

The past, present and future prospects of an abandoned Tisza riverbed, the Karcsa

Introduction

Study area

Our surveyed lake, Karcsa runs from the western border of Pácin in north-south direction to the northern part of the village of Karcsa. In the cadastral map of Pálfai (2001), the characteristic dead-bed, which is the dominant feature of the landscape, has a length of 3.6 km, an area of 23 ha, an average width of 65 m, an average depth of 2.5 m, and a water volume of 575 thousand m³. It can be drained via a sluice gate into the Karcsa Canal and filled by gravity from the Upper Berecki Canal. It should also be noted that it is not connected to a watercourse. At the beginning of this century, its bed was moderately silted and less vegetated. The recreational area on its shores did not represent an excessive anthropogenic pressure, but the lake environment was in need of cleaning and rehabilitation by the beginning of the century. Ecologically, it is home to several protected bird species and provides a resting place for migratory birds. In addition to recreation, its functions include fishing, fishing and inland water storage.

In order to understand its development, we need to look at the wider environment, i.e. the changes that have taken place in the Bodrogeköz surface since the end of the Pleistocene, and the processes and factors behind them. The Bodrogeköz is situated between the Zemplén Hills, the Nyírség and the Rétköz. The Tisza-Bodrog-Latorca river triangle borders on a small area of 945 km² of which 556 km² between the Tisza-Bodrog-Karcsa river valley belongs to Hungary (Borsy et al. 1988). Today, about 90% of its surface is covered by Neocene casts, meadow clays and marsh-cotta sediments, while the remainder is filled with sand islands of Pleistocene age (Borsy 1969, Dövényi 2010).

Quaternary surface development of the Bodrogeköz in the light of the river water work

The surface evolution of the north-eastern part of the Great Plain in the second half of the Quaternary is one of the most remarkable in the Great Plain (Borsy and Félegyházi 1982). The Bodrogeköz is one of the areas which has undergone the greatest changes in the last 25 000 years. The area has been so heavily influenced by flowing water that knowledge of the hydrological changes is essential for understanding the geology and topography (Borsy et al. 1988, Borsy et al. 1989, Csongor et al. 1982). It is necessary to add that the reverse is also true. The past hydrological, topographical and geological processes of the Bodrogeköz must be studied together, emphasising their mutual influence.

The most important morphological processes of the Pleistocene surface of the Bodrogeköz were already described by Trenkó (1909). Borsy (1953) was the first to confirm his thesis that the Nyírség and the Bodrogeköz were still connected in this period and that most of the quicksand areas of the latter were eroded by fluvial water after the subsidence of the latter. From the results

of drilling and pollen analyses available to him, he proved that in the Pleistocene both were part of the vast debris cone plain extending from the Carpathians in a north-east to north-east direction. This cone was crossed by the Tapoly, Ondava, Laborc and Ung rivers in a north-south direction. Pollen analyses have shown that in the Nyírség, at the latest by the middle of the preboreal phase, the deposition of mud in these basins had started, indicating the loss of contact with the living water. This can be explained by the fragmentation of the alluvial cone and the vertical displacement of the blocks, which greatly altered the hydrography of the region (Borsy 1953). In the longer term, this alteration of the hydrography has led to a reduction in the area of inter-bodyish interbedded quicksand. The changes in the hydrography of the basin and the decline of the quicksand areas can be traced back to the same processes. Without more details on the former, it is difficult to interpret the Holocene surface development of the Bodrogeköz.

The appearance of the Tisza can be seen as the result of tectonic movements that began around the middle of the Würm. The northern part of the Bodrogeköz, the Beregi Plain and the Satu Mare Plain started to subside more than before 50 000-45 000 years ago (Borsy et al. 1988, Borsy et al. 1989). The DK part of the Nyírség and the Érmellék began to rise in parallel with the above. For a while, the Tisza compensated for the rise by cutting into the river. During a major flood, however, it left the Érvölgy and turned towards Záhony, bypassing the Berehovo Hills, from where it then made its way towards the sinking Bodrogeköz (Borsy and Félegyházi 1982, Borsy et al. 1988, Borsy et al. 1989). According to Borsy (1953), the subsidence of the Bodrogeköz could not have exceeded much more than 10-12 m by the preboreal phase. The D part, on the other hand, subsided mainly by the Atlantic phase by 3-5 m, which resulted in the formation of the present water network. Bertalan and colleagues (2016) have demonstrated the role of the Nyírség uplift in the directional change of the Tisza by means of field experiments with river water. Their results show that the subsidence of the Bodrogeköz alone would not have been sufficient to divert the river in this direction.

From the beginning of the Quaternary, the Ancient Tapoly, the Ancient Ondava and the Ancient Laborc, flowing through the Bodrogeköz, built up a cone of alluvium with the streams of the Zemplén Hills towards the Nyírség, where the formation of quicksand started at the beginning of the Upper Pleniglacial approximately 25 000-26 000 years ago. However, on the present-day surface of the Bodrogeköz, the Eolian forms occur only in isolated patches. Their decline began with the appearance of the Tisza 20 000-18 000 years ago. In the late glacial period, the rivers of the Great Plain increased their water volume and, as a result, their working capacity. The Bodrogeköz suffered the greatest transformation. The Bodrog and the Tisza, while calving almost its entire area, eroded most of the quicksand formations during lateral erosion and filled their places with their own sediment (Borsy 1969, Borsy and Félegyházi 1982, Borsy et al. 1988, Borsy 1989, Borsy et al. 1989, Dövényi 2010). The river water diversified the form of the Bodrog, which was formerly connected to the Nyírség.

Wherever the Tisza stayed for a longer period of time, it started to build river embankments along its banks. Raised only a few metres from their immediate surroundings, these river embankments contributed to the expansion of the areas without water. Behind them, swampy, marshy areas were created (Borsy 1969, Borsy and Félegyházi 1982, Borsy et al. 1988, Borsy et al. 1989). In addition to the current course of the Tisza and Bodrog, a notable flat river embankment with an average height of 2 m and a width of 2 km north-east of Pácin was created along the Karcsa (Borsy 1969, Borsy et al. 1988). The sediment grain types accompanying the

two rivers and the Karcha cover a wide range in a 0.5-4 km wide band. Most of them are river bed material (Borsy et al. 1988).

Changes to the bed of the Tisza in the Bodrogeköz

The appearance of the Tisza in the region has fundamentally changed the hydrology. The watercourses that used to flow through the Nyírség region have now merged with the Tisza in the Bodrogeköz. For a very long time, the Tisza and its tributaries did not flow in their present bed, but changed their course several times in the past millennia due to changes in their flow, tectonic movements and their working activity (Borsy and Félegyházi 1982, Borsy et al. 1989). According to Csongor et al. (1982), a thorough study of the dead basins of the region is essential for understanding the Holocene evolution of the Bodrogeköz. The main changes in the basins can be divided into the following sections based on the literature by examining the morotvae and the dead pools:

