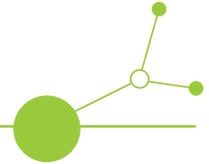


# Report on testing and data collection in Malá Fatra NP

## D2.2.1 - 9/2025



Version 2  
09/2025

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## A. PILOT ACTIONS - final report

**PROJECT PARTNER:** LP, University of Zilina

**LOCATION:** Malá Fatra NP, Slovakia

**PILOT SITES:** Snilovske sedlo - Chleb, Hromove sedlo - Chata pod Chlebom, Velky Krivan, Chrapaky, Varinka river stream, Stohovy potok stream

**PILOT ACTIONS:** Erosion monitoring (LiDAR measurement), Visitors monitoring (Strava Metro, Eco counters, photo traps), Vegetation monitoring (iNaturalist, plants and habitats survey), Wildlife monitoring (photo traps), Soil monitoring (presence of soil mites), Water pollution monitoring (surface water quality analysis)

### 1. VISITORS MONITORING

#### STARTING DATE

September 2024 (counters and cameras), STRAVA data available from January 2023.

#### 1.1. METHODOLOGY DESCRIPTION

This monitoring activity aims to understand the spatiotemporal behaviors of hikers and bikers in pilot areas and other areas in Malá Fatra NP. Visitor monitoring helps us to understand the frequency of hikers and bikers on official and promoted trails as well as on unofficial trails, and to better understand in which areas high-frequency visitation may result in negative environmental impacts on different natural assets. We focus especially on the monitoring of trampling processes at pilot sites, to identify species that are threatened by visitor impacts, as well as the impact of the increased activity of tourists and the presence of tourist infrastructure on wildlife and erosion development. All the monitoring activities at the pilot sites are complementary to each other.

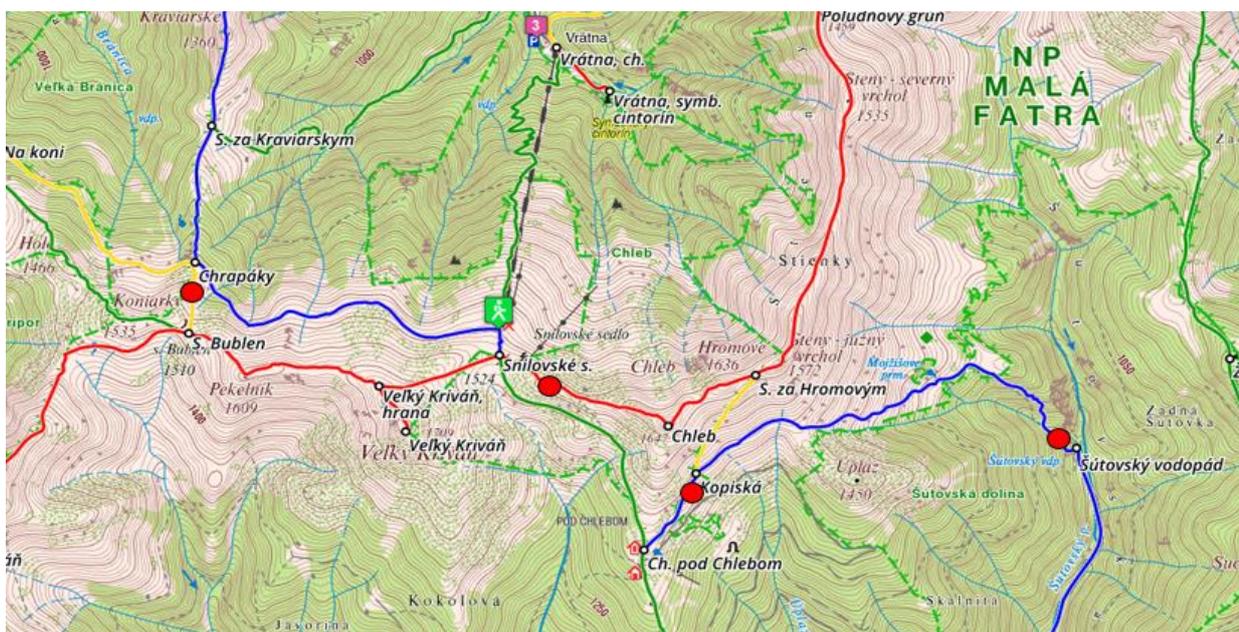


Fig. 1 Positions of visitor counters in Malá Fatra NP used for HUMANITA project purposes



UNIZA performs digital visitor monitoring for all pilot sites that are part of the HUMANITA project. Data from the STRAVA Metro app were analyzed regarding user activities and digital information on official and unofficial trail networks. Some of motion-triggered camera traps were used to efficiently collect data on humans and wildlife through a single data collection process. This cost-effective method will provide long-term data useful for monitoring both human trail-based activity or tourist infrastructure and wildlife presence.

## 1.2. EQUIPMENT AND TOOLS USED

### 1.2.1. Visitor counters

We use five **ECO-Counter PYRO NANO automatic tourist counters**, installed next to the trails, which detect visitors by evaluating the change in the thermal field generated by them in the profile adder (Fig. 2). The width of the counting profile is 4 m. The counters distinguish the direction of movement. The calculator does not require an electrical power supply; it works on a battery with a capacity of 2 years. The recording interval is 1 hour, and the memory capacity is 1.5 years. One counter is of an older type. Data are downloaded by rangers manually as needed, at irregular intervals.



Fig. 2 Example of equipment installed, camera (on the left), counter (on the right)

We placed three tourist counters in high-traffic areas to gain an overview of the total number of visitors at the pilot sites. One of them was installed in a location where tourists violate the rules by moving off marked trails. These are also areas where rare species are present. This will help us determine how prohibited activities affect the abundance of rare species. Another counter helps us determine the number of visitors coming from the Šútovská Valley to Chata pod Chlebom, or moving in the opposite direction. This allows us to more accurately define the number of tourists moving between Chata pod Chlebom and the Hromové saddle. The most visited place is the Mt. Chleb. Fig.3-4.



