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From decadal runoff depletion to daily streamflow cycles: The role of riparian evapotranspiration in a forested catchment

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Abstract: This study investigates the role of evapotranspiration in the hydrological balance of the small forested Vydrica catchment (Slovakia) by linking long-term climatic trends with short-term streamflow dynamics. A 60-year mass balance analysis (1961–2020) was integrated with high-frequency streamflow observations across nine severe summer drought events (1992–2025). The long-term analysis revealed a paradoxical trend: despite a slight increase in precipitation, annual runoff significantly decreased. This decline is driven by rising air temperatures and increased evaporative demand, causing altered seasonal runoff distribution and more severe summer low flows. The short-term event analysis demonstrated that diurnal streamflow fluctuations are strongly controlled by available baseflow. During moderate droughts, active riparian vegetation generates distinct diurnal streamflow cycles with a typical six-hour lag behind maximum air temperature. However, during extreme low-flow periods, the diurnal amplitude flattens and evapotranspiration losses drop by an order of magnitude, indicating that the groundwater table has fallen below the effective root zone. The findings prove that climate-driven long-term warming continuously depletes baseflow reserves, progressively restricting the daily transpiration capacity and resilience of riparian forests.

Keywords: Evapotranspiration; Hydrological balance; Small forested catchment; Diurnal streamflow fluctuations; Low flows.

1 INTRODUCTION

The hydrological cycle in small catchments is the result of a complex interaction between climatic inputs, geological bedrock, and the character of the land cover. In recent decades, scientific attention has increasingly focused on the active role of vegetation, which is not merely a passive element of the landscape but a dynamic agent that significantly modifies the hydrological balance in catchments (Gribovszki et al., 2010). In particular, vegetation in riparian zones and forest stands with access to shallow groundwater functions as powerful "biological pumps." Through evapotranspiration (*ET*), they actively withdraw water from both the saturated and unsaturated zones of the soil profile (Bolla et al., 2025). This process exhibits a distinct daily (diurnal) cycle, driven by the availability of solar radiation and the physiological processes of plants. The consequences are measurable, regular fluctuations in the groundwater level and, subsequently, in the streamflow of adjacent watercourses.

The analysis of these daily signals has become a valuable tool for quantifying water consumption by vegetation, understanding interactions in the soil-plant-atmosphere system, and assessing the resilience of ecosystems to hydrological stress, such as drought (Gribovszki et al., 2010; Dobó et al., 2025). The phenomenon is well-documented: the basic mechanism causing daily fluctuations in groundwater levels and streamflow is directly linked to the photosynthetic cycle of plants (Troxell, 1936). During the day, when photosynthesis is active, plants open their stomata to uptake CO_2. However, through this process, they inevitably lose a large amount of water via transpiration. To compensate for this loss, the root system intensively draws water from the soil. If the roots reach the capillary fringe or directly the groundwater table, this uptake causes a local depression of the groundwater level. In small watercourses hydraulically connected to groundwater, this drop in the groundwater level reduces the hydraulic gradient towards the stream bed, leading to a reduction in baseflow and a measurable decrease in streamflow (Bond et al., 2002).

After sunset, photosynthesis ceases, stomata close, and transpiration is radically reduced. Water uptake by roots ceases, but groundwater continues to flow into the local depression. Since uptake is minimal but inflow continues, the system begins to regenerate, and the groundwater level rises. This process leads to the restoration of the hydraulic gradient and an increase in inflow to the watercourse, with streamflow reaching its maximum in the early morning hours, just before the resumption of transpiration (Lundquist and Cayan, 2002).

The amplitude of these daily fluctuations directly reflects the intensity and volume of water consumed by riparian vegetation (Glanville et al., 2023), making diurnal streamflow fluctuations a valuable indicator of actual evapotranspiration in small catchments.

Key observations from our own long-term experiments provide strong motivation for deeper research into evapotranspiration in our region. A comparison of the hydrological regime and water balance in three micro-catchments – Rybárik, Lesný, and Cingeľová (Pekárová et al., 2005, 2009) – situated in similar geological, orographic, and climatic conditions, showed that afforestation in small catchments reduces annual runoff. During the study period of 1964/65–1993/94, the runoff coefficient (the ratio of annual runoff to annual precipitation totals) in the agriculturally used

Rybárik micro-catchment ranged from 0.21 to 0.43, with an average of 0.32. In the case of the Lesný catchment (hornbeam stand), the ratio ranged from 0.1 to 0.37, with an average of 0.23. In the Cingeľová catchment (spruce forest), the runoff coefficient reached an average value of 0.26 (0.14–0.40) (see Fig. 1). Seasonal differences in runoff were more pronounced during the period without vegetation cover in the agricultural Rybárik catchment compared to runoff from the forested micro-catchments. In the months of April to June, runoff conditions in the catchments were similar and flows were comparable, whereas in dry summer periods, the hornbeam forest in the Lesný catchment consumed the most water for transpiration compared to the agriculturally used catchment.

These results clearly demonstrate the decisive role of forest vegetation in regulating runoff, yet the question remains insufficiently explained at the level of short-term, daily processes.

The foundations for quantifying evapotranspiration from groundwater were laid by White (1932), whose method remains the basis for many modern approaches. Gribovszki et al. (2008, 2010) and other authors modified and refined this method using high-frequency water level measurements. These methods allow not only for the estimation of total daily water consumption but also for the analysis of water management strategies of different plant species.

The study by Dobó et al. (2025) in the Danube Lowland is an example of such an analysis. By comparing daily fluctuations under a stand of pedunculate oak (Quercus robur) and hybrid poplar (Populus euramericana), the authors showed that poplar has a higher overall water consumption, which is reflected in larger seasonal and daily water level drops. At the same time, however, they found that during dry years, the oak's dependence on groundwater increased, while the poplar's uptake decreased, likely due to the falling groundwater level dropping below its effective root zone.