1. Between 20 000 and 16 000 years ago, the Tisza started from Záhony and headed west-northwest, bypassing the Királyhalmec Mountains from the north, then meandered towards Tiszacsermely on the eastern border of Pácin, and then turned north-northwest. Today, the oldest part of the Tisza's bed is only traceable, having been largely destroyed by the river's later alterations. In Hungary, its memory is preserved by a section of the basin to the DNy of the Pácin-Nagyrozsóly line, which is difficult to identify today (Borsy et al. 1988, Borsy et al. 1989). The oldest basement remains are slightly older than 16 000 years and their filling started already in the second half of the Upper Pleniglacial (Borsy et al. 1988).
2. According to the drilling data, the Tisza was already flowing westwards from the border of Pácin towards Becsked 16 000 years ago, from where it then headed southwards to DNy. The results of radiocarbon dating suggest that the river must have remained here for about 2 000-3 000 years. Filling of the riverbed started at the Upper Pleniglacial-Late Glacial boundary (Borsy et al. 1988, 1989).
3. At the beginning of the Late Glacial, the river flowed in a westerly direction from Pácin to the lane between Karos and Becsked, and from there it continued its course towards Bodroghalom and Csengőkut. In addition to the above-mentioned change of the riverbed, the Tisza is already found in the pre-Boreal period (10 200 years ago) to the south of the Királyhalmec hill. This change in the basin marked the birth of the Karcsa. The persistent presence of the Tisza is also attested by the well-developed meanders and the numerous morotva (Borsy et al. 1988, Borsy et al. 1989). According to Borsy and Félegyházi (1982), the Karcsa-bed is clearly of boreal age, as confirmed by radiocarbon dating of charcoal residues from a drilling sample of the adjacent morotva and by pollen analysis. Csongor and colleagues (1982) suggest that the size and development of the morotvinae along the Karcsa must have been the result of a live water flow at least at the end of the boreal period. Borsy and colleagues (1988, 1989) have carried out several borings in the morotvogs along the former course of the Karcsa. Palaeontological analysis of the samples showed that recharge had already begun in the beds from the mid-Atlantic phase. The radiocarbon dating of the samples from the area around the Bodroghalom has yielded results of a minimum of 6 000 and a maximum of 7 500 years.
4. Probably during a major flood, the Tisza changed course again. Turning northwest from Záhony, it reached Zemplén via the villages of Lelesz and Zétény, where it joined the

watercourses from the north in the middle of the Atlantic phase. This well-preserved bed, like Karcsa, is called Tice. It also has well-developed sinuosities and numerous morotves, testifying to the long presence of living water. According to research carried out by the Geographical Institute of the Slovak Academy in Bratislava, the Tice may have been abandoned by the Tisza in the middle of the Subboreal (5 000-2 500), after which it occupied its present position (Borsy and Félegyházi 1982, Borsy et al. 1988, Borsy et al. 1989).

5. We can speak of the present-day Bodrogek from the last major change of the Tisza riverbed, as it previously flowed uninterrupted into the swampy surface of the Rétköz (Borsy et al. 1988).

We should not only parallel the development of the meanders of each basin with the time elapsed. The radius of curvature of the bends is most influenced by the water yield of the rivers. The former is most influenced by the climate of a given phase and by the vegetation, which has a significant influence on runoff and evaporation (Borsy et al. 1989).

From the late glacial period onwards, the Tisza covered the whole of the Bodrogek before occupying its pre-regulated bed in the sub-boreal period. The best preserved of the river basins created during this period are the Karcsa and the Tice. The importance of the former is enhanced by the fact that, despite its older age, some of its sections are still in the same condition as if they had been left by a river only a few hundred years ago (e.g. in the villages of Karcsa and Pácin). In addition to the long-standing presence of the Tisza, various natural and anthropogenic influences over time have also contributed to this. Csongor et al. (1982) focused their studies on the Karcsa Lake, since without determining its age and origin, no complete conclusions could be drawn about the history of the hydrography of the small area.

History of Lake Karcsa and main parameters of Lake Karcsa

The Karcsa Lake can be regarded as a remnant of the former aquatic world, which, according to Borsy and colleagues (1988), is the most preserved former basin section of the Karcsa Lake, the focus of our study. The role and natural processes of the Karcsa and the Tice basins over time are similar, and it is therefore worthwhile to consider the changes that have occurred in the Karcsa since the Tice regulations in order to understand the processes affecting the Karcsa more thoroughly.

Based on pollen samples from drillings carried out in 1952, the wider basin of the Karcsa north of Pácin was clearly defined as boreal in age. The north-south direction of the bed deviated significantly from the main run from E to NW, which raised questions about the origin of this section of the basin. To answer this question, former beds and moraines to the E and W of our sample area were investigated. The large morotva between the Sentinel and the Great Ridge is thought to have been formed between 6 000 and 6 500 years ago, based on pollen analyses. In the upper layers, there is also a significant amount of material deposited from the surrounding higher arable land, which confirms the increasing anthropogenic influence of the recharge over time. In order for moraines of this type to have developed at the Karcsa site, there must have been a living watercourse by the end of the Boreal at the latest. A river of at least the size of the Tisza would have been needed to form morotvogs of this size and depth. The recharge of the morotva in the Atlantic was 2 mm/year at the time of the sedimentation, whereas in the subboreal period it was 0.8 mm/year (Csongor et al. 1982).

Filling of the abandoned basin west of the Karos began at the beginning of the subboreal period, around 4500-5100 years ago. It was probably not formed by the same watercourse as the former meanders between Pácin and Ágcsernyő, since the width and depth of its bed are also different (Csongor et al. 1982). This claim was later proved by Borsy and colleagues (1988, 1989) by analysing further drilling data, because their results showed that the Tisza had left the Karcsa basin by the Atlantic and had shifted its main course to the Tice basin to the north. The abandoned basin studied by Csongor et al. (1982) could therefore have been created by the independent Karcsa valley with its much lower water yield until the beginning of the subboreal. At the beginning of this period, the bed began to fill up, so it must not have been flowing in the direction of Vajdáciska. The rate of recharge in the sub-boreal was 0.8 mm/year, similar to the Morotva (Csongor et al. 1982). During the subboreal the main riverbed may have remained in continuous contact with the Tisza, which could have supplied its water. The lively activity of the Karcsa River is attested by the presence of the formerly large moraines on the left bank of the Bodrog (Borsy et al. 1989).

Even without the full flow of the Tisza, the Karcsa river was able to fulfil an infrastructural role. Written records show that it was used as a waterway in the 17th century. In 1613, the chief bailiff of Zemplén county asked the king for the right to use it as a toll-booth. In 1646, Transylvanian Prince György Rákóczi had Western military engineers regulate the Karcsa Strait to provide a permanent shipping route for salt from Tárkány to Tokaj instead of the more unpredictable Tisza, and also to drain a considerable area. The construction proves that the Karcsa Lake had not yet begun to swamp at that time. The importance of the project is underlined by the fact that the Zemplén County was only temporarily part of the Principality of Transylvania. The canal served its function until 1705, when Ferenc Rákóczi II had it destroyed for military reasons during the War of Independence (Mailáth 1896, Borovszky 1905, Trenkó 1909, Károlyi 1973).

Before the river was regulated, the Karcsa often left its bed and spread its waters in several directions, mainly feeding the swamps of the Hosszúrét. By the beginning of the 20th century, its bed was so covered by floodwater that it could only be followed from Kis-Dobra. In the past, it was connected to the Bodrog by two branches. One reached the river near Lower Oroberceki, the other near Bodrogszerdahely. On a map from 1799, the two branches were still visible, but they were no longer connected to the Bodrog (Trenkó 1909).

According to Vázsonyi (1973), between the Bodrogeköz and the Rétköz the Tisza meandered in the middle of a marshy area. This area was already flooded by medium tidal waves, while the water did not recede from the deeper parts even after they had receded. A report from the mid-19th century also notes that there were many 'taps' or 'fens' along the Tisza. It could leave the riverbed through them even if the water level was 150 cm deeper than its banks. At low tide, the water could return to the main riverbed through the fjords or continue its journey along the Bodrogeköz in permanent channels such as the Karcsa and the Tice. The watercourse feeding the former broke off from the Tisza downstream of Csap at Kis and Nagytárkány.

