate (RVPP, 2022), the demand for water is increasing. Based on relevant UN research, the population's growing trend is expected to reverse in 2024.

From the point of view of water availability, it is important to consider the type of water shortage that may occur. On the one hand, in many regions of the world, the physical presence of water is scarce. In other words, it is not available in sufficient quantities to satisfy the water demand. These countries are typically located in the Middle East and the Sahara (Roser et al., 2013). On the other hand, in many cases, it can be observed that although water is available in sufficient quantity, its quality does not meet the needs of consumption. Some examples can be listed as though seawater is available, but it cannot be used for irrigation, or there is no sufficient amount of drinking water available on the banks of large rivers because adequate infrastructure for water transport and/or water treatment technologies are absent (water.org). In terms of the availability of drinking water, communities in the Sub-Saharan regions and Southeast Asia are the most exposed (Figure 1) (Roser et al., 2013). Access to safe drinking water in 2020 was the lowest in Chad at 5.59%. A more serious problem is that in 2000, this value was 5.64%, meaning that access to drinking water in the country was almost stagnant at a very low rate for twenty years. In the central regions of Asia, it can also be observed that although the access rate to drinking water is higher, the twenty-year trend shows a setback. In the case of Nepal, for example, this value means a decrease of about 9% between 2000 and 2020.

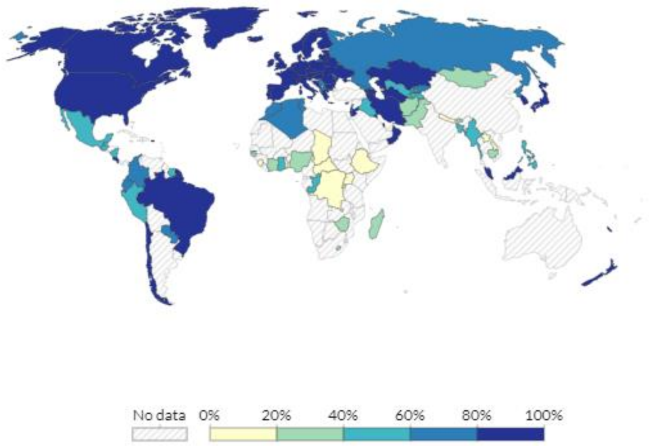


**Figure 1. Distribution of the world population having access to safe drinking water in percentage in 2020 (Roser et al., 2013)**

Specifically, in the case of Hungary, the three main water sources are underground water resources, rainfall, and rivers. The key to the depletion of our water resources is to be found in the main effects on the water resources.

Examining the meteorological trends of the past decades and based on the results of an available scientific project (LIFE-MICACC project, 2021), it can be said that Hungary is moving forward on the path of slow but sure drying out by an amount of 7 km$^3$ water per year.

The target of this paper was to evaluate the trends of determined climatic effects on the examined river bank filtered watershed. Also, it was important to explore the related aspects of drinking water safety related to the expected changes and their mechanisms of action.
Therefore, the work focused on to deter
mine the main tendencies in the change of the average annual water level and water temperature of the Danube and the trends of outliers. These outliers can be identified as various natural disasters connected to climate change, like floods, severe droughts, or other unexpected events related to natural extremes.

### *1.1 Riverbank filtration*

In Hungary, one of the most important processes related to drinking water production is riverbank filtration (RBF). 30% of the operating water resources and over 50% of prospective water sources are based on RBF (Hungarian River Basin Management Plan, 2022). Therefore, this technology is key in securing safe drinking water for the Hungarian population. Also, RBF is the most sustainable water production technology compared with any other alternative. RBF is applied in Hungary along the riverbanks of the Danube, the Mura, and the Hernád Rivers.

The Danube, which provides the capital's water supply, is the most international river in the world. Its catchment area is 801,463 km2, covers 19 countries, and is about 2,850 km long. It originates at the confluence of the Brigach and Breg rivers near Donaueschingen and flows into the Black Sea. The profession divides the Danube catchment area into three larger units. The Upper Danube stretches from its source to Bratislava. The Middle Danube section is located between Bratislava and the Iron Gates (Vaskapu) in the Carpathian Basin. The section of the Lower Danube stretches from the Iron Gates to the Danube Delta (ICPDR, n.a.).

RBF is a pump-induced water treatment process based on the generated water pressure gradient. By definition, over 50% of the extracted water must originate from surface water, taking into account extreme environmental effects. The source water is generally a lake or river – the Danube River, in the case of Budapest (Hiscock, 2002). Through filtration, the water quality is improved by complex physico-chemical and microbiological processes (Teng, 2020). As the system directly communicates with the source surface water, any major influence occurring to that media affects the riverbank filtrate as well. Hence, every RBF system and water base is considered vulnerable, meaning that environmental factors such as climate change, environmental pollution, and disaster risks should be considered while drinking water safety risks are assessed.

Based on the present professional knowledge, it can be established that the change in concentration of pollutants arriving from the Danube is typically related to the phenomenon of flood waves. However, the measured increase in concentration is not directly linked to the flood wave but rather precedes it. The detailed presentation and evaluation of this process is currently ongoing within the framework of the Clean Drinking Water Project.

### *1.2 Groundwater resources*

The amount of available groundwater directly affects not only the drinking water supply but also the processes of agricultural and industrial activities.