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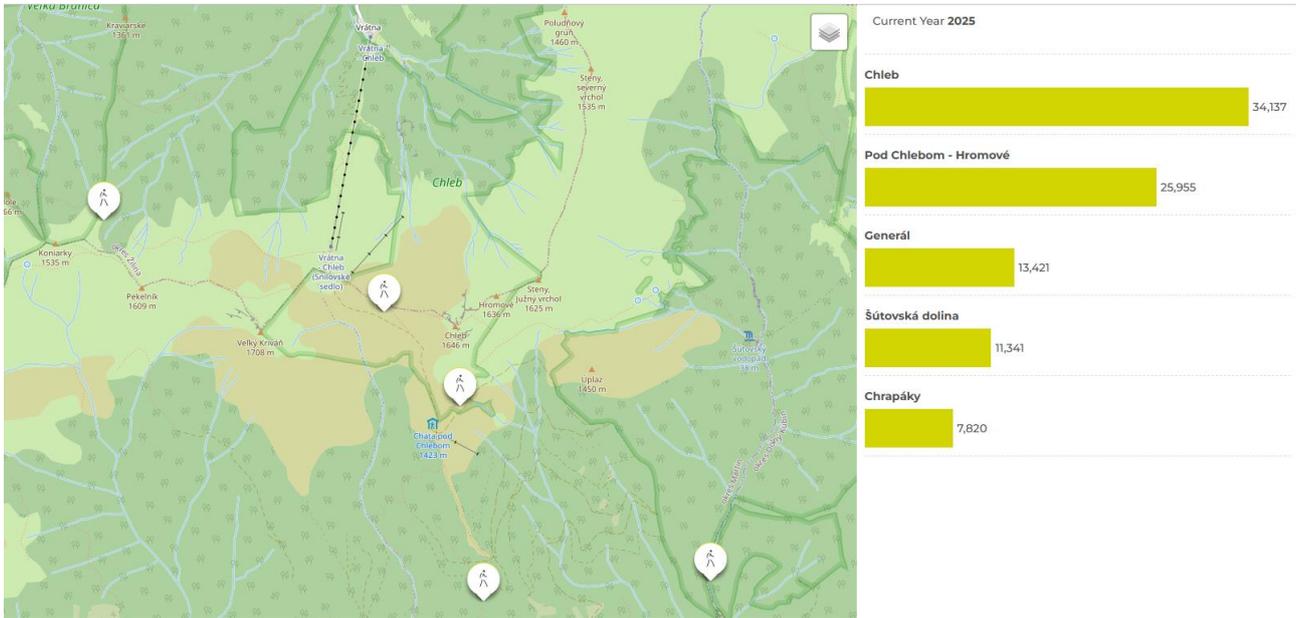


Fig. 3 Number of visitors on five trails in the period January 1, 2025 - August 13, 2025.

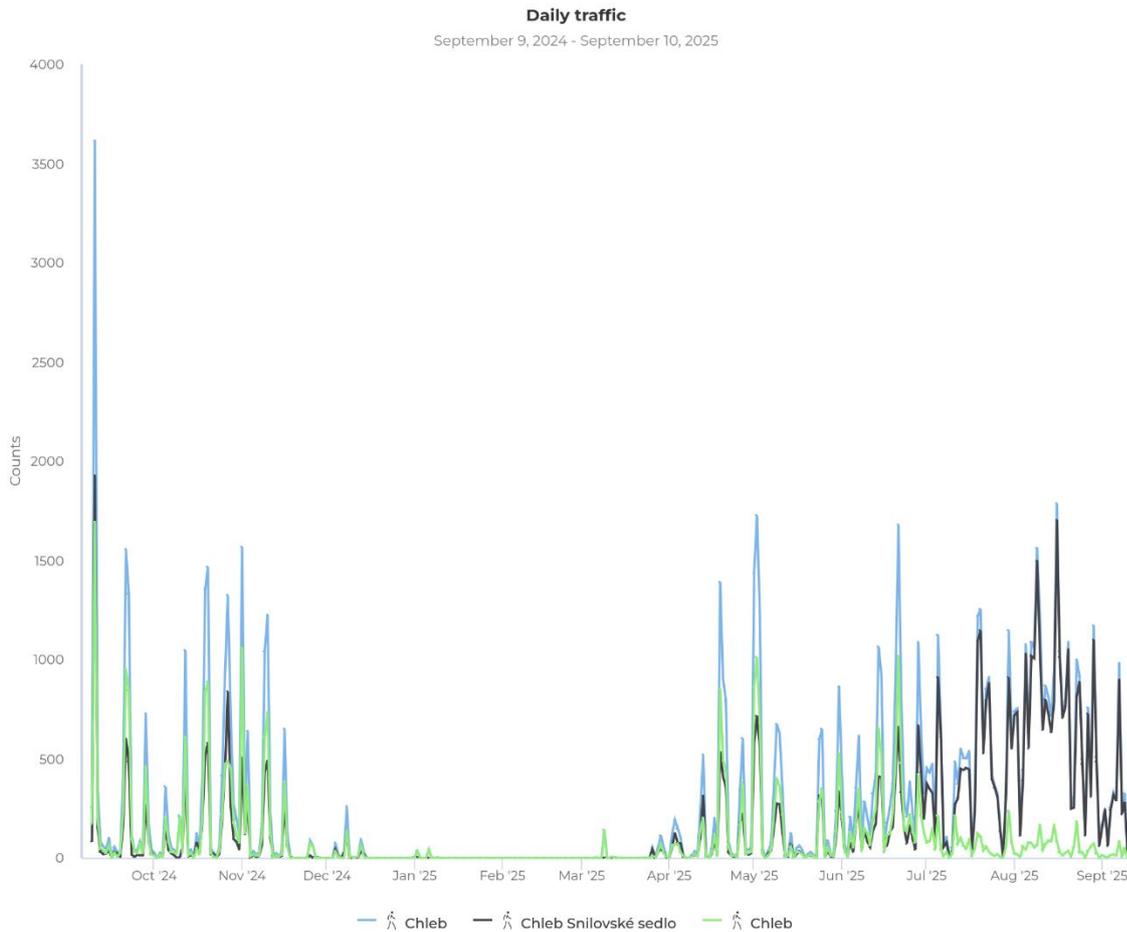


Fig. 4 Daily traffic on the mostly visited trail in the period September, 2024 - September, 2025.



UNIZA, in collaboration with the Administration of Malá Fatra NP (A-NPMF), step by step installed 19 new **Camera traps**. Together with some older ones, we use them as a standard monitoring tool for wildlife monitoring in Malá Fatra NP. However, we also test their application for visitor monitoring at some selected places. Because the objectives differ between these two applications, protocols for camera placement and performance also vary. In this study, we try to optimize camera trap protocols to quantify human activities (frequency on trails, unauthorized entrances, etc.).