According to Trenkó (1909), the Tice was already in a much more advanced state of recharge than the Karcsa at the beginning of the last century. Upstream of Leles, the Medre did not even resemble a small ditch. In times of major droughts, upstream from Zétény, it broke up into a number of small lakes, which were becoming increasingly overgrown. The Medre can be traced as far as Battyán, from where it is barely recognisable as a meander to Tárkány, where it once

flowed out of the Tisza. Borsy (1953) also recorded the rapid filling of the Tice basin from the river regulation works in the 1950s, noting that the section of the basin between Battyán and Tárkány is barely traceable. According to Bogoly (2008), a major problem for the future of the former Tisza riverbed system in the north is the lack of complete recharge from the rivers, while almost all water management plans have been aimed at draining it.

Like the Tice, the Karcsa also lost its former size by the 1950s. Its bed between Battyán and Órös became quite narrow and shallow. However, the part between the villages of Órös-Pácin and Karcsa has remained well preserved. There are sections of considerable depth and width with well-developed meanders in several places. In this area, two north-south runs of the Karcsa can also be observed. One of the former is our study area, which reaches the village of Karcsa by turning D from the western backwaters of Pácin. Its considerable water depth is well characterized by the fact that, despite the very dry weather in 1952, drilling was carried out in a water column of 3-4 m (Borsy 1953, Csongor et. al. 1982). The eastern section of the Karcsa is nowadays hardly found in the Upper Bodrog Basin. Only the riparian grasses indicate the former riverbed east and south of Királyhelmec (Bogoly 2008). According to the standing water cadastre based on the 1951 maps of VITUKI (1962), Lake Karcsa covered an area of 24.5 ha.

River regulation and its effects in the Bodrogköz

Before the great river regulation works of the mid-nineteenth century (1846), the total area of permanent and temporary water cover in the Carpathian Basin amounted to 48 700 km² (Lászlóffy 1938). This is more than half of our present-day national territory. Over the last 150 years, man has transformed the aquatic world of the Bodrogköz, which has evolved through natural processes. In addition to changing the hydrography, the regulations have also had a major impact on the surface and the life of the population. A review of the regulatory works in the area is also relevant to the study of Lake Karcsa, which has played a major role in shaping the present-day image of the Karcsa Lake.

In our country, the devastation of the Turkish era and the Rákóczi War of Independence meant that the large marshlands also played an important protective role in the lives of the population. Due to the presence of the Turks, its previously shrinking area began to expand again. For a long time in the early 18th century, the sparse population also hampered the country's economic development and the carrying out of water works. The aquatic world sustained the fishing and piscatorial way of life. And in the water areas, the rigid pastoralism remained in the lead (Károlyi 1973).

As the country was rebuilt, uninhabited areas were repopulated. This led to an increase in the area under arable cultivation. During the deforestation movements of the 18th century, the population reclaimed large areas of land from the water. A decisive process of the period was the large-scale loss of the forests of the Lowlands due to the Deforestation Act, which was intended to meet the raw material needs of Austrian industry. Over the course of the century, some 50 000 km² of forest were felled in the Carpathian Basin. This mainly affected the mountain areas bordering the lowlands, where run-off increased. As the water retention and storage capacity of the catchment areas decreased, so did the time for floodwaters to accumulate. The resulting increase in the magnitude of floods also threatened previously free areas (Károlyi 1973, Somogyi 2004). The loss of forest cover in the river basins also forced the Bodrogköz to be cleared of floodwater. In the area, which rises only a few metres above the

previous flood level, previously protected settlements and farmland were directly threatened (Frisnyák 2005).

Before the deflooding works, the Bodrogtörzs was a literal flood plain. Its surface before river regulation was shaped mainly by the small and large watercourses that wandered through it. The area, which was completely vulnerable to river flooding, was densely interwoven with marshes, bogs, veins and branches. 56% of our territory was covered by marshes and bogs. The old records of the Bodrogtörzs water network preserve the names of many of the standing and running waters. These were once part of a water course (Trenkó 1909, Borsy et al. 1988). According to Ihrig (1973), ancient peat bogs covered an area of 19 km² in the Bodrogtörzs. These ancient marshes were formed in peripheral, subsiding basins such as the Bodrogtörzs. The damming effect of the river embankments also enriched the ancient marshland here by increasing the area of impervious land.

The first comprehensive regulation works in the area were carried out in 1775-82 under the direction of Lőrinc Orczy, but they mainly consisted of land consolidation (felling of trees, removal of backwater mills) and cleaning of the streams (Károlyi 1973). In the first decades of the century, the combined pressures of population growth, the hunger for new land in the grain economy that had been booming since the early 19th century, the development of the economy and the public demand for the control of the devastating floods led to the start of the major surveys in preparation for the works. The survey of the Tisza's aquatic world was carried out by Sámuel Lányi's group between 1834-46 (Somogyi 1967, 2004). The surveys were followed by the start of the works, which in most cases lasted until the end of the century.

Paleocapa proposed to increase the Tisza's embankment between Csap and Tárkány when planning river regulation works. This would prevent the river's floodwaters from washing away large areas of the Bodrogtörzs via the Karča and Tice (Konecsny 2008). In addition to the importance of the latter veins, Paleocapa's proposal also demonstrates the complexity of the hydrology of the small valley. In the low-lying Bodrog river basin, densely dissected by veins such as the Karcsa Vein, water could easily spread during a major flood. Water could have flowed through the former riverbeds to the river banks and high ground.

The Bodrog Intertisza Regulating Society was founded in 1846 to coordinate the regulatory work in the area. As in many other places, the foundation was facilitated by the personal intervention of István Széchenyi. Until 1866, progress with the protection was slow, due to shortcomings in the budget and professionalism. The difficulties of the company's work are illustrated by the fact that the flood of 1876 was the first major flood that they were able to deal with successfully. The final regulation of water in the Bodrogtörzs lasted for nearly half a century. During this period, embankments were built along the rivers to protect them against the flood levels and a system of inland water drainage channels was constructed in the interior areas. In addition, it took a long time to acquire the vast experience needed for flood protection and water management (Mailáth 1896).

Over time, the waters of the northern areas of the Bodrogtörzs have been conveyed by the Karcsa stream to the area's impervious marshes in the south. Regulatory works required not only the construction of embankments but also the parallel construction of an inland water drainage system. With the increase in arable cultivation, the previous practice of storing inland water in ponds and depressions behind sluices that remained closed during floods was no longer sustainable. During 1895, the huge amount of water flowing down from the unchanneled upper

reaches raised the water level of the Karcsa to such a level that it flooded large areas of the lower reaches of the river in the boundaries of the Órös, Géres and Pácin. Further flooding could only be prevented by vigorous intervention. In 1897, the main canal of Karcsa-Felsőberek with its associated pumping station was opened to prevent this process, discharging the inland waters of the NW into the Bodrog. In addition to relieving the D canal system, its construction also ensured the regulation of the water level in the Karcsa Lake. The lower part of the Karcsa Lake was henceforth used as an aquifer, while the upper part was considered to require further regulation (Mailáth 1896, Borovszky 1905).

The Bodrogköz, dominated for thousands of years by fluvial landforms, has undergone significant changes in just one or two decades following the regulations. The waterlogged areas of the former wild water country shrank, while large parts of the veins were only partially filled with water even after major rainfalls (Trenkó 1909).

According to Mailáth (1896), in the 1850s there were 99 254 acres of arable land in the Bodrogköz, which increased to 146 296 cadastral acres in 1895. The 56 242 cadastral acres of infertile land at the end of the 1870s had decreased to 10 267 acres by the end of 1895. By the end of the century, the area of the former had increased by 47%, while the latter had decreased by 82%. In the case of arable land, it should be noted that in the Bach period, i.e. the 1850s, the size of arable land was regularly overestimated in order to increase the tax base. In addition to the increase in arable land, we must also mention the great improvement in the health of the population and livestock and in transport conditions, which are among the positive aspects of the regulatory works.