The intensity and character of daily fluctuations are influenced by several factors:

- Species composition and vegetation structure: Different tree species have different root depths, leaf area densities, and physiological regulation of transpiration, leading to different water uptake strategies (Dobó et al., 2025). Invasive species, such as Tamarix spp., can have extremely high water consumption and dramatically alter the hydrological regime (Goodrich et al., 2000).
- Hydrological and meteorological conditions: The amplitude of fluctuation is greatest during warm, sunny, and dry days. After precipitation events, the daily signal significantly diminishes or temporarily disappears because vegetation prefers more readily available water from soil moisture (Barnard et al., 2010; Dobó et al., 2025).
- Geomorphology and hydraulic properties: The width of the riparian zone, the permeability of sediments, and the degree of hydraulic connection between the stream bed and the surrounding aquifer determine how quickly and to what extent water uptake by vegetation is reflected in streamflow (Covino et al., 2011).
- Catchment size: Daily fluctuations are best observed in small catchments where the signal is not masked by other hydrological processes. In larger rivers, this effect is usually negligible (Lundquist and Cayan, 2002).

Although long-term analyses demonstrate the impact of rising temperatures on runoff reduction, we lack a deeper understanding of the mechanisms by which evapotranspiration regulates the daily and seasonal dynamics of runoff in small forested catchments. Specifically:

- How exactly do diurnal streamflow fluctuations in the summer/autumn period reflect the magnitude of evapotranspiration, and how much water is lost daily during progressive drought stages?
- What is the time lag between maximum air temperature and minimum streamflow, and what does this tell us about the dynamics of water movement in the soil?
- To what extent do changes in the hydrological balance (runoff decrease with rising air temperature) translate into seasonal runoff changes, and what role does vegetation play in this transformation?

The objectives of this work are:

- To quantify long-term trends in runoff, precipitation and temperature and to evaluate the changes in the **hydrological water balance** in the small forested Vydrica catchment up to the Spariská station (7.25 km²) in the Bratislava Forest Park over the period 1961–2020.
- To evaluate the **short-term dynamics of actual evapotranspiration** during nine severe, rainless summer drought events spanning over three decades (1992–2025) using high-frequency streamflow measurements (1-hour step, 15-minute step). and to determine the time lag between maximum air temperature and minimum streamflow (phase shift).

By combining long-term water balance analysis with short-term monitoring historical drought events, we aim to provide a comprehensive understanding of ecohydrological feedbacks to climate change, demonstrating how continuous long-term water depletion restricts the daily transpiration capacity of riparian forests.

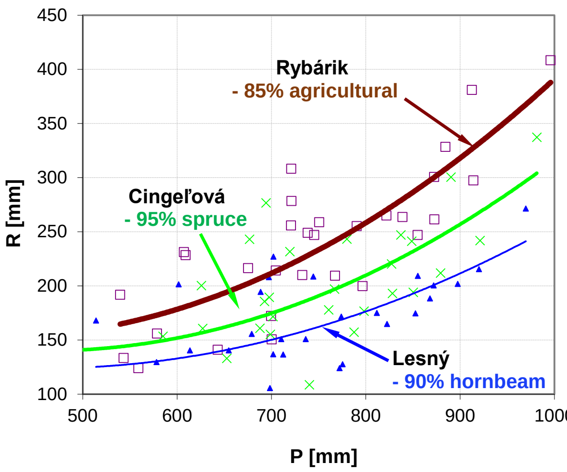


Fig. 1. Relationship between annual runoff (*R*) and annual precipitation totals (*P*) (years 1964/65-1993/94) in three experimental micro-catchments of IH SAS.

2 STUDY AREA

2.1 Description of the Vydrica stream catchment up to the Spariská gauging station

2.1.1 Hydrological conditions

The Vydrica stream catchment originates in the Dubové area near Biely Kríž in the Little Carpathians near Bratislava. It flows into the Danube near the Lafranconi bridge. Up to its confluence with the Danube River, it has an area of 32.05 km^2 and a length of 17 km (Fig. 2). Two gauging stations were built in the Vydrica catchment: the Spariská station (est. 1926) and the Červený most station (est. 1928). The average flow at the mouth of the Vydrica stream was approximately 0.22 m^3s^{-1}. However, the upper catchment extending to the Spariská gauging station is crucial for the purposes of this study. Between 1942–1960, observations were interrupted. The continuous observations that form the basis of this work have been conducted at the Spariská station since 1961. The altitude in the upper part of the catchment up to the Spariská gauging station varies from 321 m a.s.l. to 589 m a.s.l. (Malý Javorník). The average altitude of the catchment is approx. 405 m a.s.l. The Spariská station is located at river kilometer 11.50 km; the catchment area is 7.25 km^2; the altitude of the gauge zero is 321.02 m a.s.l. The length of the valley is 5.8 km, and the shape characteristic of the catchment is 0.22. For Vydrica, as for most streams in the Pezinok Carpathians, a rain-snow type of river runoff is typical, with the highest average monthly flows in March and the lowest in August and September. A significant part of the Vydrica stream is situated within the Little Carpathians Protected Landscape Area (PLA). Since February 2022, the Vydrica Nature Reserve has been declared within the stream's catchment, increasing the level of protection from the second to the fourth and fifth levels, thereby ensuring the long-term stability of the vegetation cover without significant logging interventions.