It is scientifically proven that in some areas of Hungary, a decrease in the groundwater level can be observed. The process is the most significant between the Danube and Tisza Rivers, where the groundwater level has decreased by up to 2 m compared to the values measured between 1970-2009 (Szalai, 2003). Therefore, though the groundwater is replenished to a certain degree, the rate of use is faster. This is also related to the amount and distribution of rainfall. As economic actors compensate for the lack of precipitation from groundwater sources (LIFE-MICACC project, 2021). Another important aspect of the processes could be that groundwater stored in the soil is less exposed to environmental damage than surface water. The spread of contamination is significantly slower in the soil, and the role of decomposition processes taking place under the ground also significantly contributes to reducing the level of certain types of contamination. However, it cannot be neglected that both from the river and due to background infiltration, environmental pollution directly affects the safety of drinking water in the case of RBF systems.

### *1.3 PRECIPITATION CHANGES*

In Hungary, the average annual precipitation is around 500-750 mm. However, there may be significant differences among different regions (HMS, 2022). The topographical nature of the Carpathian Basin fundamentally affects the country's climatic situation. Where the continental, drier climate is influenced by the Mediterranean Sea and occasionally the Atlantic Ocean, depending on the atmospheric processes. Depending on the wind direction, the Mediterranean climate might also become dominant. Also, an increase in altitude of 100 m results in an increase in annual precipitation of approximately 35 mm. A decrease in precipitation in the southwest-northeast direction can also be observed due to the geographical distancing from the seas. For these reasons, the southwestern part of the country and the regions of the central mountains have the highest amounts of precipitation. In these regions the measured precipitation can even exceed 800 mm on a yearly base. Our driest region of the country is the Tisza Valley, where the average rainfall does not exceed 500 mm a year. This region, also called Alföld is the most vulnerable area in terms of precipitation deficit and droughts. Because the amount of precipitation is less than the evaporation - that can reach 800 mm/year - this area lacks about 300 mm of rain every year. Another problem is that 90% of the annual precipitation falls in 65-70 days. About 300 days of the year are without any precipitation. Drought usually strikes during the summer vegetation period. Due to the climatic conditions, the precipitation that falls in winter is less useful from agricultural aspects. To aggravate the problem, the results of climate models predict an increase in extremes. Note that flash floods generated during torrential rains are not only useless but also strengthen other unfavorable processes, such as soil erosion (LIFE-MICACC project, 2021).

However, it is important to note that precipitation shows significant variability on a yearly and also on a geographical basis. When comparing the data series for consecutive years, a threefold difference can be observed. Months can pass with a complete lack of precipitation. In general, the majority of precipitation falls between May and July and the least between January and March. Depending on the cyclone activity, a secondary precipitation maximum can also be observed in the autumn period, typically to an increased extent in the southwestern and mountainous regions.

Long-term droughts and rainy periods are rather rare in Hungary. In the last forty years, the total amount of precipitation in the country has increased significantly by about 16.5%. A temporary period of less rainfall was observed in the 1980s. In seasonal terms, the amount of precipitation in spring is leveled off but shows a slight decrease. In the other seasons, however, an increase of about 20% can be observed during the analysis of the data series between 1900 and 2020 (HMS, 2022).

It is important to highlight the above-mentioned facts that even if water is abundantly available at the country level, any decrease in water availability will have serious consequences. In the case of Hungary, the use of country-level available water is relatively low, which means a favorable water withdrawals-to-availability ratio (7%). (Czako and Mnatsakanian (2007).

Based on these facts, the echoes of the extremes of individual years cannot be justified in terms of rainfall alone. What causes then events such as desertification, natural disasters, and crop failures? The problem is to be found in the increasingly uneven distribution of precipitation. Torrential rains are becoming more and more frequent, and the length of periods with a lack of precipitation is also being pushed out in time. Unfortunately, these events are very difficult to predict, and therefore, it is difficult to build an effective defense against them. One example of extreme drought is the year 2022.

The complexity of the problem clearly requires cooperation and a coordinated strategy. One of the important benefits of this was the development of the National Water Strategy (Jenő Kvassay Plan) (Pákozdi, 2016).

### *1.4 CLIMATE CHANGE IN THE ALPS*

Hungary is rich in rivers, and we are in an exceptional situation due to the nature of the basin. These rivers originate in the mountain ranges surrounding the country, and their water supply is ensured by the snow melt coming from there. It is often said that Hungary is a water superpower. However, this is only correct from one side: 109 km3/year of water arrives in our country. Due to the river regulations, however, the currently built water infrastructure blocks the flood plains from the rivers, even though we could retain a significant amount of water in the country with controlled flooding. One cubic meter of soil can store up to 500 liters of water. Hence, the expression that the soil as a water bank could be included in the water retention strategy. This would also be a particularly critical aspect because, at the moment, about 7 km3 more water is leaving our country every year than is flowing in - this is roughly four entire water masses of Lake Balaton (LIFE-MICACC project, 2021).