Landuse

The regulations have changed the economic conditions of the Bodrogköz. Land use adapted to the former wetland habitats has been replaced by arable farming. The transformation is not considered to be the most ideal for the changed conditions. Knowledge of the former land use is therefore strongly justified in order to make recommendations for the future.

Before the regulations, floodplains and flood-free areas were different cultural levels with complementary economic functions. In the Upper Tisza Basin, the smallholdings mainly enriched the floodplains. In the Bodrogköz, the low floodplains were formed by areas covered by water between 95-97 m during most of the year, while the high floodplain was located 2-3 m above. The parts of the lowland above 100 m can be considered as flood-free. The former were represented by the remaining sandbanks and river banks, such as the Karcsa ridge (Frisnyák 2005).

Only 10% of the Bodrogköz was above the flood level, so the proportion of arable land was very low before the regulations (Borsy and Félegyházi 1982). The most ancient land use in the area was based on the cultivation of grassland and the associated fishing and grazing of large livestock (Frisnyák 2005). This type of wetland use and arable farming of drier areas complemented each other both locally and nationally (Somogyi 2004).

After the regulatory works were carried out, the flooding no longer affected the separation of the land surfaces. The former floodplain management conditions have slowly disappeared or been reduced. The once huge fish population had been reduced to 5% of its former level by the 20th century due to the separation of floodplains and rivers (Frisnyák 2005). Water-influenced

landscapes such as the Bodrogeköz have been completely transformed by regulation, as have the lifestyles of their populations. Most of the formerly natural or semi-natural landscapes have been transformed into artificial landscapes (Somogyi 2004). Small-scale agriculture has shifted towards arable farming, which has not been able to exceed the value-creating potential of large-scale livestock farming on local soils. The mistakes made in the land-use strategy could be corrected in the future by a more careful restructuring (Frisnyák 2005).

Data and methodology

Palfai Aridity Index

As a result of global warming, our climate is also changing and the frequency of extreme events is increasing. The increase of temperature maxima and the extreme annual distribution of precipitation may negatively affect the lake's water supply, therefore we considered it worthwhile to investigate the meteorological values in our sample area. To evaluate the combined effect of temperature and precipitation, we calculated the Pálfa Aridity Index (PAI) (Pálfa, 1990; Pálfa, 2002; Gálya et. al. 2015) values for each year, as used in the national drought research. The index takes into account the relationship between temperature and precipitation, focusing on the months that have the greatest influence on the growing season. By weighting the precipitation totals for each month, we can quantify the ability of precipitation in a given month to compensate for increased evaporation due to heat. The index uses correction factors to account for the number of heat days, the longest periods without precipitation, and the deviation of the annual mean groundwater level between November and August from the multi-year average.

For the calculations, we used the daily 1998-2019 precipitation data from the precipitation gauge station in Cigánd, the closest to our sample area, provided by the North Hungarian Water Directorate (ÉMVIZIG), and the daily maximum and mean temperature and precipitation data from the E-OBS temperature and precipitation database for the whole of Europe, downloadable from the European Union's Copernicus programme. The E-OBS database contains meteorological data from 1950 onwards, of which we downloaded the data sorted into a grid with a resolution of $0.1^\circ \times 0.1^\circ$ (Cornes et al. 2018). Our sample area was covered by 4 cells, so we used the average values of these cells for the calculations. To more accurately assess the PAI values, we also had to consider groundwater measurements. The latter were also provided by ÉMVIZIG. For the calculations, we used the measurements of the groundwater monitoring well in the village of Karcsa, which were recorded daily between 1998 and 2019.

The index values are calculated on an annual basis. As each database covered a different time span, two calculations were performed. One of them, using only the E-OBS database, allowed us to review a longer time interval (1951-2019), but in this case we had to forego the use of groundwater standing corrections. The other data set was produced using precipitation and groundwater data from ÉMVIZIG and temperature data from the E-OBS database for a shorter time interval (1999-2019). The operations were carried out according to the recommendations of Pálfa (1990). The base value of the index was calculated using the following formula:

$$PAI_0 = \frac{t_{V-VIII}}{P_{X-VIII}} * 100$$

where:

PAI₀ is the base value of the drought index (°C/100 mm),

t_{IV-VIII} - mean air temperature in April-August (°C),

PX-VIII - weighted precipitation totals for the October-August period (mm).

From the base value of the index and the correction factors, the drought index is obtained as follows:

$$PAI = k_t * k_p * k_{gw} * PAI_0$$

where:

PAI - drought index,

k_t - the temperature correction factor,

k_p - the precipitation correction factor,

k_{gw} - the groundwater correction factor.

To calculate the PAI values, it was necessary to pre-process the databases mentioned earlier. The sub-calculations were performed using Python scripts, where the databases were managed using the pandas library (McKinney, 2010). Before generating the final annual index values, monthly rainfall totals and mean temperatures were first calculated for each month. Also, we had to separately summarize the data needed to calculate the correction factors, i.e. the number of heat days and the length of the longest periods without precipitation in the given months. The groundwater correction factor also required preliminary calculations in order to separate and average the individual periods. Following the preparations, runs were performed with the two data sets already mentioned after fitting the data into the formulae, where first the baseline value of the drought index and then the drought index itself were determined.

Surface cover

The processes taking place in the dead pool are influenced by the quality of its environment, as it can be both a source and a sink for pollutants entering the lake, and also affects the microclimate and water balance of the area. In the light of the above, it was considered worthwhile to carry out a detailed study of the surface cover over a 500 m radius of the Karcsa Lake. Due to the small size of the chosen area (4.27 km²), we decided not to use the Corine Land Cover (CLC) database, because the minimum size of each unit (25 ha and 100 m wide (Internet-1)) would mean that many important details would be lost in such a large area. The 1:50 000 scale database built during the CLC50 project with its minimum 4 ha and 50 m wide units and increased number of categories has proven to be much more suitable for this purpose (Büttner et al. 2004). However, since the former only covers a single time period (based on 1998-1999 records) and is not a database of our own making, we built a separate database, while the CLC50 database was used for comparison only. For detailed analysis, manual digitization of the surface cover was considered the most accurate option.

The analysis was based on the digitization of various remotely sensed images in ArcGIS 10.8 software environment. For this purpose, free available images covering the sample area were downloaded from 5 time points (1966, 2000, 2005, 2007, 2020). These include archival aerial photographs (1966) from fentrol.hu, orthophotos from the continuous coverage of Hungary

(2000, 2005, 2007) from geoshop.hu, and space images (2020) from planet.com. In order to make our digitised data comparable, we had to use the same 500 m buffer zone, which was delimited by the 2000 extent of Lake Karcza. During the digitisation process, 8 surface cover categories were defined (forest; field; shrubland; open water; grassland; terrestrial wetland and dense aquatic riparian vegetation; area under strong anthropogenic influence; orchard).

The vector databases were first converted to raster using the Polygon to Raster tool in the ArcGIS 10.8 Conversion Tools toolbox. A pixel resolution of 5 meters was used for the settings and the Cell center option was used to extract the values. The generated raster files were compared using Python scripts. The crosstab tables were calculated using the crosstab function of the pandas library (McKinney, 2010), while the Cohen's kappa (Cohen, 1960) values were calculated using the `cohen_kappa_score` function of the `sklearn.metrics` module (Pedregosa et al. 2011). After the runs, we could also quantify the proportion of changes between time points broken down into categories and the amount of change in each category in favour of other categories.