Many visitors to Malá Fatra NP track their rides, runs, or walks using the Strava Metro app on their phones or GPS devices. With respect for their privacy, Strava Metro strips this dataset of identifiers and aggregates it. So-called heat maps enable us to visualize which trails people avoid or favor, as well as where high concentrations of people occur (Fig. 5). By evaluating these data alongside other information, we can identify high-frequency corridors and uncover the factors that contribute to an increased risk of environmental impact at specific locations. It is also possible to use different visualizations of results (Fig. 5 - 8)

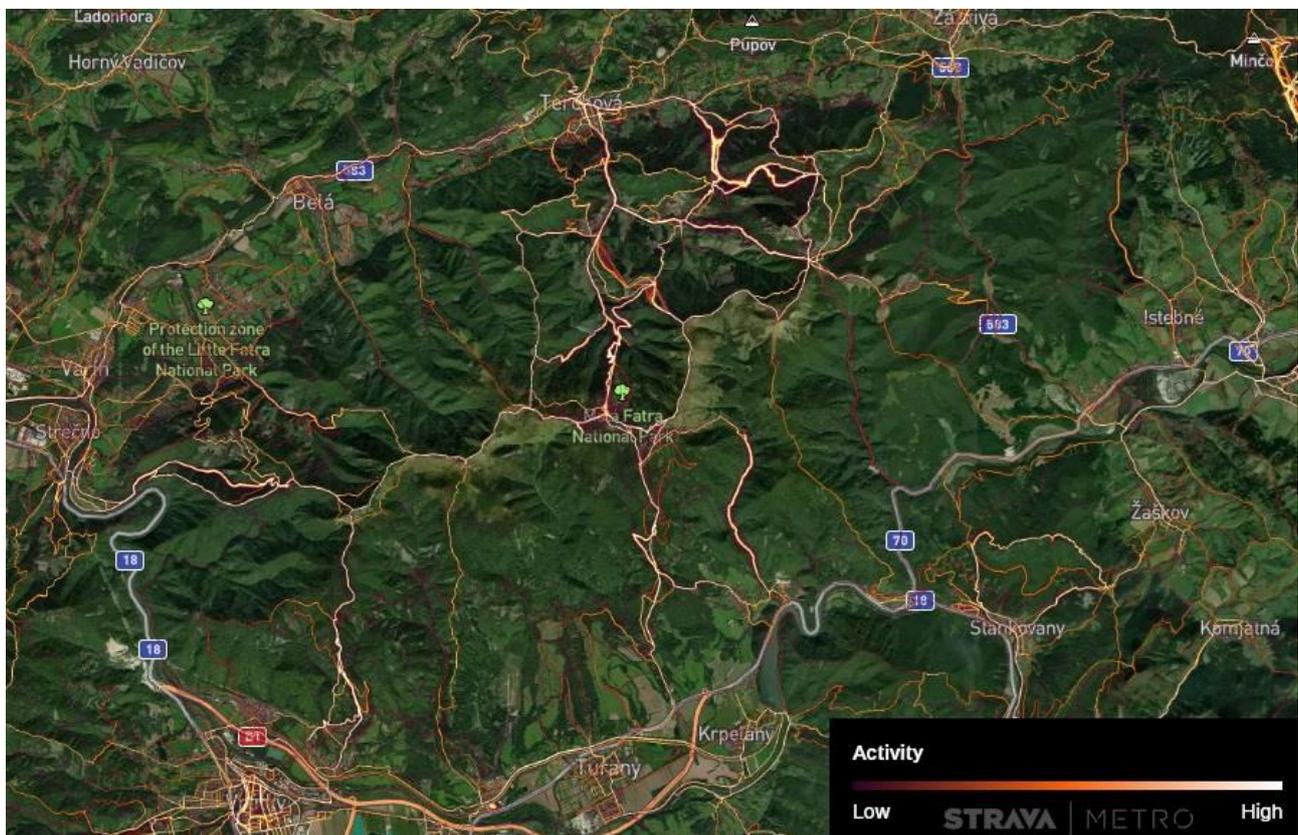


Fig. 5 Visitor trip frequencies - heat map (hiking and running, 2025)



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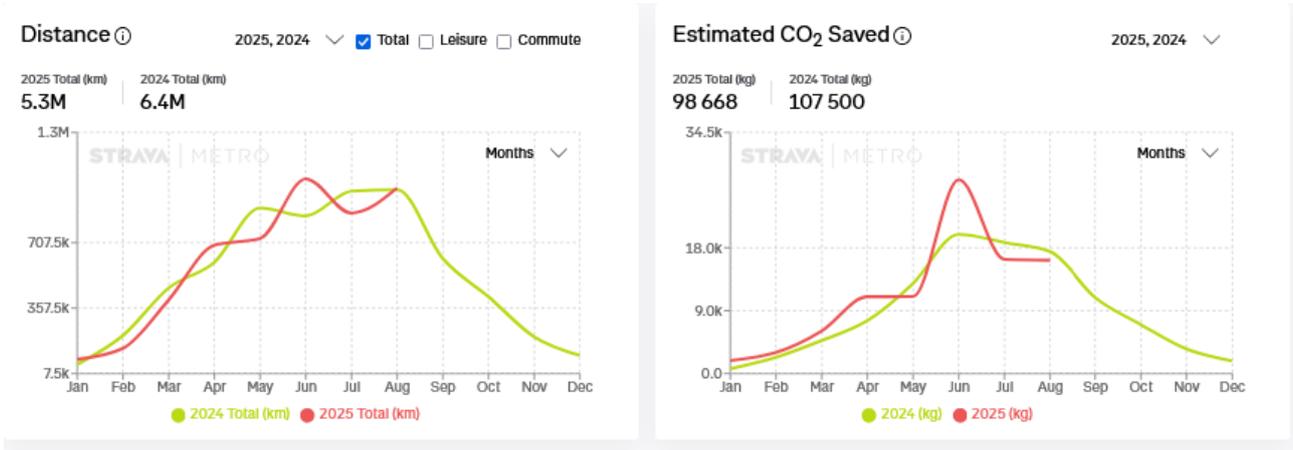


Fig. 6 Visitor activities distances (total km comparison for 2024 and 2025) on the left, estimated CO2 saved (kg comparison from 2024 and 2025) on the right.