2.1.2 Geological conditions

The Vydrica catchment is located in the Little Carpathians, which are mainly formed by Mesozoic sedimentary rocks such as sandstones, shales, and limestones. These rocks affect the permeability and storage capacity of groundwater, which has a significant impact on the hydrological regime of the catchment. In the floodplain areas of the stream, there are Quaternary fluvial sediments, which form the main aquifer in the area. Groundwater circulation in these sediments is tied to the riparian, sub-slope, and central mixed zones, which differ in the way groundwater is replenished and moves (Urbánek and Novotný, 2012). The predominant soil type in the catchment is modal cambisol, mainly associated with slope and sub-slope sediments.

2.1.3 Vegetation

The Vydrica catchment up to the Spariská station is part of the Bratislava forest park zone, which is used mainly by the city's inhabitants for recreational purposes and partly for timber harvesting. The Bratislava Forest Park was declared on the southeastern slopes of the Carpathian massif in 1973. Currently, the catchment up to the Spariská station is more than 90% forested. The dominant tree species is European beech (Fagus sylvatica), which in certain places forms tall, homogeneous stands. Among coniferous trees, Scots pine (Pinus sylvestris) and Norway spruce (Picea abies) are the most common in the area. Ash-alder submontane floodplain forests also play an important role, lining a significant part of the Vydrica stream banks. These communities are characterized by the dominance of black alder (Alnus glutinosa) and common ash (Fraxinus excelsior), thus contributing to the significant diversity and ecological stability of the locality.

3 DATA AND METHODS

3.1 Hydrological balance

In the first part of the study, average daily discharge from the Vydrica: Spariská station were used for the period 1961–2020, along with daily precipitation totals, and average daily air temperatures for the catchment, estimated from the Bratislava-Koliba and Malý Javorník meteorological stations. The data are provided by the Slovak Hydrometeorological Institute (SHMÚ). The Vydrica catchment area up to Spariská station belongs to moderately warm climatic region M1 (Climatic regions of Slovakia, 2015). To present the long-term development of air temperature in the Vydrica catchment, we utilized data from the station Bratislava–Koliba, where secular changes and long-term trends can be assessed using the air temperature series originally derived by Konček (1979). Fig. 3a shows the series of average annual air temperatures for the 250-year period 1775–2024 (data source: http://www.zamg.ac.at/histalp, supplemented by the authors). This series represents the development of air temperature at the Bratislava: Koliba station (48°10'07", 17°06'38", 287 m a.s.l.). Until 1990, the 30-year average air temperatures ranged between 8.41–9.34 °C. In the 30-year period 1991–2020, the air long term average temperature reached 10.65 °C, and the last 10-year period 2011–2020 was the warmest with 11.45 °C. The area is characterized by high windiness, especially around the Devín and Lamač Gates, which affects the microclimatic conditions and evapotranspiration in the catchment (Polčák and Šťastný, 2011).

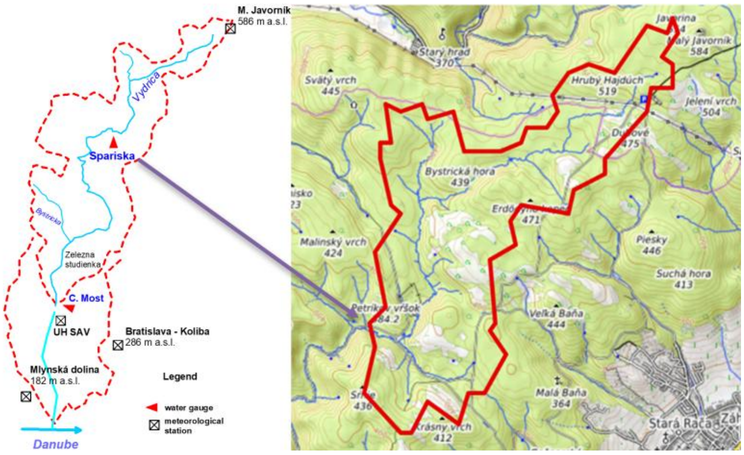


Fig. 2. Scheme of the Vydrica catchment to its confluence with the Danube, gauging stations in the catchment and meteorological stations in the vicinity of the Vydrica catchment (left), Vydrica stream catchment up to the Spariská gauging station (right).

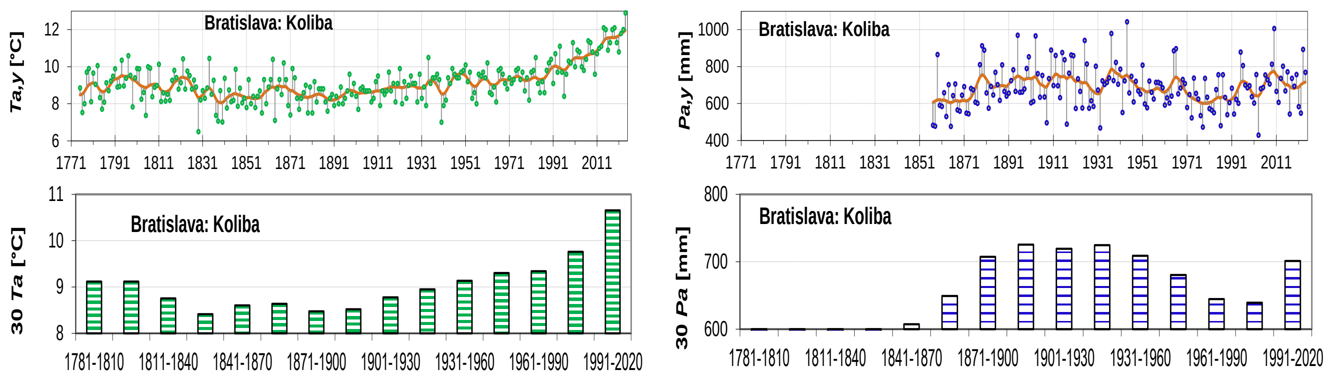


Fig. 3. Development of average annual air temperature, annual precipitation totals, and 30-year averages of air temperature and annual precipitation totals at the Bratislava: Koliba station..