Results

Surface cover

To analyse the surface cover in the images from different dates, we used cross tabulation tables and Cohen's kappa coefficient to characterise the changes in addition to the spatial percentages of the categories. In our study, the latter shows the probability that a given pixel has the same value as the one it carried in the reference database. The variation of the values between time intervals shows the degree of variation or stability for the whole study area and for each type. In calculating the kappa values, the starting year was always taken as the reference. Cross tabulation tables are used to quantify the transition between categories.

If we compare the average kappa values between each recording, we do not find large differences. The more time elapsed between each recording, the higher the value of the Overall Kappa (Table 1). The smallest value of 0.69 between 1966 and 2000 also shows a significant agreement, while the same indicator shows an almost perfect agreement for the other time points. Nevertheless, it is still worth taking a closer look at what we can observe for each surface cover category. In this case, the picture is much more varied.

1. Table Changes in Cohen's kappa values by category between the time points examined

	1966-2000	2000-2005	2005-2007	2007-2020
Forest	0,29	0,78	0,82	0,64
Plough, garden	0,67	0,90	0,92	0,85
Shrubby, scrubby area	0,14	0,40	0,49	0,48
Open water surface	0,86	0,87	0,91	0,88
Grassland	0,12	0,41	0,32	0,17
Marshes, waterfront vegetation	0,49	0,68	0,76	0,60
Built-up areas	0,68	0,84	0,85	0,77

Fruit tree plantations	0,10	0,29	0,95	0,79
Overall Kappa	0,69	0,85	0,87	0,82

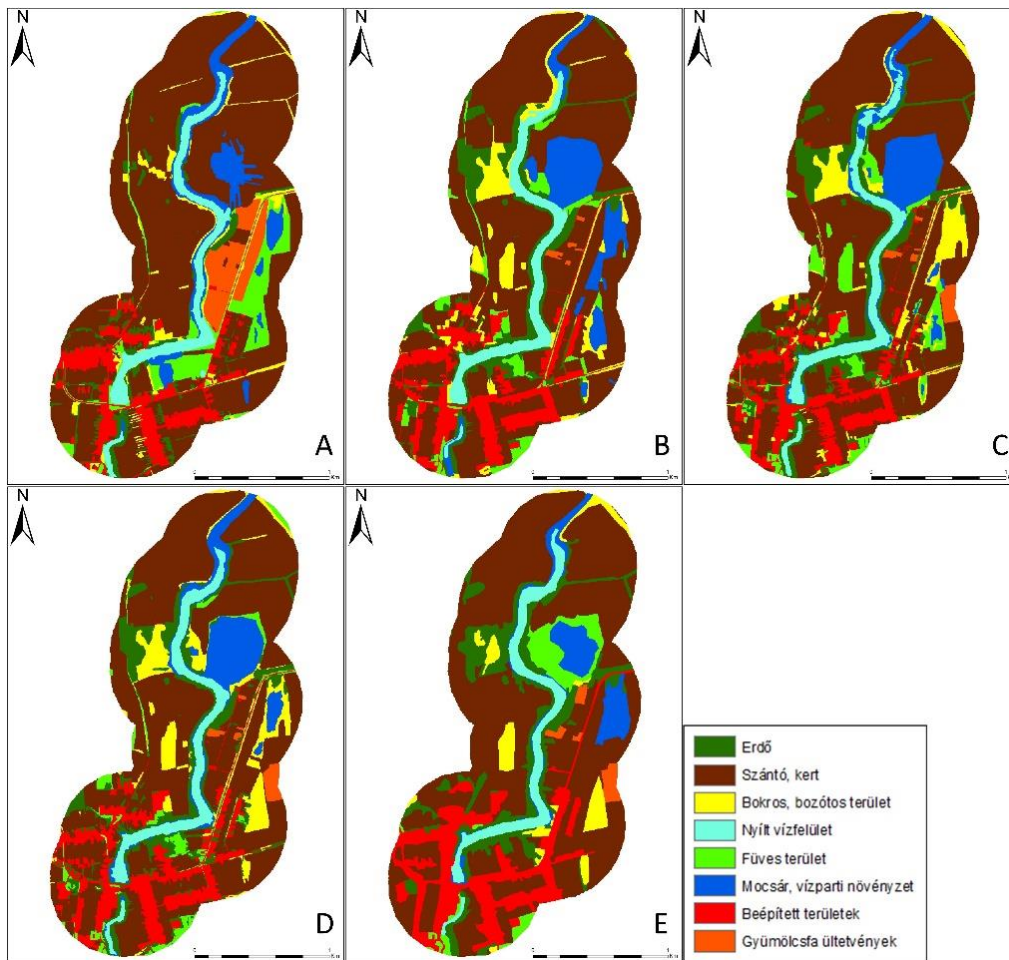
Analysing Table 1, we can conclude that although the time elapsed between the first and the second date is a multiple of other observed periods, we should not explain the different trends for each category by this alone. The significant time gap between the two records is not sufficient to explain the slight or no relationship between forests and fruit tree plantations. The values calculated for the first period show the differences between the situation under the socialist regime and the situation created by the processes that started after the regime change.

2. Table Proportion of surface cover categories at each time point

	1966	2000	2005	2007	2020
Forest	4,47%	9,55%	10,87%	10,84%	12,27%
Plough, garden	60,52%	55,60%	54,13%	54,32%	54,66%
Shrubby, scrubby area	3,52%	6,04%	6,46%	7,07%	4,00%
Open water surface	5,48%	5,75%	5,44%	5,66%	5,65%
Grassland	6,40%	3,80%	5,16%	3,02%	3,86%
Marshes, waterfront vegetation	6,66%	8,37%	7,26%	7,60%	5,63%
Built-up areas	8,36%	10,62%	9,77%	10,56%	12,76%
Fruit tree plantations	4,59%	0,26%	0,92%	0,92%	1,19%