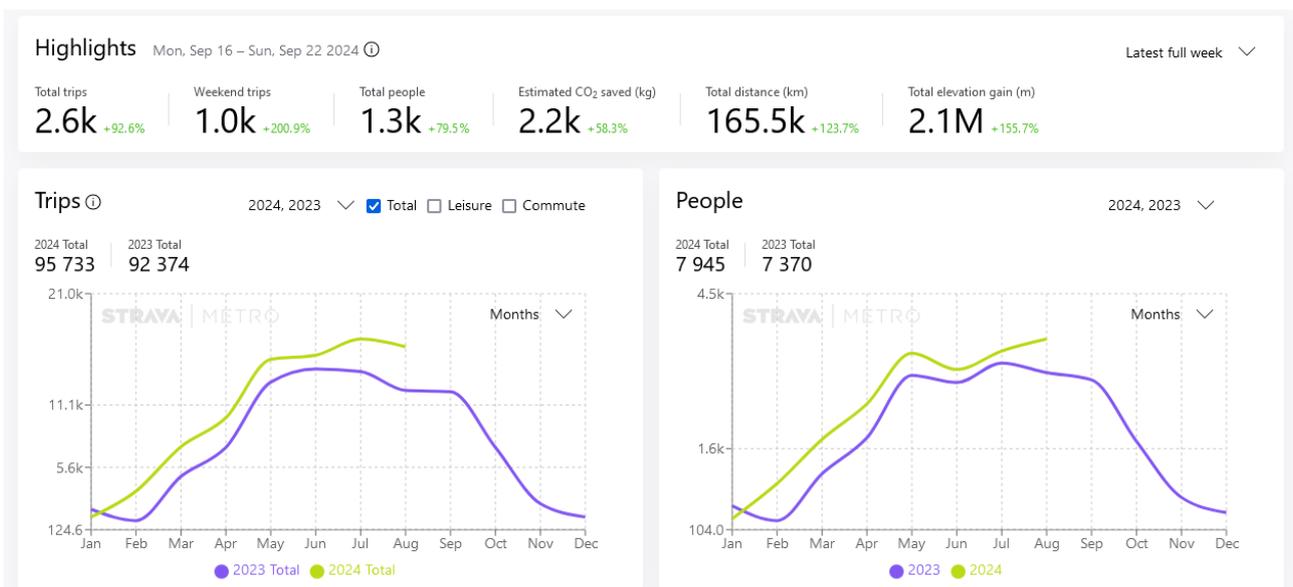


Fig. 7 a) Number of trips (comparison between the years 2023, 2024 and 2024, 2025) on the left, Number of visitors using the app (same years) on the right



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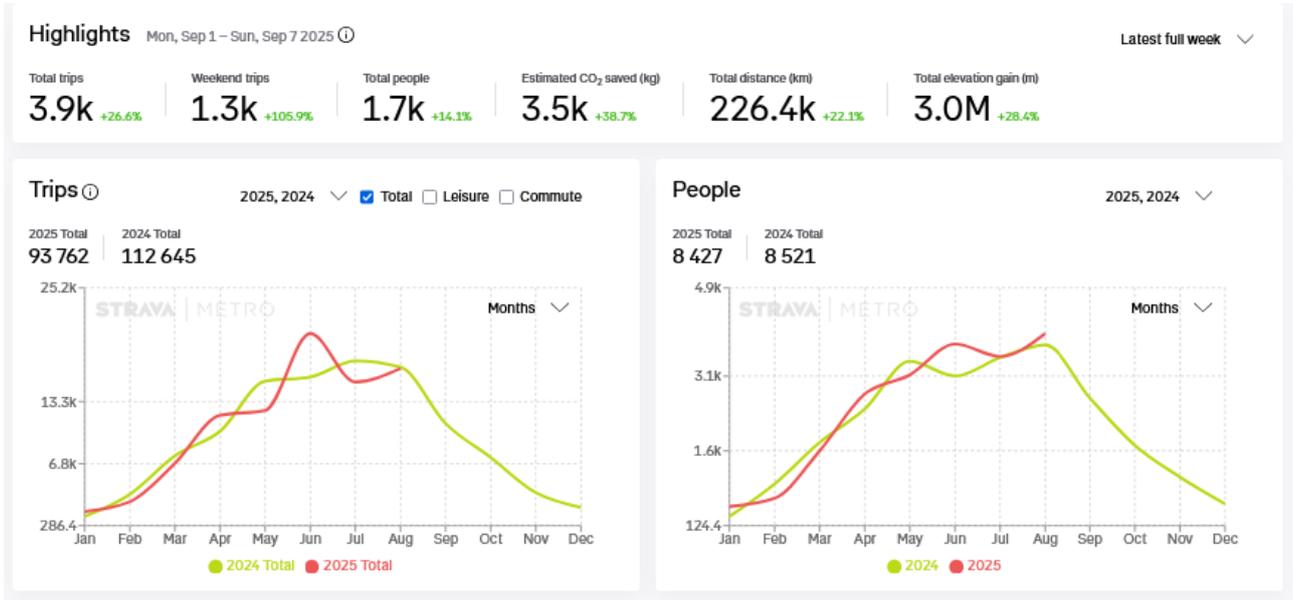


Fig. 7 b) Number of trips (comparison between the years 2023, 2024 and 2024, 2025) on the left, Number of visitors using the app (same years) on the right