The hydrological balance in the catchment was compiled based on long-term time series of annual areal precipitation, air temperature and discharge series from the 60-year period 1961–2020. At this time step, it is assumed that the change in water storage in the soil and groundwater is negligible, as seasonal fluctuations balance out in the long-term average (Keszeliová, et al., 2021). The basic components of the balance are the precipitation total (*P*), runoff from the catchment (*Q*), and actual evapotranspiration (*ET*). In this simplified form, the hydrological balance can be expressed by the equation:

$$P = Q + ET. \quad (1)$$

Areal precipitation totals were determined by spatial averaging using data from the Bratislava: Koliba (long-term series 1951–2020) and Malý Javorník (data available since 1981) meteorological stations. For the period of overlapping observations (1981–2020), we first derived the relationship between precipitation totals from both stations and the mean catchment altitude (vertical precipitation gradient). This ratio was then applied to correct (reconstruct) precipitation totals for the entire catchment for the period prior to 1980, when only data from the Bratislava–Koliba station was available. Runoff was determined based on measured flows in the closing profile of the catchment. By calculating the balance for different periods, it is possible to identify changes in the hydrological cycle (Vargas Godoy et al., 2024; Keszeliová, et al., 2021).

3.2 Decrease in runoff caused by water transpiration by vegetation

For the second part of the study, dry periods with extremely low hourly water levels occurring between June and September were selected from the SHMÚ (Slovak Hydrometeorological Institute) database starting from the year 1992. The following extremely dry periods were chosen, representing conditions under which it can be robustly assumed that the streamflow in the Vydrica River consisted entirely of groundwater baseflow:

- 15. 08. 2025–20. 08. 2025
- 01. 09. 2024–08. 09. 2024
- 19. 07. 2023–24. 07. 2023
- 01. 08. 2022–04. 08. 2022
- 04. 07. 2021–10. 07. 2021
- 12. 09. 2020–20. 09. 2020
- 01. 07. 2018–04. 07. 2018
- 08. 08. 1998–17. 08. 1998
- 22. 09. 1992–28. 09. 1992

Water level data for the Vydrica stream were available at an hourly time step, with the exception of the year 2025, for which 15-minute resolution data were provided. The selection of a period representing pure groundwater discharge (baseflow) is illustrated in Figure 4a, based on the 24-hour fluctuations of water levels in the Vydrica stream observed in July 2023.

When determining the decrease in runoff caused by water transpiration by vegetation, it is important to correctly estimate the discharge at very low water levels. The weir at the Vydrica gauging station has a triangular shape. Figure 4b shows scheme of the gauging station weir, and Figure 4c photos of the Vydrica catchment. A staff gauge is attached to the vertical wall of the weir structure, where a limnigraph was historically located. During previous field experiments, we performed several hydrometric discharge measurements at this station (Pekárová and Pekár, 1998). During field measurements on August 20 at 13:00 MEDT, a discharge of 0.003 $m^3 s^{-1}$ was recorded at a water stage (WS) of 11 cm. The rating curve for low flows (WS <20 cm) was derived from the hydraulic geometry (triangular cross-section of aged concrete with natural sediment accumulation) and calibrated against this in-situ discharge measurement. Computed discharge values were compared with SHMI data from September 2024.

Based on our observations, for water levels of 5 to 20 cm at the Vydrica: Spariská station (Fig. 4b), we derived an empirical equation for the indirect estimation of discharges *Q* [m^3s^{-1}] in the form:

$$Q = 0.000235 \exp(0.22203\, WS) \quad (2)$$

where: *WS* – water levels in cm.

Using this relationship, we have converted low water levels to discharges since January 1, 2008.

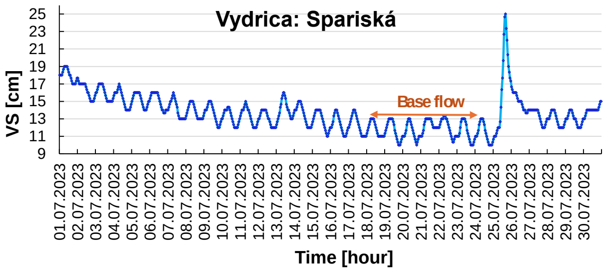
Meteorological data for the August 2025 low flow period were obtained from the meteorological station of the Institute of Hydrology SAS on Dúbravská cesta, recorded at 10-minute intervals. Data were recalculated to a 15-minute time step.

3.2.1 Method of estimation of the amount of evaporated groundwater

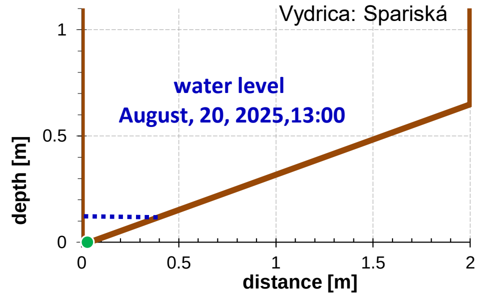
The methodology for estimating evaporated groundwater in the Vydrica catchment is demonstrated using the example of low flows from August 2025. Based on the rating curve (eq. 2) for low water levels measurements, the discharges of the Vydrica at the Spariská station were estimated at a 15-minute interval. On Fig. 5, the discharges of the Vydrica in liters per second during the rainless hot period of Aug 13–21, 2025, are plotted with blue triangles. The orange line shows what the baseflow in the

Vydrica stream would be if there were no evapotranspiration (Aug 15–21, 2025). The green line shows the amount of missing water – i.e., the amount of evaporated water. The other lines show the courses of selected meteorological data (air temperature, water temperature at Spariská water gauge, solar radiation and humidity).