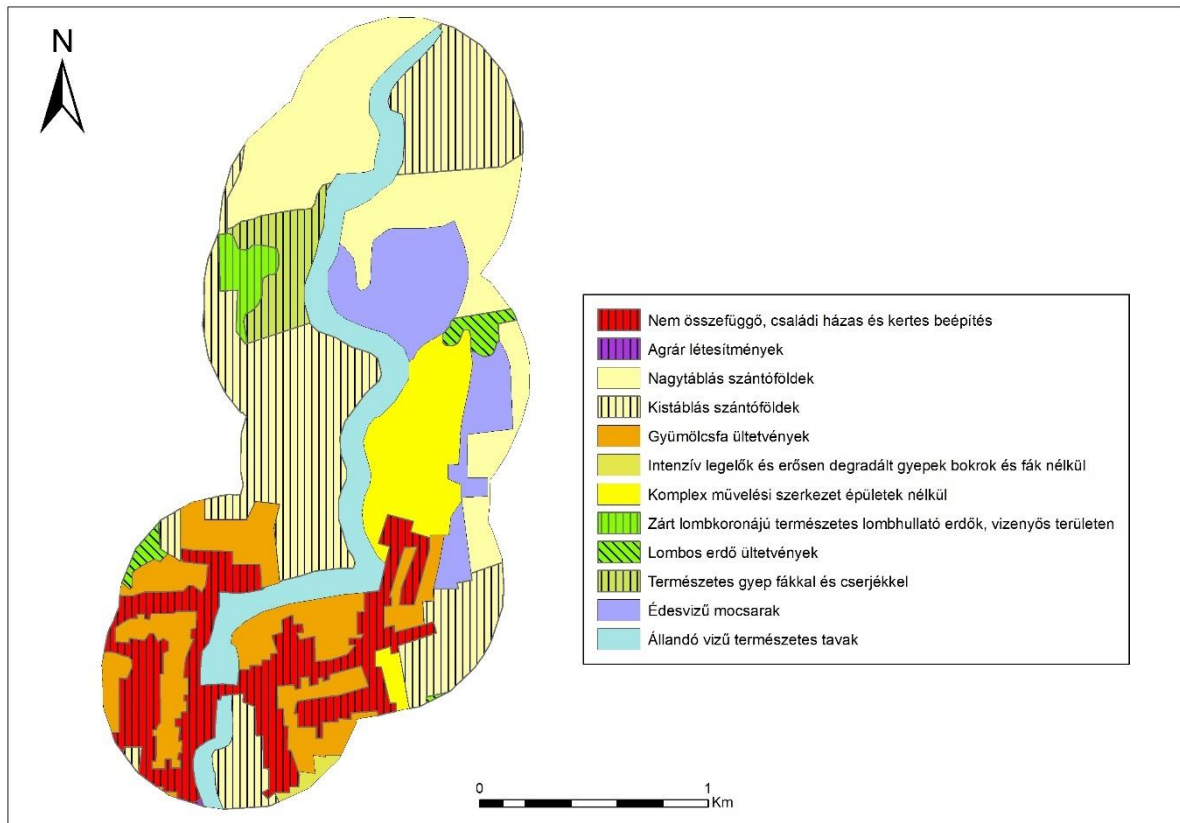
In the period following the change of regime, the forested area around the lake has increased significantly (Table 2), with both planted forests and the increasing forest cover along the shores. In addition to the low kappa value in Table 1, Table 3 shows that these wooded areas have not only increased but have also been reorganised by 2000. In fact, only 23.38% of the areas covered by forest in 2000 were still covered by forest in 1966. This means that only about 50% of the former forest remains. During this period, the largest increase in forest cover was at the expense of the arable land and garden category, which meant that 34% of the forest area measured in 2000 was previously in this land cover category. After the turn of the millennium, the proportion of forest area gradually increased (Table 2). This increase was typically due to the encroachment of shrub and bush areas in addition to the arable land already mentioned. Coastal willow-softwood forests occupy an increasingly wide band, but the acacia and poplar plantations identified during the survey have also expanded away from the coast in recent decades (Figure 1). The widening green corridors along the coast can provide an uninterrupted corridor for several kilometres of wildlife from the border to the interior.

1. Figure Surface cover maps of the 500 m radius of Karcza Lake based on images from different dates (A-1966, B-2000, C-2005, D-2007, E-2020)



Fruit tree plantations have undergone the greatest change (Table 1). Orchards once located east of the Dead Basin (Figure 1) have almost disappeared since the change of regime (Table 2). Their earlier existence is attested by an archival aerial photograph from 1979, which unfortunately could not be included in the analysis as it only covered part of our sample area. Some 86.72% of the area had been converted to arable land and gardens by 2000. Only a small part of their former extent was recovered by the plantations observed in 2005 and 2020 (Figure 1).

2. Figure Surface cover map of the 500 m radius of Karcsa Lake based on the CLC50 database



Grassland and heathland generally have the lowest Cohen's kappa values across all records (Table 1). The cross-tabulations (Tables 3, 4, 5 and 6) also show that these two categories are the most prone to change in almost all categories, but it should also be noted that in our case the potential for manual misclassification is also the highest.

3. Table Cross tabulation table of surface cover between 1966 and 2000

1966/ 2000	Forest	Plough, garden	Shrubby, scrubby area	Open water surface	Grassland	Marshes, waterfront vegetation	Built-up areas	Fruit tree plantations
Forest	23.38 %	2.21%	4.32%	0.31%	2.74%	1.27%	4.84%	0.44%
Plough, garden	34%	83.34 %	59.28%	0.07%	58.81%	31.34%	23.39 %	1.55%
Shrubby, scrubby area	16.05 %	1.28%	12.71%	0.9%	4.8%	0.15%	2.4%	0.66%
Open water surface	2.3%	0.04%	1.93%	84.32 %	1.59%	2.43%	0.14%	0%
Grassland	10.13 %	3.39%	12.19%	0.85%	19.6%	18.56%	4.36%	0.22%

Marshes, waterfront vegetation	11.84%	0.46%	5.83%	13.56%	4.29%	45.99%	1.21%	0%
Built-up areas	1.54%	2.11%	3.58%	0%	5.28%	0%	62.35%	0%
Fruit tree plantations	0.75%	7.16%	0.16%	0%	2.89%	0.25%	1.31%	97.12%

In contrast to the former categories, arable land is stable in both size and situation in the 2000s. Following the change of regime, their extent has decreased by an amount similar to that of orchards. This decrease can typically be attributed to a change in perception. Less suitable areas were also cultivated in earlier decades, so that ploughland often extended directly to the banks of the Karcsa (Figure 1).

4. Table Cross tabulation table of surface cover between 2000 and 2005

2000/2005	Forest	Plough, garden	Shrubby, scrubby area	Open water surface	Grassland	Marshes, waterfront vegetation	Built-up areas	Fruit tree plantations
Forest	74.96%	0.63%	6.45%	1.49%	4.36%	3.15%	1.15%	0.25%
Plough, garden	9.32%	94.67%	14.36%	0.00%	15.15%	4.68%	5.57%	81.03%
Shrubby, scrubby area	6.76%	1.36%	40.97%	2.41%	26.23%	4.99%	0.80%	0.00%
Open water surface	1.36%	0.00%	0.28%	89.76%	0.17%	9.56%	0.00%	0.00%
Grassland	2.92%	1.00%	7.89%	0.11%	36.92%	2.57%	3.49%	0.00%
Marshes, waterfront vegetation	1.03%	0.34%	23.87%	6.24%	14.46%	75.05%	0.00%	0.06%
Built-up areas	3.62%	1.85%	6.18%	0.00%	2.70%	0.00%	88.93%	0.00%
Fruit tree plantations	0.03%	0.16%	0.00%	0.00%	0.00%	0.00%	0.05%	18.65%

5. Table Cross tabulation table of surface cover between 2005 and 2007

2005/2007	Forest	Plough, garden	Shrubby,	Open water	Grassland	Marshes, waterfront	Built-up areas	Fruit tree plantations
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			scrubby area	surface		vegetation		
Forest	83.26%	1.20%	3.35%	1.22%	7.36%	5.79%	2.12%	0.13%
Plough, garden	5.48%	94.51%	8.77%	0.00%	12.01%	1.59%	9.98%	4.69%
Shrubby, scrubby area	4.73%	1.25%	49.13%	0.17%	16.42%	12.29%	3.36%	0.00%
Open water surface	0.93%	0.00%	0.00%	89.13%	0.00%	3.82%	0.00%	0.00%
Grassland	1.70%	1.90%	32.81%	0.12%	45.54%	0.82%	1.67%	0.00%
Marshes, waterfront vegetation	1.16%	0.26%	5.51%	9.35%	10.58%	75.68%	0.00%	0.00%
Built-up areas	2.60%	0.84%	0.44%	0.00%	8.10%	0.00%	82.87%	0.00%
Fruit tree plantations	0.14%	0.05%	0.00%	0.00%	0.00%	0.00%	0.00%	95.18%