The IPCC's 2019 report on the situation of the oceans and ice sheets in relation to climate change describes (Hock et al., 2019) that the temperature in Europe's highest mountains has risen by about 2°C in the last 120 years. This is about twice as much as the global average. Alpine glaciers are particularly sensitive to climate change, considering that the area of the Alps is smaller than any other high mountain region and because the snow cover on the peaks is proportionately smaller. The average atmospheric temperature of the Alps rises by about 0.3°C in a decade. If the concentration of greenhouse gases continues to rise at the current level, about 80% of the ice mass of the Alpine glaciers will disappear by the end of the XXI. century. According to Austrian, French, Swiss, and Italian glacier researchers, record melting levels were observed in the year 2022 due to the extremely hot, long, and dry summer. Since the end of the XIX. century, about 200 glaciers have completely disappeared from the Alps. The rate of glacier disappearance in the last ten years is 2% can be placed around it. (Zimmer et al, 2021)

This is a cause for concern, on the one hand, because due to the melting of snow and ice, an increasing amount of precipitation enters the water cycle. Extreme weather conditions change long-term patterns that require a good operational routine to handle. This was the case in December 2023 when unprecedented degree II. flood levels occurred. On the other hand, there is an increasing trend of local warming, resulting in a higher rate of evapotranspiration. Considering that the rocks are heated by the summer sun and thus cause locally unusual heat waves that are unbearable for the ecosystem, especially in less adaptative high mountain areas. In 2022, Efi Rousi and her colleagues at the Potsdam Institute for Climate Impact Research established that the current climate models underestimate the degree of warming in Europe (Rousi et al., 2022). In summary, it can be concluded that the warming experienced in the Alps is taking on ever greater proportions. Currently, even the climate models cannot estimate its extent, and what remains after the glaciers is only rock and rubble.

### *1.5 DANUBE WATER TEMPERATURE CHANGES*

The temperature of the Danube varies according to the geographical location. The influence of the oceanic climate can be observed in Vienna, then the Pannonian, and finally, the Mediterranean-continental influence adds up in the lower section. The mountainous climate characteristic of the Carpathians also affects the atmospheric conditions and, thus, indirectly, the river's temperature. A mixed Mediterranean-oceanic-continental effect prevails on the Danube water basis at Budapest and its surroundings. This section can be characterized by both the extremes of heavy rains and prolonged dry, drought periods.

BOKU records and displays water temperature data for major European rivers and lakes. According to their results, a conclusion can be drawn that a general trend is true. Regardless of geographical location, the temperature of European surface water bodies has followed a continuously rising trend in the last hundred years. Based on the data measured in the Danube at Vienna, the annual average increase of the measured value was determined as 0.014°C/year based on the slope of the trend.

Hassan et al. (1998) admit that the direct effect of climate change will be reflected in the temperature rise of rivers and lakes in the future since water bodies maintain a direct balance with the atmospheric temperature. An increase in atmospheric temperature directly results in an increase in the temperature of water bodies. The Hungarian aspects of this were widely and comprehensively investigated by the VAHAVA project (Láng, 2006). The project emphasizes that it is important to recognize the effects of climate change in our country and to prepare appropriately for these changes. Furthermore, it was stated that it is not enough to formulate the results in academic circles, but it is also important to be aware of the processes taking place in our environment at the social level. (Láng et al., 2006)

Pekarova et al. (2008) investigated the environmental factors influencing Danube water temperature near Bratislava. It has been shown that there is a delayed relationship between atmospheric temperature and water temperature, called hysteresis, based on seasonality. It was also shown that a drastic decrease in the flow rate of the river (from 3000 m3/s to 1400 m3/s) raised the water temperature by about 2°C under the same conditions.

In his 2013 study, Lovász (2012) investigated the changes in the water temperature of the Danube in the Hungarian section between Dunaremete and Mohács in the period of 1951-2010. According to his results, the average annual water temperature of the Danube is 10.4°C at Dunaremete and 11.7°C at Mohács. The increase in the average water temperature between 1951 and 2010 was 1.2°C for the entire year. In the months of July and August, he found that the increase in the examined period was +2.7°C, while a very slight temperature decrease was observed in the months of December-January-February.

The temperature change of the Danube is primarily determined by the ambient temperature and its changes, as well as the degree of direct sunlight (Pekarova et al., 2008). The average atmospheric temperature values peak at 22.4°C in July, and the average water temperature values of the Danube peak at 19.7°C in August, an observation that supports the theory of hysteresis based on seasonality.

## 2. MATERIALS AND METHODS

Water level data of the Vigadó tér guage – that is a frequently measured gauge in the heart of the capital close to the production site - for the period of 1943-2021 (Danube 1646.5 km, 94.97 mBf) was downloaded from the website www.hydroinfo.hu. Missing data and obvious outliers were not considered and were left blank during the calculations.

In order to analyze the water temperature data of the Danube, the daily results from 1947-2019 of the Vigadó tér gauge sampling point in Budapest (General Directorate of Water Management (GDWM) station code: 001026, distance from the mouth of the Danube: 1646.5 km) were evaluated. The data were downloaded from the vizügy.hu website. The missing data was completed with the data provided by the general directorate (GDWM). Sporadic missing data were not included and left blank in the calculations.

The daily values of the calendar year were taken as a common data set, and their statistical characteristics were examined. Hence, a comprehensive overview could be formed in terms of seasonal changes that can be observed in the Danube watershed.