The daily amplitude was determined as the difference between the maximum and minimum of the residual flow. The flow deficit during the day was then converted to specific runoff and recalculated to the height of evaporation (mm·day^{-1}) relative to the catchment area. This value may be interpreted as an estimate of daily evaporation from Vydrica basin.



a)



b)

c)

Fig. 4. a) Diurnal fluctuation of the water level at Vydrica: Spariská, July 2023. The selection of a period representing groundwater discharge (baseflow).
b) Diagram of the gauging station weir, the green dot indicates the location of the datalogger for measuring water level and temperature.
c) Source of the Vydrica (Photo: Miklánek 29. 03. 2017); Malý Javorník – catchment peak, meteorological station; Gauging station Vydrica: Spariská. (Photo: Bezák 27. 04. 2005 and Bajtek, 20. 08. 2025).

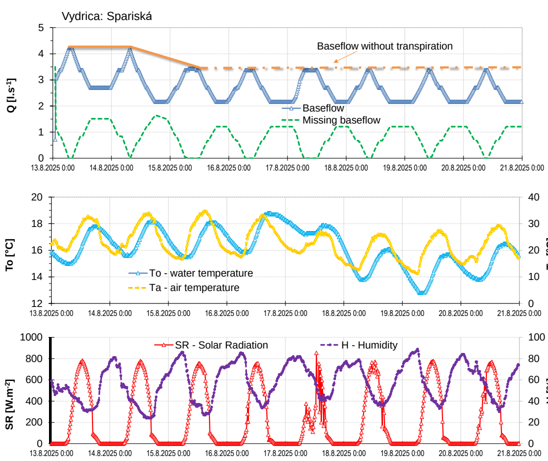


Fig. 5. The course of 15-minute flows of the Vydrica at the Spariská station and the amount of evaporated water (orange line). Measured meteorological data, Bratislava, Dúbravská cesta, 15-minute values, August 15–21, 2025.

This identical separation methodology was subsequently applied to all selected low-flow events to quantify the evapotranspiration-induced discharge deficit across different levels of baseflow.

4 RESULTS

4.1 Hydrological balance in the Vydrica catchment

4.1.1 Long term variability and trends

The measured series of daily discharges (period 1961–2020) were statistically evaluated in detail. The basic hydrological characteristics of the daily discharges *Qd* at the Spariská station for three periods (1961–1990, 1991–2020, and the full period 1961–2020) are presented in Table 1. The first 30-year period was wetter, with an average annual runoff depth reaching 261 mm. In the second period (1991–2020), variability was higher, while the average annual runoff was lower (240 mm).

Table 1. Basic characteristics of the average daily discharges *Qd* of the Vydrica stream at the Spariská water gauge. *Qd,av* – average daily discharge, *Qd,min* – minimum daily discharge; *Qd,max* – maximum daily discharge; *Qd,330* – refers to the flow value exceeded 330 days per year; *cs* – coefficient of skewness, *cv* – coefficient of variability.

	Qd,av [m^3s^{-1}]	***Qd,min*** [m^3s^{-1}]	***Qd,max*** [m^3s^{-1}]	***Qd,330*** [m^3s^{-1}]	***cs***	***cv***
1961–1990	0.0599	0.0010	1.1300	0.0090	3.7491	1.34
1991–2020	0.0552	0.0009	2.5690	0.0065	8.6113	1.67
1961–2020	0.0575	0.0009	2.5690	0.0070	6.6830	1.50

Average daily discharges for the observation period 1961–2023 are plotted in Fig. 6 on the lower graph in dark blue. The multi-year fluctuation is presented using 4-year moving averages (in a daily step) with a light blue line. The long-term polynomial trend of flows in this period is shown by the orange line. In an analogous way, daily precipitation totals from the Malý Javorník (1981–September 2024) and Koliba (1950–September 2024) meteorological stations are presented. During the period 1981–2020, the course of the linear trend for precipitation is rising, while for runoff it is decreasing (red line).

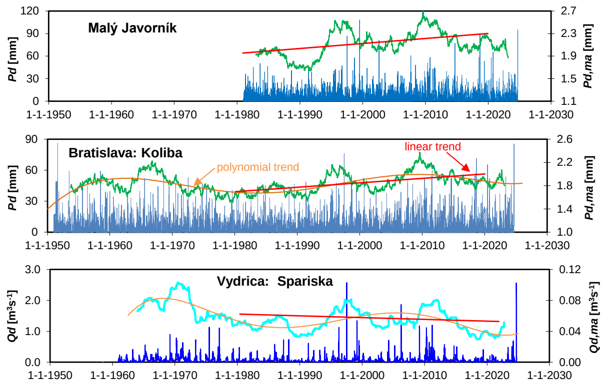


Fig. 6. Daily precipitation totals (*Pd* - grey-blue color) and 4-year moving averages of daily precipitation totals (*Pd,ma* - green color) from the meteorological stations Malý Javorník and Koliba for the period 1981, and 1950–September 2024 respectively. Average daily discharges at the Vydrica: Spariská gauging station (*Qd* - blue color) and the course of 4-year moving averages of daily discharges (*Qd,ma* - light blue color) for the period 1961–2023**.**

The average annual flow for the period 1961–2020 was 0.0575 m^3s^{-1}, the minimum average annual flow was in 2022 (0.01 m^3s^{-1}) and the maximum was in 1970 at 0.144 m^3s^{-1}. In the period 1929–1940, the long-term average annual flow was 0.078 m^3s^{-1}.

In Figure 7, it is possible to visually compare the changes in discharges (a) and precipitations (b) between two 30-year periods, 1961–1990 and 1991–2020, using the 10th and 50th percentiles of discharges along with long-term monthly precipitation totals. A paradoxical trend is observed: although precipitation totals in the second period are actually higher in July and October, runoff during the summer months (July–September) has significantly decreased. This decoupling confirms that the observed hydrological shifts, specifically the earlier onset of spring high flows and the intensification of summer low flows, are not caused by precipitation deficits but are primarily driven by rising air temperatures and the resulting increase in evapotranspiration demand.