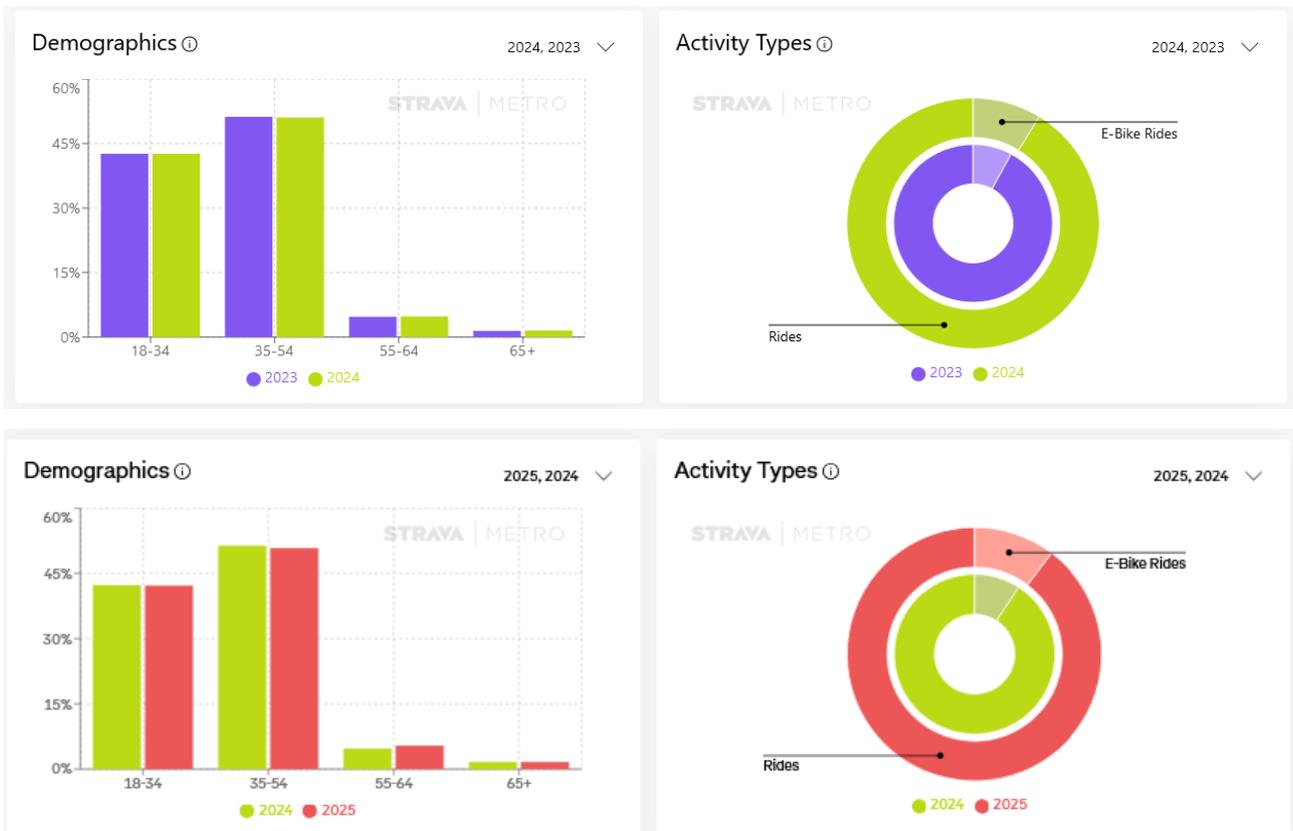


Fig. 8 Demographic data (comparison between the years 2023, 2024 and 2024, 2025) on the left, activity types - bike rides (same years) on the right

When we compare the data obtained from STRAVA METRO, we can see the increase in trips from 92 374 (2023) to 112 645 (2024). There are still more than 3 full months in this year (2025), but number of trips is already higher than that of 2023. Number of STRAVA app users expanded from 7530 in 2023 to 8521 in 2024,



value in September 2025 is 7945. The interesting thing is a spike of activity in the trips and distance in June 2025 compared to previous years, since then it's decreasing. We can only speculate what the reason was for such a significant change in recorded data.

Demographics distribution stayed the same, and the number of e-bike users grew slightly.

### 1.3. RESULTS AND OBSERVATIONS

Different technologies installed at tourist trails, or outdoor apps, can provide a variety of valuable information:

1. Number of Visitors - Track how many people use a trail daily, weekly, or seasonally, and define peak and off-peak times.
2. Trends Over Time - Monitor changes in visitation across months or years. Evaluate the impact of events, interventions or new infrastructure on the trail.
3. Trail Popularity - Compare different trails to see which are most or least used. Support decisions about maintenance, upgrades, or closures.
4. Environmental Impact - Correlate high foot traffic areas with erosion or habitat disturbance.
5. Visitor Behavior - Understand visitor flow (e.g., which direction they go, how long they stay). Detect patterns such as weekday vs. weekend usage.
6. Impact of Weather or Season - By combining with meteorological data, analyze how weather conditions affect trail usage.

This information can help A-NPMF to ensure adequate safety measures and emergency planning based on visitor load, plan seasonal management accordingly, optimize waste management, signage, and facilities, and introduce measures to support sustainable tourism and conservation planning.

During the HUMANITA project, partners tried to introduce more complex methods used for visitor counting in national parks that go beyond basic mechanical or infrared counters. In Malá Fatra NP, we tested a combination of classic counters, with camera traps, and data from the STRAVA app. UNIPR developed a method for photo or video analytics based on an AI system to count people and classify them. Combining multiple methods often gives the best results. This combination allowed us to use infrared sensors for basic counting, mobile phone tracking for movement patterns, and photo trap analytics in key spots.

### 1.4. FUTURE DEVELOPMENTS

We will continue data collection in the next seasons. We are very interested in what results we can achieve with the cameras. We would like to know more about human-wildlife interactions at some specific places in the park. Fine-scale long-term data collected simultaneously on humans and wildlife could be crucial in exploring these interactions, and could ultimately lead to improved conservation of wildlife species in Malá Fatra NP. We realize that it is very important to place the cameras in the right places and to set the appropriate recording protocols for them. We believe that our results for the next year will be valuable for all project partners as well as for other protected areas. A combination of



different monitoring methods can yield interesting, more comprehensive results and information. Some partners focused on comparing the accuracy of various methods during the project.

## 2. VEGETATION MONITORING

### STARTING DATE

The botanical survey started at the beginning of June 2024, when the alpine vegetation was optimally developed. The participatory monitoring for the HUMANITA project via iNaturalist started in July 2024, when A-NPMF posted a propagation video on their website and social media about the use of the app.

### 2.1. METHODOLOGY DESCRIPTION

This monitoring aims to record the presence of habitats of European and Slovak importance, as well as protected and endangered species of plants. We observed pilot sites step by step, wrote down all species, and assigned them a level of coverage according to the Braun - Blanquet scale. We took a lot of photos, and some plants were collected and later identified in the office. We determined the occurring habitats according to the recorded species (Fig. 10).

For purposes of participatory monitoring, we used the iNaturalist app, which is a great and user-friendly tool for recording and identifying plant species.

### 2.2. RESULTS AND OBSERVATIONS

We confirmed the expected occurrence of habitats 4070\* Bushes with *Pinus mugo* and *Rhododendron hirsutum* (*Mugo-Rhododendretum hirsute*), 6150 Siliceous alpine and boreal grasslands, 6170 Alpine and subalpine calcareous grasslands, 6230\* Species-rich *Nardus* grasslands, on siliceous substrates in mountain areas (and submontane areas in Continental Europe), 6520 Mountain hay meadows.

Recorded protected plants of European importance: *Aconitum firmum* subsp. *moravicum*, *Campanula serrata*, *Dianthus nitidus*.