For both datasets, daily values were summed up and grouped into weeks. For floods, therefore, weekly maximum levels, and for drought, weekly minimum water levels were determined and evaluated. In the case of water temperature evaluation, maximal weekly values were taken into account. Three different flood preparedness levels were applied in accordance with the GDWM guidelines. Where the water level exceeded 620 cm, 700 cm, and 800 cm at the Vigadó tér gauge I, II, and III. Degree floods were taken into account for the assessment. In the case of low water periods, three categories of the Danube water level values were determined, based on operational experience related to low flow severity water level thresholds. Here, the number of days considered where the water level dropped below 120 cm, 70 cm, and 50 cm, respectively.

Finally, based on the water temperature of the Danube, in the case of values exceeding 20°C, which are considered critical from microbiological reproduction rate perspective. This resulted in the determination of number of days for every week where the Danube water level exceeded 20°C, 22°C, 24°C and 26°C. Once the dataset was assessed as described above, their superposition was analyzed as well.

To summarize the identified risks, the above-mentioned three defined and elaborated categories were taken into account together. In the case of floods, based on the previously presented flood preparedness levels, three categories were taken into account. These categories were weighted by one, two, and three, respectively. In the case of low water periods, the previously determined three categories of the Danube water level values were also used. Here, weekly water levels below 50 cm were weighted three times, the values below 70 cm were weighted twice, while the values below 120 cm were weighted once.

Finally, based on the water temperature of the Danube, the four temperature categories were determined and grouped into four classes per 2°C range. were also weighted. For each group single, double, triple and quadruple weighting were applied in line with the level of severity for the weekly values. The product of the three weighted values for each week were than calculated and the total risk for every week has been determined as the basis of preparedness unit.

This result served as the basis for determining the cyclical annual climatic risk directly influencing the water safety of the system.

The results of the assessment served as an input to determine the most critical periods of the calendar year in respect of water level and temperature changes in the area of Budapest. The risk assessment was based on the severity of the dangers and the probability of their occurrence. In the risk matrix, we quantified the value of the risks with the help of the product of three parameters, on the basis of which the relative importance of the dangers could be determined.

## 3. Results

### *3.1 Climate change threats directly affecting water safety*

In everyday operations, it is key to be aware of all the risks that may affect water quality. These risks can arise from many aspects, such as maintenance, hygiene, operational circumstances, and, for instance, climatic effects. Figure 2 shows the main threats influencing drinking water safety that can be linked to climatic changes. Here, the water supply system is represented through five distinct steps as: production, transport, treatment, disinfection, and supply. The system can be evaluated by a risk assessment method based on the HACCP approach used in other segments of the food industry. Climatic effects directly affect production. However, considering that the steps of the process are built on each other, it is necessary to evaluate the entire system. Below, the main hazard groups in light of changes in the water level and temperature of the Danube are represented.

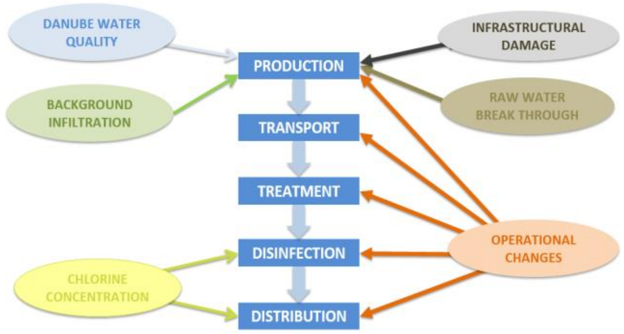


Figure 2. Major climate change-related threats affecting drinking water safety; property of the authors

### *3.2 Flood related threats*

The dangers associated with flooding can be grouped according to two different perspectives. On the one hand, during floods, the protection of the infrastructure is of particular importance in relation to the production facilities and collection pipes, as well as the electricity network. The flood can endanger the place of water extraction and its transmission zones when the production objects are damaged, and power outages limit the extraction and transmission of water. Damage to these infrastructures (even in the case of minor involvement) can lead to permanent loss of capacity.

In addition, in the case of high water levels, there is a risk that Danube (raw) water will enter the production facilities through raw water intrusion. This event is mainly a problem because impurities of Danube origin can enter the RBF water at this time, which would otherwise be removed by the RBF process under normal operating conditions. These contaminants can be physical, chemical, microbiological, or biological in origin. Raw water intrusion can be detected most effectively by measuring turbidity - the process causes a sudden increase in turbidity - or by microscopic examination of the sampled water. With the latter method, the effect of possible contamination can also be detected at more distant points of the collection-distribution system. Raw water intrusion primarily endangers wells and siphoned systems. That is why it is extremely important to protect productive areas at risk of flooding (Nagy-Kovács, 2018).

In the case of production objects, flood involvement therefore carries a double threat. Considering that in the case of the affected objects, exclusion, disinfection and flushing are necessary before re-commissioning, all such events additively reduce the available water production capacities. On the other hand, if the flood involvement causes more serious structural damage, the exclusion of the object can permanently reduce the amount of water that can be extracted.