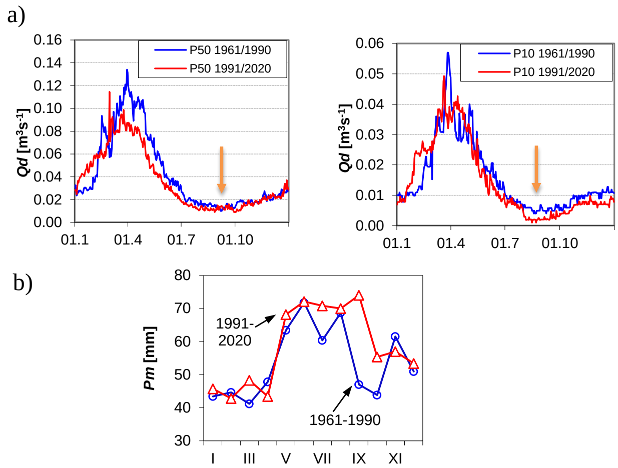


Fig. 7. a) Comparison of the 50th percentiles (P50) (left) and 10th percentiles (P10) for two 30-year periods in a daily step, Vydrica: Spariská. b) Comparison of the long-term monthly precipitation totals for two 30-year periods, Bratislava-Koliba precipitation gauge.

4.1.2 Changes in the hydrological balance of the Vydrica catchment at the Spariská station

Figure 8 presents the long-term course of annual precipitation totals (*P*), annual runoff depths (*R*), and annual balance evapotranspiration (*ET*) in mm. It should be noted that water level observations were interrupted between 1941 and 1960. The upper graph displays the average annual air temperatures recorded at the Bratislava-Koliba station.

The highest runoff during the observed period was measured in 1970, up to 627 mm. In 1970 and 1971, the flows (or precipitation totals) of the Vydrica were evaluated with a high probability of being incorrect; the annual runoff is extremely high with a simultaneous absence of precipitation in these two years. The second highest annual runoff was measured in 1938 (570 mm) and the third in 2010 (517 mm). The lowest runoff was recorded in 2022, only 45 mm, then in 1990 – 83 mm.

Based on the data provided in Table 2, an increase in mean air temperature of 1.31 °C between the second (1961–1990) and third (1991–2020) observation periods was accompanied by a 64 mm rise in precipitation. However, this increased precipitation input did not translate into higher streamflow; instead, it resulted in a 85 mm rise in actual balance evapotranspiration and a corresponding 21 mm decrease in runoff. According to Hrvoľ et al. (2009), the long-term actual evapotranspiration in the xerothermic oak altitudinal vegetation stage in southern Slovakia during the period 1971–2020 was 460.9 mm. This value is consistent with our estimate of 481 mm for the same period. Báder (2025) reports that in the Danube River basin, the 30-year average evaporation increased by 29 mm (from 482 mm to 507 mm) when comparing the periods 1961–1990 and 1991–2020. Our results are higher.

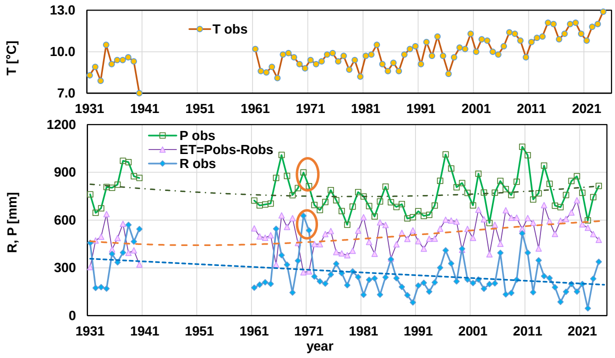


Fig. 8. Annual values of air temperature *T*, annual precipitation totals *P*, annual runoff depth *R*, and water balance-based evapotranspiration *ET* Vydrica: Sparišká.

Table 2. Hydrological balance of the Vydrica stream up to the Spariská station for 4 periods: 1931–1940 (according to Zídek, 1967), 1961–1990, 1991–2020, and 1961–2020. *P* - precipitation total for the catchment, *R* - annual runoff depth, *ET* - actual water balance evapotranspiration (*eq. 1*).

Period	*P* [mm]	*R* [mm]	*ET* [mm]	*T* [°C]
1931–1940	819	368	451	8.94
1961–1991	734	261	473	9.34
1991–2020	798	240	558	10.65
1961–2020	766	250	511	10.0

4.2 Influence of baseflow magnitude on diurnal streamflow fluctuations and riparian evapotranspiration

The analysis of nine dry-period events revealed a clear positive relationship between mean daily discharge and evapotranspiration-related discharge loss. Mean daily discharge (*Qd*) ranged from 1.71 to 10.62 $l.s^{-1}$, while the estimated evapotranspiration loss (*Qv*) ranged from 0.145 to 2.296 $l.s^{-1}$. The corresponding specific discharge (*q*) varied between 0.020 and 0.317 $l.s^{-1}.km^{-2}$, and the daily runoff-depth equivalent (*R*) ranged from 0.0016 to 0.0274 $mm.day^{-1}$.

Figs. 9a-d show that the amplitude of diurnal streamflow fluctuation decreases markedly with declining catchment water availability. During higher-flow periods, riparian vegetation has better access to groundwater and produces pronounced daytime water losses. During severe drought, the daily fluctuation becomes much smaller, indicating reduced groundwater availability in the near-stream zone and a weaker evapotranspiration signal.