6. Table Cross tabulation table of surface cover between 2007 and 2020

2007/2020	Forest	Plough, garden	Shrubby, scrubby area	Open water surface	Grassland	Marshes, waterfront vegetation	Built-up areas	Fruit tree plantations
Forest	62.97%	3.03%	4.94%	1.46%	5.04%	2.71%	6.29%	2.90%
Plough, garden	14.81%	89.93%	13.30%	0.00%	11.30%	4.47%	14.58%	22.91%
Shrubby, scrubby area	9.10%	2.68%	69.03%	0.00%	13.14%	16.86%	2.10%	0.10%
Open water surface	2.70%	0.00%	0.01%	88.47%	2.55%	3.78%	0.17%	0.00%
Grassland	3.96%	1.95%	6.82%	0.08%	16.39%	0.02%	4.41%	0.00%
Marshes, waterfront vegetation	4.74%	0.40%	3.77%	9.98%	50.37%	72.15%	0.66%	0.00%
Built-up areas	1.55%	1.90%	2.14%	0.00%	1.20%	0.00%	71.78%	3.64%

Fruit tree plantations	0.17%	0.12%	0.00%	0.00%	0.00%	0.00%	0.00%	70.45%
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Only the highest resolution CLC50 data from the Corine Land Cover database could be used in the study, which can be compared with the land cover map produced from the 2000 orthophoto (Figure 1 Map B). By visual inspection, we can determine whether similar or identical categories have been applied to the same areas during digitisation (Figure 2). When quantifying the individual categories of the thematic maps, we found that while the difference is almost negligible for wetlands, the difference increases for categories with more small polygons and more dispersed distribution, so that the area of built-up areas is almost 20% larger than the area of the CLC50 database for built-up areas and about 50% larger for the area of lakes. The forest areas with the narrowest and smallest polygons have been the most affected by generalization, and therefore the total area of those digitized by us is nearly 4 times the combined area of the *closed canopy natural deciduous forest*, *wetland* and *deciduous forest plantation* categories in the CLC50 database. In view of the above, it can be reiterated that the resolution of the Corine Land Cover database made it unsuitable to represent the land cover of the area in sufficient detail.

The time series study of the Karcsa Lake environment has provided us with the opportunity to understand the immediate environment of the dead pool and the changes that have occurred in it over the past half century or more. The changes over time in each of these categories of cover have been described in more detail previously. Overall, the land cover of the study area has undergone changes over the last decades that may help to maintain standing water, increase the ecological diversity of its surroundings and reduce its pressure. These include an almost threefold increase in forest cover and a reduction of almost 10% in the area of arable land and gardens. However, the increase in the proportion of built-up areas by a factor of one and a half over the period under review is a cause for concern, even though the municipality has also been the subject of a closed sewerage network since the turn of the millennium. And the various marshy areas are shrinking. Of course, without a detailed water chemistry analysis of the lake water, no definitive conclusions can be drawn as to whether the high proportion of built-up areas and ploughland means that the Karcsa is exposed to the organic matter, nitrate and phosphorus loads that would facilitate the processes that lead to the long-term recharge of the lake. In view of the above, it can be concluded that careful management and protection of Lake Karcsa is necessary. Without this, the pressures from the above-mentioned areas of land cover could contribute to the loss of open water, the proliferation of aquatic vegetation and the deterioration of water quality.

Palfai Aridity Index

To classify the results, the intervals in Table 7 are used in the literature (Pálfai, 1990; Pálfai, 2002). If the index is greater than 6, then drought is indicated. Thus, the higher the value, the higher the probability of drought.

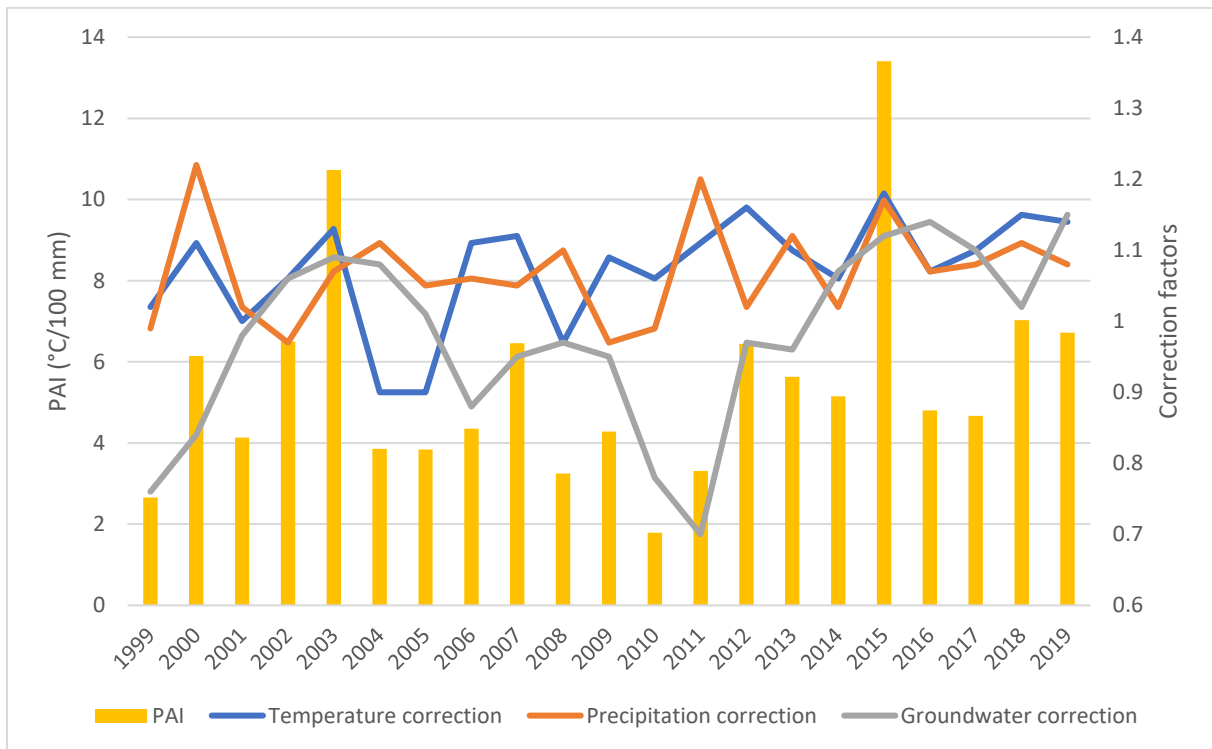
The final value of the PAI is still determined by 3 correction factors, so we have plotted their values in Figures 3 and 4 to illustrate their changes and, in turn, the effects on the PAI over time. As noted in the methodology, two sets of data were produced, one based on the E-OBS database (Figure 4) without calculation of the groundwater correction (1951-2019) and one based on data from the Water Directorate monitoring stations (Figure 3) and E-OBS temperature data (1999-2019).

7. Table Determination of the extent of drought based on the Pálfai Aridity Index (PAI) (Pálfai, 1990)

<6	drought-free year
6—8	moderate drought
8—10	moderate drought
10—12	severe drought
12<	extremely severe drought