In 2024 we recorded protected plants of Slovak importance: Orchids: *Dactylorhiza viridis*, *Gymnadenia conopsea*, *Orchis mascula* subsp. *signifera*, *Platanthera bifolia*, *Pseudorchis albida*, *Traunsteinera globosa* and other significant species: *Androsace lactea*, *Botrychium lunaria*, *Cetraria islandica*, *Diphasiastrum alpinum*, *Dryas octopetala*, *Gentiana asclepiadea*, *Gentiana verna*, *Linum extraaxillare*, *Pyrola rotundifolia*, *Rhodiola rosea*, *Salix reticulata*, *Saxifraga caesia*, *Saxifraga paniculata*, *Selaginella selaginoides*. Other interesting species may be present in the next season.

In 2025, we continued our monitoring efforts at the pilot sites. Newly observed plant species include *Dactylorhiza fuchsii* (last flowering individuals), *Helianthemum nummularium*, *Lilium martagon*, *Minuartia langii*, *Sedum atratum*. All of them are either protected by law or included in the Slovak Red list. Especially *Sedum atratum*, a species of stonecrop, is not common and easy to overlook. (Fig. 11)

The start of the vegetation monitoring took place approximately at the same time as in year 2024 - half of the June. At first glance it was obvious that the vegetation was developing slower, maybe 7-10 days later. Many of the species recorded last year (e.g. orchids) were only beginning to form inflorescence, compared to full bloom in 2024.

We also observed three interesting species of lichens: *Dibaeis baeomyces*, *Rhizocarpon geographicum*, *Umbilicaria deusta*. *Rhizocarpon geographicum* and *Umbilicaria deusta* prefer to grow on silicate rocks (granite, granodiorite, quartzite), which are found near the pilot site Hromovce sedlo - Chata pod Chlebom, *Dibaeis baeomyces* grows on the nutrient poor soils on the same pilot site.

In 2025 a tourist trail at pilot site Chata pod Chlebom - Sedlo za Hromovým was partially reconstructed and erosion measures were implemented. Nets made of sheep wool were placed on bare soil without vegetation. We hope that it will help in returning the plant cover. The most widespread habitat in the vicinity of netted



places is 6520 Mountain hay meadows. We hand-mowed tufts of grasses and herbs and placed them between the nets, so that the ripe seeds will fall directly on the desired spot. We used mostly grasses (*Agrostis capillaris*, *Briza media*, *Calamagrostis arundinacea*, *Deschampsia caespitosa*, *Carex sempervirens*) and herbs (*Campanula glomerata*, *Carduus defloratus* subsp. *glaucus*, *Cirsium eriophorum*, *Chamaenerion angustifolium*, *Geranium sylvaticum*, *Senecio ovatus*, *Solidago virgaurea*). The results of this experiment will be visible during subsequent growing seasons (Fig. 9).



Fig. 9 Covering the surface with cut grass

In September 2025 there were 6658 (3909 in 2024) observations of 1232 (903 in 2024) species from 324 (244 in 2024) observers in our iNaturalist project “Biodiversity of Malá Fatra National Park” (Fig. 10). Compared to last year, the number of observations in the project grew by 2749, which is a pretty high percentage of the total number of observations (41 %). The number of recorded species and observers also grew by 302 and 80 respectively. So it can be said that our campaign for this participatory monitoring was successful (Fig. 12).



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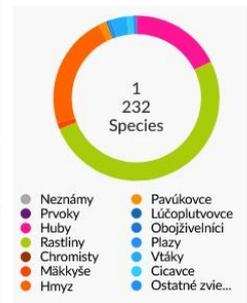
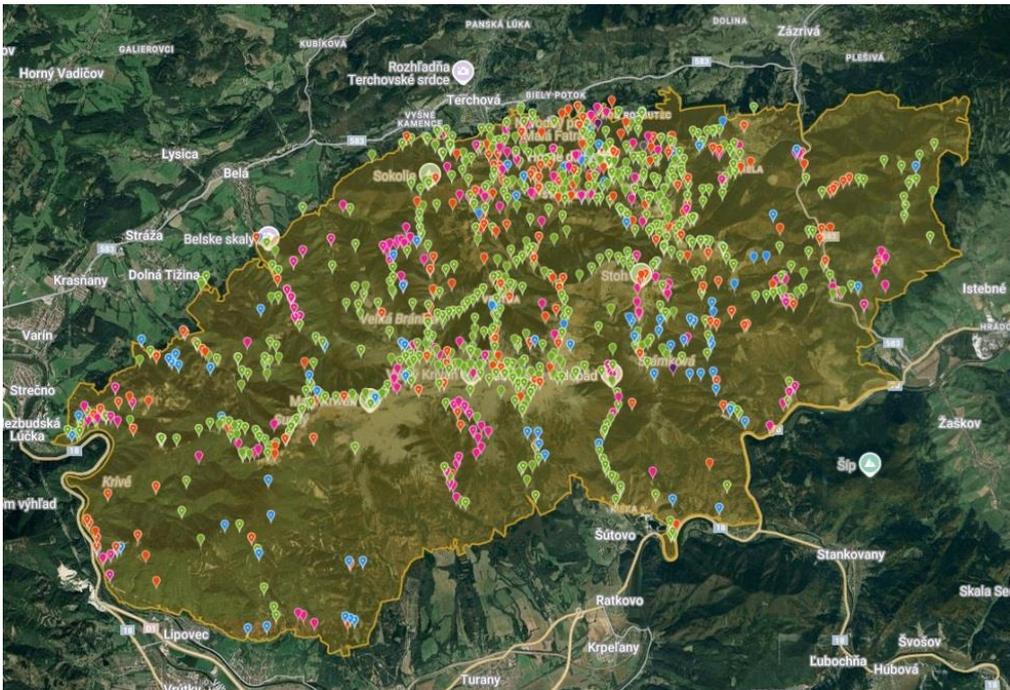


Fig. 10 Map of iNaturalist observations in Malá Fatra NP, a chart showing number of observations and types of organisms recorded on the right



Fig. 11 Botanical survey on the left, *Traunsteinera globosa* (orchid) on the right



Fig. 12 Photos of plants observed by iNaturalist observers

## 2.3. PROBLEMS AND OBSTACLES THAT EMERGED DURING TESTING

The success of monitoring also depends on weather conditions and sufficient time in the vegetation season at the site.

- A lot of observations in iNaturalist are common species, more unique, and new species are not as well represented.
- Potential observers are limited to the tourist trails, which are already well-examined.
- It is difficult to communicate directly with the observers and motivate them.