The highest evapotranspiration losses were observed during events with the highest baseflow. Under these conditions, riparian vegetation likely had direct and sustained access to shallow groundwater, which allowed strong daytime water uptake and a pronounced diurnal discharge cycle. In contrast, during extreme low-flow periods, groundwater levels likely fell below the rooting zone of riparian vegetation, limiting transpiration and thus damping the diurnal streamflow fluctuations (Huang et al., 2024). This suggests that groundwater levels declined below the most active part of the root zone, reducing plant access to water and weakening the hydrological response in the stream.

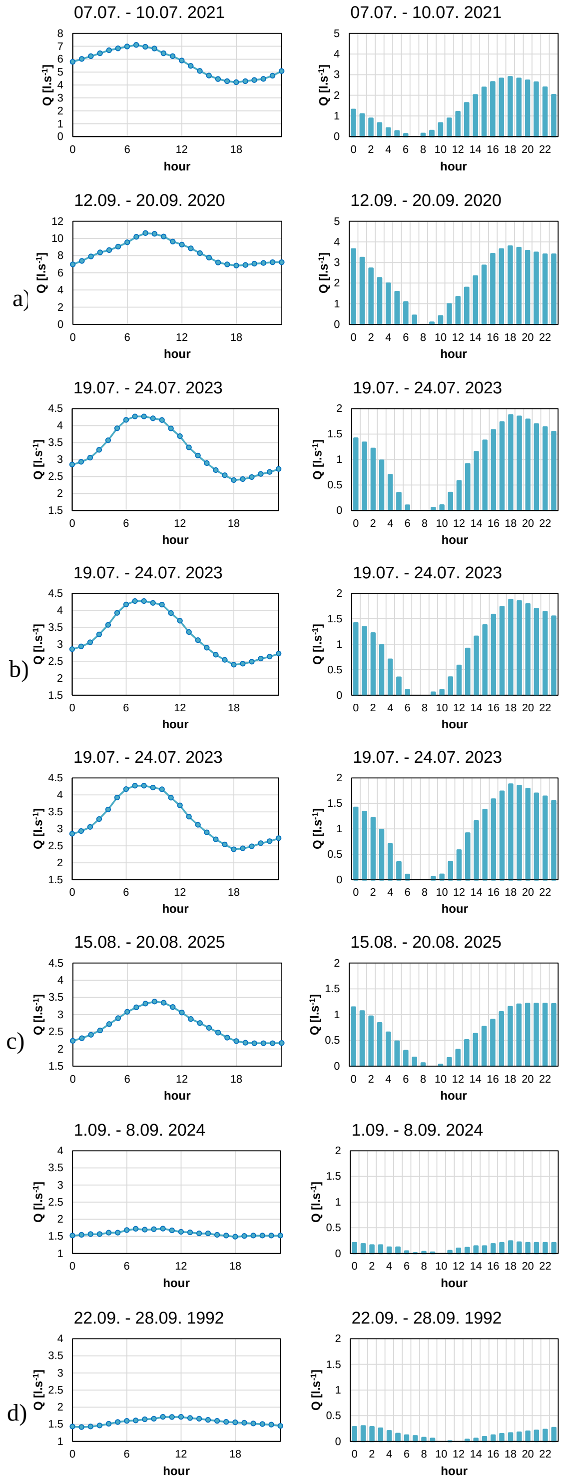


Fig. 9. Mean diurnal courses of streamflow (left) and estimated evapotranspiration-induced discharge losses (right) for selected rainless periods in the forested Vydrica catchment. The events were grouped into four classes according to mean daily discharge: (a) high-flow conditions, (b) moderately high-flow conditions, (c) low-flow conditions, and (d) extreme low-flow conditions.

Table 3. Hydrological characteristics of nine selected dry-period events in the Vydrica catchment, showing the relationship between mean daily discharge (*Qd*) and estimated evapotranspiration losses.

	12.9.2020–20.9.2020	4.7.2021–10.7.2021	19.7.2023–24.7.2023	8.8.1998–17.8.1998	1.7.2018–4.7.2018	15.8.2025–20.8.2025	1.8.2022–4.8.2022	1.9.2024–8.9.2024	22.9.1992–28.9.1992
Qd [$l.s^{-1}$]	10.62	7.10	4.27	4.21	4.11	3.38	2.43	1.72	1.71
Qv [$l.s^{-1}$]	2.296	1.451	1.014	0.818	0.747	0.717	0.439	0.135	0.145
Q [$l.s^{-1}.km^{-2}$]	0.317	0.200	0.140	0.113	0.103	0.099	0.061	0.019	0.020
R [$mm.day^{-1}$]	0.0274	0.0173	0.0121	0.0097	0.0089	0.0085	0.0052	0.0016	0.0017
Hr [hour]	8	7	7.5	8	7.5	9	8	10	11

Note: *Qd* = mean daily discharge; *Qv* = mean daily discharge loss caused by evapotranspiration; *q* = specific discharge; *R* = daily runoff-depth equivalent of evapotranspiration loss calculated for the entire catchment area; *Hr* = time of maximum streamflow recovery.

A second important feature is the shift in the timing of streamflow recovery. In higher-flow periods, the daily streamflow maximum, corresponding to the time of minimum evapotranspiration impact, occurred earlier, typically around 07:00–08:00. In lower-flow periods, this recovery was delayed to approximately 10:00–11:00. This shift indicates slower hydraulic replenishment of the riparian zone during drought, probably caused by a reduced hydraulic gradient and lower effective conductivity of the drying shallow aquifer.

Overall, the results indicate that the diurnal signal in streamflow is strongest when the catchment retains sufficient groundwater storage and weakest during advanced drought. The observed pattern supports the interpretation that the diurnal fluctuation is controlled mainly by evapotranspiration from the riparian zone hydraulically connected to the stream, rather than by the entire catchment area.