Another important aspect is that in the riverbank filtered layer, simply because of the rising water level, infiltration can start in the direction of the wellbore through soil layers where the biofilm performing biological filtration has not been formed. Therefore, the produced coastal filtered water may temporarily change in terms of water quality: higher dissolved oxygen and dissolved organic carbon concentrations can be observed (Hock et al., 2019). Indirectly causing microbiological proliferation. One possible way to eliminate this is to reduce the risk of microbial contamination by increasing the free active chlorine level when using chlorine-based disinfection. However, an increase in dissolved organic carbon concentration (DOC) with a higher chlorine dosage may pose an increased risk of Adsorbable Organic Halides (AOX) and Trihalomethanes (THM) formation due to the oxidative reaction between the compounds. Considering that the risk of microbiological origin is of particular importance according to the relevant Hungarian and European Union regulations, the optimization of disinfection is definitely a priority. For example, when fecal indicator organisms are detected, the produced water is objectionable. It is of non-drinking water quality. Nevertheless, the by-products formed during disinfection and their health effects are currently a highly researched area and are being investigated by numerous domestic and international projects (Nagy-Kovács, 2019).

It is also known that floods have other effects on water quality. A more intense tidal wave can significantly modify the riverbed, removing the sediments that have settled at the bottom of the riverbed. Given that this layer is part of the hyporheic zone, which is the site of the most intensive processes of coastal filtration, flood events also affect the processes of coastal filtration, the effect of which is not clear in terms of current literature sources (Clean Drinking Water Project). Overall, therefore, flood exposure can lead to loss of capacity due to water quality on the one hand and infrastructure on the other. If the flood affects not only the inundation but also structurally, i.e., objects are damaged, it can also lead to loss of permanent capacity.

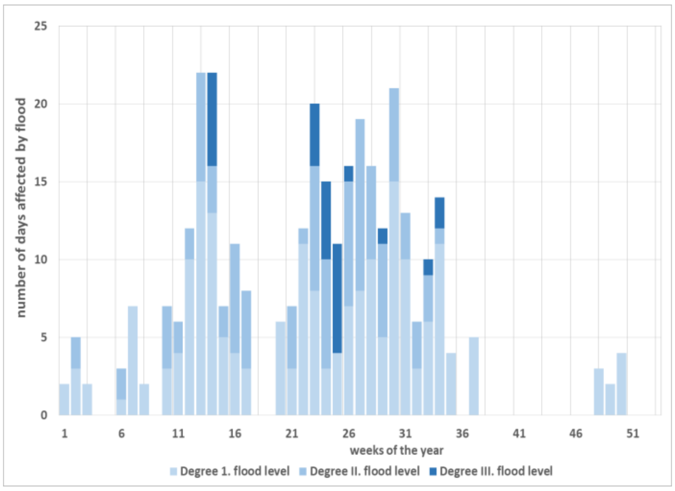


**Figure 3. Flood events length and severity between 1943-2021 (water gauge at Vigadó tér, Budapest); the property of the authors**

All the above-mentioned reasons emphasize the importance of assessing flood-related events and their annual pattern. Figure 3 shows the annual (seasonal) changes of days affected by the flood levels of the Danube for the period 1943-2021. The critical levels of flood water are based on the current determined flood levels (Balatonyi, n.a.).

It can be observed that the days above 620 cm are mostly observed between 10 and 17 weeks (glacial mud) and between 20 and 34 weeks (green mud). Apart from these periods, for a short time and typically only 620 cm, level one flood preparedness can be observed from the available data. It can also be established from the data that severe floods - the third level of preparedness - are typically observed in the second wave in the summer period.

Therefore, Figure 3 summarizes the most critical seasonal periods regarding the probability of elevated Danube water levels and, in serious cases, floods. Two separate periods can be observed, the first occurring in spring and the second during the summer months.

### *3.3. SUMMARIZING DETERMINED THREATS RELATED TO LOW-FLOW EVENTS*

In the case of low water levels, the processes are more complex. During riverbank filtration, in addition to riverbank filtered water arriving from the river, up to 50% of water can also enter the well body from the background. The extent depends on many factors, but the water level of the river has a decisive influence. On the one hand, background water leaks towards the river from the aquifer at low water levels, thereby increasing the ratio of background-origin water to the ratio of filtered water arriving from the river. In this way, the concentration of background contaminants and, thus, their risk also increases, which is important in terms of water quality. In severe cases, the exclusion of the well may be justified, which also reduces the available capacity in the production processes. In general, it can be said that the water coming from the background is of a lower quality than the filtered water from the shore. Typically, the activities taking place in the closer area of the watershed can lead to agricultural and industrial contaminants entering the drinking water distribution system. That is why RBF systems are considered vulnerable water bases (Government decree 123/1997 (VII. 18.)). In 1997, the governmental decision was made to prevent this above-mentioned problem and hence protect efficiently the watersheds that are considered vulnerable.

On the other hand, in the case of low water levels, the production capacity of the wells also decreases, which is a concern due to the amount of water that can be extracted. In relation to a given water level, the depression level that can be maintained without structural damage to the wells can be determined. Above this level, damage to both the wells and the aquifer begins. This process is also undesirable because the repair of structural damage to the well can be carried out with expensive and highly skilled procedures, on the other hand, the restoration of the aquifer cannot be carried out in a simple and cost-effective way. In addition, the increased turbidity values observed in the case of low water levels indicate the “sanding” of the well, which, in addition to the deterioration of the water quality, can contribute to the increased depreciation of the well structure (Nagy-Kovács, 2018).