## 2.4. FUTURE DEVELOPMENTS

We will continue to monitor the vegetation on the pilot sites next spring and summer. Repeated visits to all sites are necessary to observe and record significant plants and their communities growing there. It will be necessary to regularly communicate with iNaturalist observers via social media and other channels.

# 3. WILDLIFE MONITORING

### STARTING DATE

Older cameras in 2023, new cameras from 9/2024.

### 3.1. METHODOLOGY DESCRIPTION

Understanding the nature, distribution, and intensity of visitor activities can lead to better management of protected areas, potentially improving also visitor experience while reducing impacts on the environment. Although motion-triggered cameras - photo traps are now a standard monitoring tool for protected areas, they are less commonly applied for visitor monitoring. In our monitoring, we will observe both visitors and animals and their interactions. Camera traps should be calibrated with field-based observation and positioned in different ways. This cost-effective method can provide long-term data useful for monitoring



both human trail-based activity and wildlife presence. Because study objectives differ, protocols for camera placement also vary.

Two types of cameras were used:

- SPROMISE S 308 - here the recording time was changed to a limited period of the day because these devices are positioned near quite frequented pilot areas. The actual time of making the shots was set from 6:00 p.m. to 7:00 a.m.
- EVOLVEO StrongVision PRO 4G - the recording time was not changed on these devices, because they were positioned in locations with less frequency of human activities.

We defined 5 specific types of locations for both types of cameras as follows:

- Locations with a high intensity of human activities, i.e. pilot locations along tourist trails, or near mountain chalets
- Hunting trails: where less movement of people is expected
- Animal trails in the territory of the national park
- Animal trails in areas with a high degree of protection such as reserves
- Winter dens of animals



Fig.13 - Installed and masked photo traps

Data from the camera traps are stored on SD cards. These are collected at regular intervals (about every 3 months), in dens intended for wintering, to prevent the disturbance of the animal (about every 5-7 months). In the case of cameras located near dens, appropriate timing of installation is important. At least 1 month before the animal (bear, badger) enters the den for hibernation. The collected data is stored in the designated database and later transferred to UNIPR for further analysis.

### 3.2. RESULTS AND OBSERVATIONS

We visually checked the recordings from the cameras. Here we show results from that one installed at the pilot site Chata pod Chlebom - Sedlo za Hromovým. The camera was installed there on 1.7.2024. The data were sent to the database designated for that purpose. In 2024 camera was active from 6:00 p.m. to 7:00 a.m. to observed animals. Camera footage and video captured animal activity near the trail. It is mainly



visited by deer and roe deer in the evening or morning times. Illegal activities were caught on the trail. People rode horses or collected blueberries, and tourists after permitted visiting hours (Fig. 14-15).



Fig. 14 Deer



Fig. 15 Roe deer

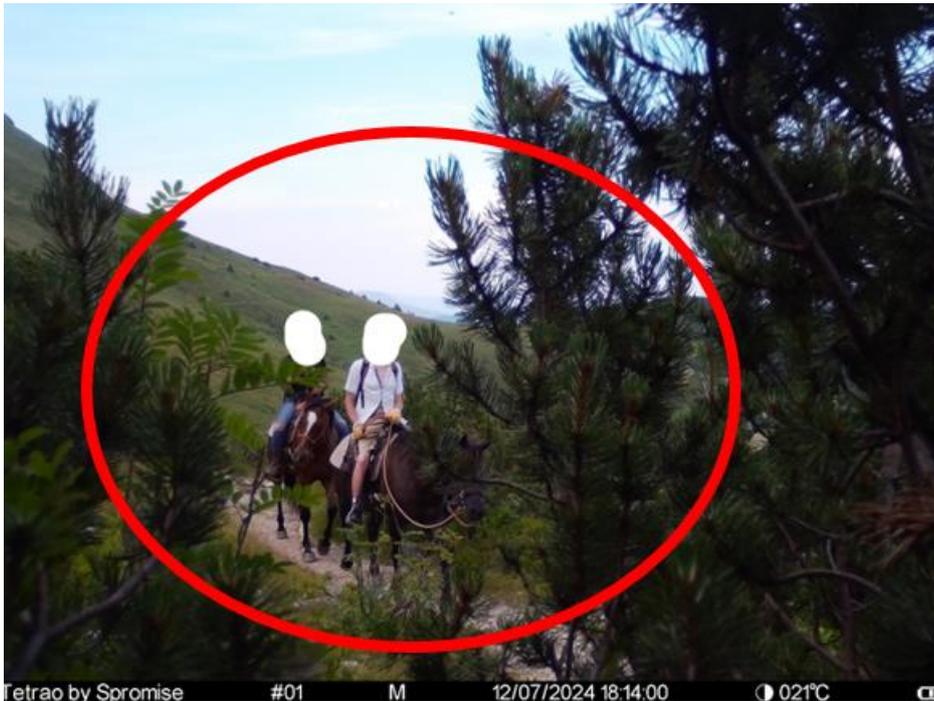


Fig. 15 Unauthorised entrance of horses

After consultation with experts from University of Parma, the camera traps at the pilot sites - Sedlo Hromové - Chata pod Chlebom and Chrapaky - had to be installed perpendicular to hiking trails to increase the likelihood of capturing movement along them (both people and wildlife). Compared to the previous year, the camera traps were set to operate continuously for 24 hours instead of only during the evening and nighttime hours (6:00 pm to 7:00 am). The data is continuously sent to the database.

An interesting finding was the presence of wild boars at one pilot site, whose activity even caused the camera trap to be displaced. One wildlife camera was attacked by a great spotted woodpecker (*Dendrocopos major*); however, it remains functional, and we also have a video recording of the incident, as the camera was set to record videos only.

The assumption that animals would avoid these locations during the day and be active during the night and early morning hours was confirmed. Red deer and wild boar were observed at these sites, and they also caused the camera trap to be displaced. Among the bird species recorded were *Turdus merula*, *Turdus torquatus*, and *Erithacus rubecula*.

At the Wildlife camera trap sites Tižinská hoľa 16 and Magurka 22, which were installed near less frequented hiking trails, in addition to the already mentioned red and wild boar species, carnivores were also recorded – for example *Canis lupus*, *Ursus arctos*, *Martes martes*, *Martes foina*, and *Vulpes vulpes*. These animals were using the trails as migration routes.