The peak solar radiation occurs at 13:00 CEST. According to the measurements of Molnár and Mészáros (1995) conducted in the summer of 1994, the daily maximum transpiration of a representative ash tree occurs between 13:00 and 15:00 CEST, with daily transpired water ranging from 50 to 550 liters.

- The time lag between solar radiation and air temperature is 2 hours.
- The time lag between air temperature and water temperature at the Spariská station was 3 hours and 45 minutes.

5 DISCUSSION

Our results demonstrate that evapotranspiration is the dominant factor shaping the hydrological regime of small forested catchments across both long-term and short-term scales. The long-term mass balance analysis of the Vydrica catchment (1961–2020) revealed a paradoxical trend: although precipitation totals have not decreased, runoff has shown a statistically significant decline. This apparent imbalance is driven by rising air temperatures, which increase evaporative demand and thus intensify actual evapotranspiration. This shift manifests not only in reduced annual runoff depths but also in altered seasonal distribution—spring high flows occur earlier, while summer low flows become more severe and prolonged. These findings are consistent with observations from other catchments (Giese et al., 2025) and confirm that climate-induced changes in air temperature and evapotranspiration play a more critical role in runoff reduction than precipitation variability alone.

Comparable macro-scale results have been reported across Europe. Teuling et al. (2013) demonstrated that evapotranspiration amplifies European summer droughts by deepening soil moisture deficits and reducing streamflow, which agrees with our findings in the Little Carpathians. Masseroni et al. (2021) analyzed 63 years of streamflow records across Europe and found significant reductions in runoff volumes, largely driven by rising evaporation. Similarly, Bruno et al. (2025) and Deman and Boé (2025) projected that future reductions in runoff will be increasingly determined by changes in evapotranspiration and seasonality rather than precipitation totals. However, while these large-scale studies confirm the trend, they rarely capture how these long-term deficits physically manifest at the scale of daily catchment processes.

To bridge this gap, the second part of our study utilized high-frequency streamflow monitoring to evaluate diurnal streamflow fluctuations across nine severe summer drought events spanning over three decades (1992–2025). This approach addresses the critical question of how the long-term depletion of catchment water storage restricts the short-term physiological functions of the riparian forest. Our multi-event analysis revealed a strong positive correlation between the magnitude of the baseflow and the volume of water lost to diurnal evapotranspiration. During early stages of summer drought (when baseflow exceeds 4 $l \cdot s^{-1}$), riparian trees act as efficient "biological pumps," inducing distinct diurnal oscillations with losses exceeding 1 to 2 $l \cdot s^{-1}$. This confirms the findings of Gribovszki et al. (2010) and Lupon et al. (2016), who demonstrated that riparian evapotranspiration significantly influences stream hydrology by extracting several millimeters of water per day directly from the shallow aquifer.

However, our comparison of multiple drought events clearly showed that as the drought progresses and baseflow drops below critical thresholds (e.g., below 2 $l \cdot s^{-1}$ in September 1992 or September 2024), the daily evapotranspiration signal almost disappears, falling by an order of magnitude. This flattening of the diurnal amplitude indicates that the groundwater table has dropped below the effective root zone, triggering physiological water stress and stomatal closure in the riparian vegetation. The observed six-hour lag between maximum air temperature and minimum streamflow further highlights the buffering role of groundwater storage and its diminishing efficiency during severe water deficits.

Thus, our study provides a mechanistic link between the two investigated scales: the long-term climate warming increases the overall evaporative demand, causing a structural decline in summer baseflow, which eventually forces the forest vegetation into severe short-term water stress, suppressing the diurnal transpiration cycle. High-frequency sub-daily monitoring (as also validated by Tian et al., 2024, and Fahle and Dietrich, 2014) is therefore not just a supplementary tool, but an essential method for understanding the true ecohydrological impacts of prolonged climate-driven droughts on forest resilience.

6 CONCLUSIONS

The present study bridges the gap between long-term hydrological mass balance changes and short-term ecohydrological processes by integrating a 60-year trend analysis (1961–2020) with high-frequency streamflow monitoring across nine summer drought events spanning over three decades (1992–2025). Rather than viewing decadal trends and daily fluctuations as separate phenomena, this dual-scale approach highlights their strong interdependence. The main findings are:

Long-term climate-driven runoff depletion: The long-term mass balance analysis confirmed that forested catchments in temperate climates are highly sensitive to rising air temperatures. Despite a slight long-term increase in precipitation totals, the annual runoff depth significantly decreased. This paradox is driven by increased evaporative demand and higher actual evapotranspiration, which alters the seasonal distribution of runoff, shifting spring flows earlier and aggravating summer low flows.

- Dependence of daily ET loss on available baseflow: By evaluating drought events of varying severity, we documented a strong positive relationship between mean daily baseflow and the absolute volume of water lost to daytime evapotranspiration. During moderate droughts, the forest vegetation maintains access to shallow groundwater, creating distinct diurnal streamflow fluctuations with a typical six-hour hydraulic lag between peak atmospheric temperature and minimum streamflow.
- Physiological stress during extreme low flows: As long-term climate warming forces baseflow to critically low levels (below 2 $l \cdot s^{-1}$), the diurnal streamflow amplitude drastically diminishes. Evapotranspiration losses drop by more than an order of magnitude, indicating that the groundwater table has declined below the effective root zone, leading to severe physiological water stress in the riparian forest.

In conclusion, the integration of these two methodological approaches proves that long-term climatic warming continuously depletes the baseflow reserves of the Vydrica catchment, leading to observable constraints on the daily transpiration capacity of the riparian forest. This highlights the critical need to systematically account for short-term vegetation-driven water losses in large-scale climate change impact assessments, demonstrating that riparian forests act both as active regulators of the water balance and as highly vulnerable targets of increasingly frequent summer droughts.

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