The third important consequence with regard to the low water condition is that the biological filtering layer that carries out the RBF becomes thinner. This layer regenerates over a longer period of time in case of persistent low water levels. Therefore, in the event of a sudden rise in the river water level, a temporary deterioration of water quality may occur, due to similar reasons as in the case of floods.

In other words, in the case of low water levels, the extractable capacity necessarily decreases in the case of RBF water bases.

Just as in case of the previous chapter related to flood events consequences, determining the annual pattern of low flow affected periods are also crucial. Figure 4 shows seasonal changes in days with low Danube water levels for the period of 1943-2021. The critical values representing low water levels were determined based on the applied values of Budapest Waterworks Ltd.

It is clearly seen that no drought day has been recorded between weeks 15 and 28 in the last 80 years. Low water levels started to be observed in week 29, and in terms of length, week 44 was the most critical. Extremely low water levels were observed in mid-autumn (weeks 42 and 43) and mid-winter (weeks 2 and 3). Overall, the driest period can be observed between weeks 42 and 47, when at least 70 low-water days were determined.

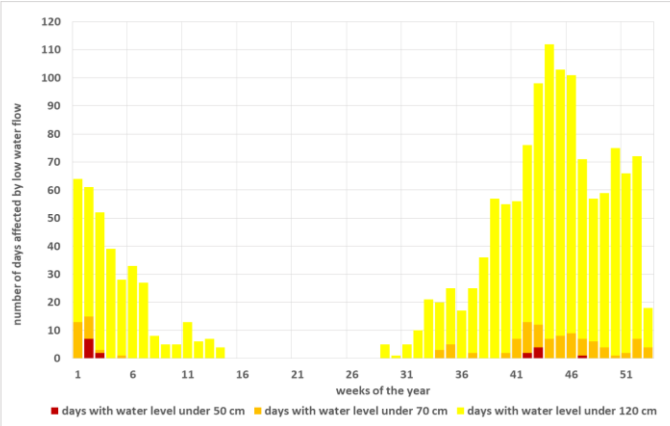


**Figure 4. Drought events length and severity between 1943-2021 (water gauge at Vigadó tér, Budapest); the property of the authors**

Figure 4 summarizes the most critical seasonal periods regarding low Danube water levels, including extreme droughts, where the most affected seasons can be easily identified, and the less influenced spring-early summer months can also be clearly determined.

### *3.4. THE EFFECTS OF WATER TEMPERATURE CHANGES ON WATER SAFETY*

In the case of the Danube River, the average annual and monthly water temperatures both show a rising trend in the examined period between 1947-2021 (Nagy-Kovács, 2023). The water flow rate of the Danube has an average volume of 2000 m3/s. Therefore, the river has a significant buffer capacity in terms of temperature changes. Another advantage is that the higher water levels are mainly characteristic of the May-June period, the effect of which trend lasts until the middle of August, i.e., the water flow rate is also more significant during the higher water temperatures. Low water levels are typically observed in the autumn-winter period based on the data of the examined period.

At the same time, water temperature has a direct effect on the concentration of dissolved oxygen and other gases dissolved in water. Water in contact with air contains oxygen in an equilibrium concentration, the amount of which depends on the air pressure, temperature, dissolved salinity of the water, the nature and degree of pollution, and aquatic life processes. The level of dissolved oxygen at 0°C is 14.65 mg O2/dm3, at 25°C it is 8.18 mg O2/dm3. In other words, the dissolved oxygen content decreases as the water temperature rises Rácz I. (2011). The decreasing dissolved oxygen concentration due to the above processes can be further reduced by the increase in the biological oxygen demand due to the increase in the relative concentration of organic pollutants. During the discharge of sewage treatment plants, an increase in the phosphate concentration and a decrease in the ammonium concentration at higher temperatures can be expected because the nitrification processes are accelerated, and this entails an increase in the nitrate concentration.

Sheili et al. (2016) determined with regression analysis which is the most critical climatic factors and water quality parameters that can be clearly associated with water quality changes. They concluded that the two most critical factors were the UV254 value measured during sampling and the raw water temperature measured 15 days before sampling. (Sheili et al., 2016)

Temperature also has a direct effect on aquatic organisms, as it influences their basic physiological processes. Their temperature optimum is a well-determined range, possibly only a few °C, where their reproduction and metabolism can take place as efficiently as possible. The change in water temperature can, therefore, have a selective effect. Even significantly shifting the sensitive balance of the riverine ecosystem. In addition to the above, the water temperature also clearly affects the physical-chemical parameters of pH, conductivity, viscosity, and density.

In the temperature range between 0°C and 20°C, the dynamic viscosity decreases from $1.79\times10^{-3}$Pa×s to $10^{-3}$Pa×s. With respect to the typical water temperature range of the Danube, a capacity difference of about 45% can be observed in terms of the amount of water that can be extracted. Davidesz and Debreczeny (2009) investigated the exposure of Budapest's water supply due to changes in viscosity. It was established that, in the case of a given group of wells, it was possible to extract a given amount of water from the same wells with different depressions in the winter and summer periods. In the summer period, with lower viscosity values, the amount of extractable water was higher. In other words, the change in temperature indirectly affects the amount of water that can be extracted (well capacities) and thus also affects water security. (Davidesz and Debreczeny, 2009)

These processes are very complex, and their effect is direct on the process of coastal filtering. Above all, extremely highwater temperatures are considered risky from the point of view of the drinking water supply. On the one hand, microbiological proliferation increases in higher temperature ranges, which increases the risk of microbiological defects. An increase in the number of colonies can be detected in higher temperature ranges, but it can be effectively treated with the help of chlorination, and no modified operating conditions are required.