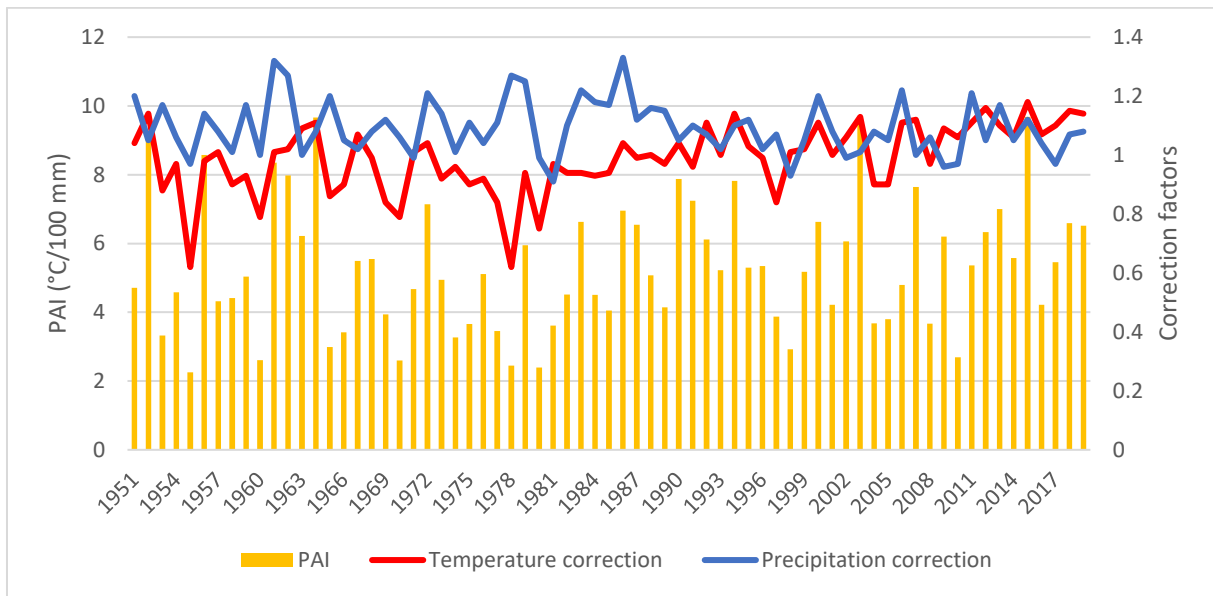
Even though the precipitation station in Cigand is located a few kilometres away from our sample area, its measured data series is still considered more relevant than the values obtained by interpolation of the E-OBS data series. 61.9% of the calculated index values were drought-free, while 38.1% were drought-prone, if we consider the severity of the droughts, we find that 75% of these 8 drought years were moderate drought, which allows us to classify our sample area in the moderate drought zone, similar to the categorization of Pálfai (1990). Due to the length of our 20-year data set, we cannot draw conclusions about trends. Based on the number of drought years, we cannot claim that the last decade has been exceptionally drier than the previous one. However, if we look at the decadal averages of PAI values, we see a significant increase of almost 30% over the period 2011-2019. It has increased from 4.9 in 2001-2010 to 6.4. Even if we exclude outliers in the data series, we see an increase of almost 10%. Examining the correction factors, their average values increased in the second decade after the millennium. The no precipitation factor increased by 5%, while the number of heat days increased by 8%. Groundwater levels typically follow slowly the current weather trends. Consequently, it was considered meaningful to exclude 2011 from the data set for the second decade, as it showed a similar spike in groundwater levels as 2010. The average of the remaining groundwater correction factors is thus 9% higher than between 2001 and 2010. However, to identify trends we also need to look at longer time series, which is why we have included E-OBS data sets in our analysis.

3. Figure Changes in the Palfai Aridity Index (PAI) and its adjustment factors over the period 1999-2019



Looking at the longer time series, we can see that while at the beginning of the period, drier decades alternated with wetter ones, the frequency of droughts has gradually increased over the last 40 years. In the period before the millennium, 70% of years were drought-free, while by the 2000s the proportion had fallen to 52.63%. The decadal average value of the index has also shown a steady increase over the last 4 decades. The average value for the years 2011-2019 has reached 6.3, while the previous maximum value was 5.6. The individual adjustment factors were also examined on a decadal basis. The average value per decade was 1.09, but it was above 1 in all cases. The mean, maximum and minimum values did not show significant variation. In contrast, the mean, maximum and minimum of the temperature correction factor have been increasing steadily since 1980. In the last decade, the increase in the mean value has reached 8%.

4. Figure Changes in the Palfai Aridity Index (PAI) and its adjustment factors from 1951 to 2019



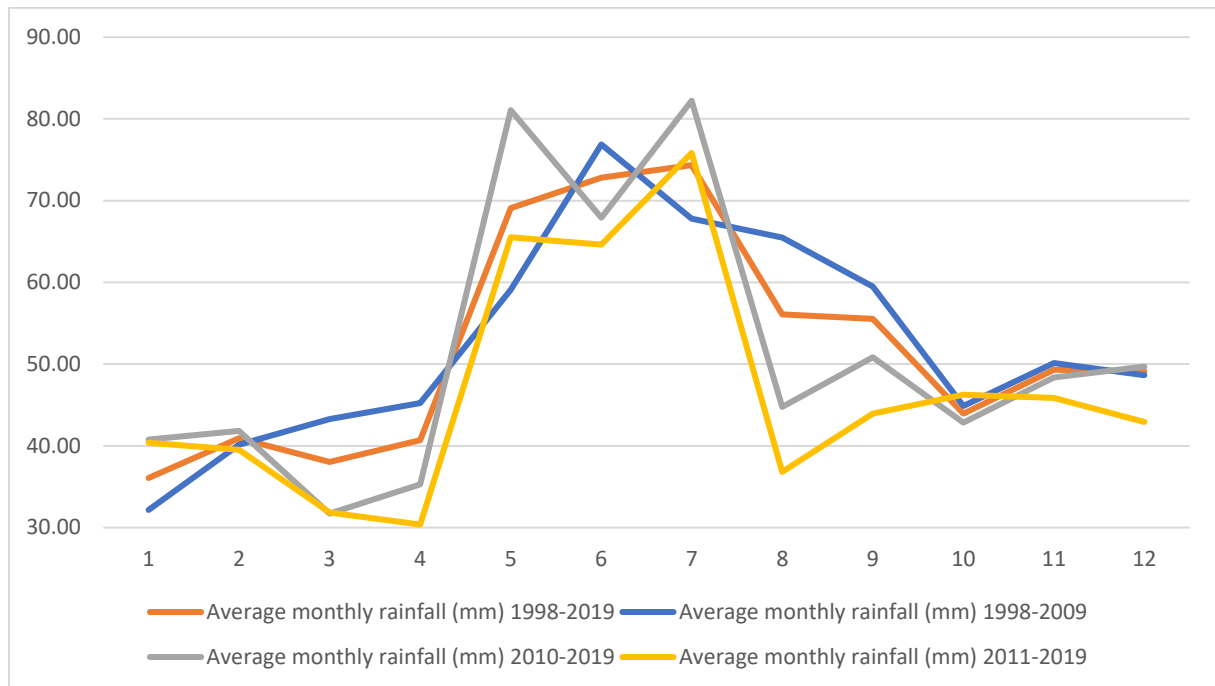
The increasing trend in the temperature correction factor points to an increase in the number of hot days in our sample area, which, like the decrease in groundwater level, could have a negative impact on the natural water balance of the dead pool in the short term. The increasing trend in the aridity index suggests that in the longer term the relationship between precipitation and temperature in the area could become more extreme, which, like the previous factors, confirms the importance of artificial recharge.

Analysis of hydrological data

In addition to examining the combined effects of precipitation and temperature, it was considered important to examine the amount and distribution of precipitation separately. In doing so, we divided the monthly mean rainfall database into two periods (Figure 5). Due to the extreme precipitation year 2010 (1098 mm), which lies approximately in the middle of our two-decade dataset, we produced two samples from the second period, one with the outlier and one without. Figure 4 shows sharply that by the second decade of the 2000s, the annual distribution of precipitation had become much more extreme. This was caused by a significant decrease in the average rainfall in early spring (-27% in March, -33% in April) and in late summer/early autumn (-44% in August, -27% in September). The former trend can also be observed in the data series for 2010.

The average annual rainfall during this period was 603 mm. The difference between the averages for the years before and after the 2010 outbreak is only 11% in favour of the former, which does not allow us to draw any major conclusions.

5. Figure Changes in monthly precipitation between 1998 and 2019 based on data from the Cigánd monitoring station



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