When the critical Danube water temperatures are grouped according to the highest water temperatures ever measured and plotted with a division of 2°C, it can be seen that the 32 weeks are the most critical, both based on the number of affected days and in terms of the water temperature value ever measured (Figure 5). Water temperatures exceeding 26°C were recorded in this one week until 2021. After that, the water temperature of the Danube does not exceed the critical temperature for 6 weeks due to the onset of autumn. Higher temperature values show a correlation with atmospheric temperature values when increased residential water consumption can also be observed, typically during the summer "peak period". Then, the amount of water can become critical, not necessarily due to the limitation of production but due to the sizing of the capacities of the distribution network.

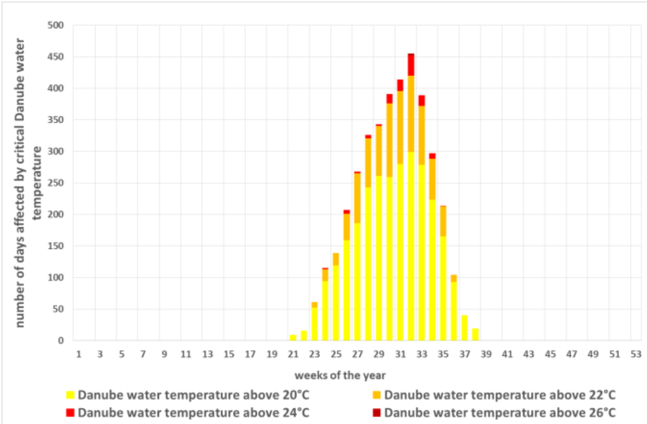


**Figure 5. Annual Danube water temperature changes between 1947-2021; the property of the authors**

In the present study, the evaluation of the trends of major climatic effects directly influencing riverbank filtration was accomplished. These effects were determined by examining river water level temperature and water quality. Furthermore, the exploration of drinking water safety aspects of expected changes and their mechanisms have also been determined.

The trends to characterize the Danube water levels and temperatures and the extremities have been assessed. These events include various natural disasters connected to climate change (floods, severe droughts, or other unexpected events related to natural extremes). This new approach is original and has not been used in drinking water risk assessments previously.

## 4. DISCUSSION

The water purification is carried out along such a fragile balance during the RBF process that climatic changes can pose a risk to drinking water safety in terms of both quantity and quality. Figures 3, 4, and 5 show the extent of these effects and their changes within a year. However, from the point of view of water safety, it is also important to evaluate how the simultaneous effect of these threats manifests itself from the point of view of water supply, which are the periods of the year that can be considered the most critical.

The most severe low-water situation is typically observed in October and January. Floods occur in two waves, first between the end of winter and the middle of spring and, secondly, from the middle of May to the end of summer. From the point of view of floods, the month of June can be considered the most critical. The water temperature of the

Danube can be considered riskier from mid-May to mid-September, the most critical period being from mid-July to the end of August. Taking into account all three risk factors, the month of August was the one where the highest level of risk could be identified from the point of view of water safety in the examined periods.

| | January | | | | February | | | | March | | | | | April | | | | May | | | | | June | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| weeks of the year | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 |
| low water flow | 2 | 3 | 3 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | | | | | | | | | | | |
| flood | 1 | 2 | 1 | | | 2 | 1 | 1 | | 2 | 2 | 2 | 2 | 3 | 2 | 2 | 2 | | | 1 | 2 | 2 | 3 | 3 | 3 | 3 |
| Danube temperature | | | | | | | | | | | | | | | | | | | | | 1 | 1 | 2 | 3 | 2 | 3 |
| summarized weighted risk value | 4 | 6 | 4 | 1 | 2 | 3 | 2 | 2 | 1 | 3 | 3 | 3 | 3 | 4 | 2 | 2 | 2 | 0 | 0 | 1 | 3 | 3 | 5 | 6 | 5 | 6 |

| | July | | | | August | | | | | September | | | | October | | | | | November | | | | December | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| weeks of the year | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 50 | 51 | 52 |
| low water flow | | | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 1 | 2 | 1 | 1 | 2 | 2 | 3 | 3 | 2 | 2 | 2 | 3 | 2 | 2 | 2 | 2 | 2 |
| flood | 2 | 2 | 3 | 2 | 2 | 2 | 3 | 3 | 1 | | 1 | | | | | | | | | | | 1 | 1 | 1 | | |
| Danube temperature | 3 | 3 | 3 | 3 | 3 | 4 | 3 | 3 | 2 | 2 | 1 | 1 | | | | | | | | | | | | | | |
| summarized weighted risk value | 5 | 5 | 7 | 6 | 6 | 7 | 7 | 8 | 5 | 3 | 4 | 2 | 1 | 2 | 2 | 4 | 4 | 3 | 3 | 3 | 4 | 3 | 3 | 4 | 2 | 3 |

| | |
|---|---|
| 3 | day under 50 cm Danube water level |
| 2 | day under 70 cm Danube water level |
| 1 | day under 120 cm Danube water level |

| | |
|---|---|
| 3 | day above 800 cm Danube water level |
| 2 | day above 700 cm Danube water level |
| 1 | day above 620 cm Danube water level |

| | |
|---|---|
| 1 | day above 20°C water temperature |
| 2 | day above 22°C water temperature |

| | |
|---|---|
| 3 | day above 24°C water temperature |
| 4 | day above 26°C water temperature |

**Figure 6. Summarizing the additive effect of identified risks**

According to Figure 6, it can be established that the most critical period is the period between 29-34 weeks, which are mainly due to the critical values of periods of flooding and high water temperatures. However, the situation is expected to worsen, assuming the worsening of drought periods (Blöschl, 2019). As a result, the more critical periods can spread further until the end of September. For now, the situation is still favorable, but it should be noted that once the naturally occurring low flow periods shift in mid-September and start to overlap with higher Danube water temperature periods - meaning that the Summer months and September is still relatively warm – the water safety risks can become an issue to be handled from an operational point of view.

Secondly, if major floods occur in an unusually hot summer month with high water consumption rates, the amount of water produced daily might not meet the needs. Considering that following flood events, even without major infrastructural damages, the relative capacity might decrease on the grounds of the disinfection process, which requires shutting down complete production well groups for days or even weeks.

Specifically, in the case of Hungary, the three main water sources in the country are underground water resources, rainfall, and rivers. The key to the depletion of our water resources is to be found in the main effects on the water resources. It should be noted that the most effective mitigation tool against the negative effects of climate change increases the role of irrigation in agriculture. Currently, the irrigated area in Hungary is a fraction of the potentially irrigable land. Studies, which also deal with the factors affecting the amount of water potentially used for irrigation, address the issue of the highest-yielding river in Hungary. Although the purpose of this study was not to examine the issues of the Danube and agricultural irrigation, it is important to mention the issue (Dogaru et al., 2019; Grujic, 2021).

## 5. CONCLUSIONS

In the past 40 years, major climatic patterns have considerably changed. As RBF is a natural process linked to freshwater sources, climate has a direct influence on RBF-based water production.

On the one hand, annual changes in the identified climatic factors and their critical limit values and annual variations have been assessed. On the other hand, it was found that their combined effect also appears to change within a year, influencing the quality and quantity of the water produced. Their superposition determined the most critical period between mid-June and the end of August, potentially limiting the water production capacity when severe climatic events occur. This period of the year also presents high water consumption, known as the summer peak season. The relationship between RBF site capacity changes and consumption rates is out of the scope of this paper with respect to length restrictions (Abd-Elaty, 2023).

According to the currently applied methodology in risk analysis, the annual, cyclical change in severity and probability of climate extremities was not explicitly considered. Also, it can be clearly established that within a year, the risks can differ significantly from each other. The result is important because it not only enables the operator to prepare but can also play a significant role in the planning of larger maintenance or investment tasks, for example.

Considering the size of the RBF site (a total of one million cubic meters per day maximal capacity), the results can serve as a good base for other water production sites that use the same technology with similar climatic characteristics. Also, the ISO 22000-based methodology used for the risk assessment can be useful for other water suppliers. In general, water safety plan methodology is available on national and international platforms (Rickert, 2019). However, in the case of more complex supply systems, prioritizing between risks is key, and many times, it is a rather complex challenge. This is the main reason why this paper does not aim to find a unique solution for the problem as a whole. However, climate is becoming more and more unpredictable. Therefore, even after taking into account and assessing available historical datasets, unexpected floods and droughts may occur, limiting water safety. Here, the only effective solution is to strengthen the cooperation and scientific dissemination between the countries and research institutes of the river watershed further.

Furthermore, it is not only climate that plays a major role in water safety, as consumption and the condition of the infrastructure also affect the availability of drinking water for consumers. The example of Cape Town has been well demonstrated to the world, as the big drought happened from 2015 to 2018, during which communication on consumption restrictions and innovative engineering solutions saved the day.

Finally, every risk related to water safety can be decreased or even avoided by creating redundant pathways and by maintaining technical and professional reserves (Ma, 2022). It is important to understand that these surpluses are the guarantee to stay afloat when water availability shrinks.

Due to climate change, it is necessary to rethink previous practices in many areas of life, like the preferences of companies and residential and industrial actors who are decisive in terms of drinking water supply security along the lines of the idea of sustainable life and sustainable development. Adaptive behavior cannot be expected without proper knowledge and information of either economic or social actors. The exploration and evaluation of the risks that can be determined from the point of view of the safety of the drinking water supply is a possible tool, with the help of which the individual levels of measures that are necessary for the appropriate hazard management can be determined.

The evaluation of the trends of the climatic effects influencing the examined RBF watersheds, like river water level, water temperature, and water quality parameter changes, helps water professionals to map and assess water safety hazards. One major expectation of water safety plans is that the documents must be capable of applying the principle of prevention. Therefore, every possible hazard that might potentially occur in the area of operation must be taken into account. Hence, various natural disasters (floods, severe droughts, or other unexpected events related to natural extremes) are typically included in water safety plans. This article aimed to contribute by identifying these risk factors, presenting a simple methodology to assess their severity, and superposing their combined effect, showing the cumulative influence of climate on water supply.

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