### 3.3. PROBLEMS AND OBSTACLES THAT EMERGED DURING TESTING

Due to the exclusion of PP7 from the consortium, the equipment was purchased later and therefore also installed later. Because of that, we installed 19 camera traps until November 2024. This delayed data collection in some locations. For this reason, we also included in our monitoring the camera traps in the park administration property that were installed earlier.

We encountered problems in valleys with no signal and difficult access to the camera traps, either due to exposed terrain or the remoteness of the locations – for example, the camera traps at Tesnô 8, Pekelná dolina 3, and Studenec 17. These were the sites where our expectations for wildlife camera traps were the highest, as we anticipated the presence of large carnivores such as *Lynx lynx*, *Canis lupus*, *Ursus*



arctos, and *Felis silvestris*, as well as the possible movement of their offspring. We also expected to detect *Tetrao urogallus*.

These areas had shown occasional signs of their presence, such as scat, tracks, lynx scratch marks on trees. We were quite disappointed when, after half a year to three-quarters of a year, we returned to the camera traps only to discover that they had been functioning for just a month or even less. Unfortunately, we were only able to collect limited and less relevant data from these locations.

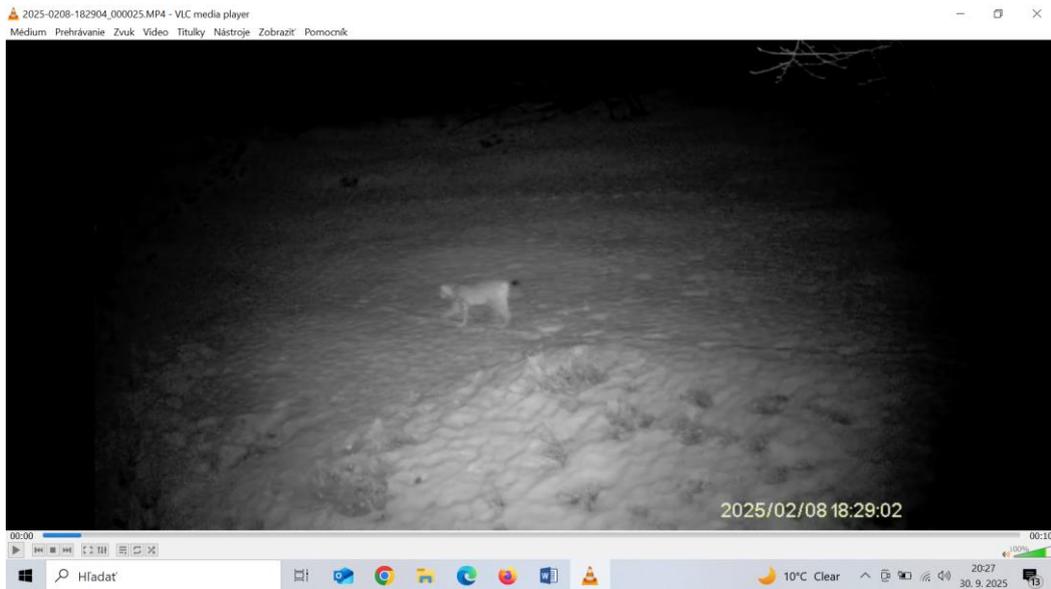


Fig. 16 Lynx lynx captured by the camera trap at Studenec 17

Wildlife camera traps such as Zadná Šútovka 10 and Ostredok 9 detected the movement of a heavily pregnant female wolf as well as a group of wolves. They also recorded a female bear with cubs. These camera traps were installed deep within the nature reserves, and our assumptions were confirmed (Fig. 17)

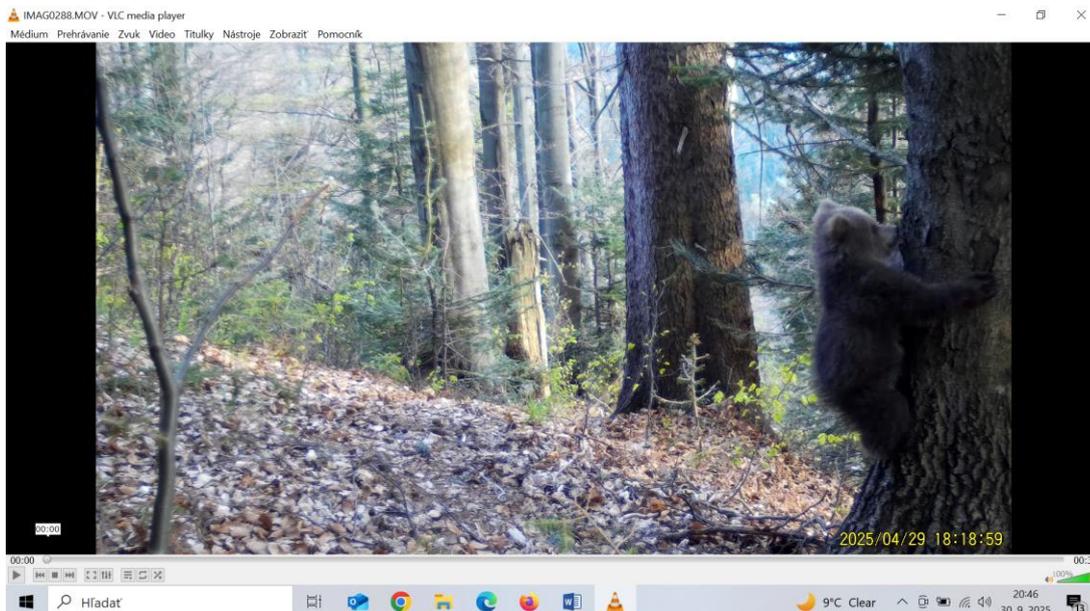


Fig. 17 *Ursus arctos* detected by the camera trap at Zadná Šútovka 10



### 3.4. FUTURE DEVELOPMENTS

It is very important to place and hide the cameras correctly. It is problematic to hide the cameras in some habitats (dwarf pine) because, in a strong wind, the branches get into the frame of the camera and turn on it. We will have to optimize this in the future. Data from the cameras will be periodically downloaded and sent to the database for processing.

## 4. EROSION MONITORING

### STARTING DATE

09/2023

### 4.1. METHODOLOGY DESCRIPTION

Successful control of erosion on hiking trails requires effective monitoring and an in-depth understanding of erosion processes and their triggering factors. Data from repeated LiDAR acquisitions is one of the possible options to derive erosion-related information across large areas, for example, by calculating a digital elevation model. Our monitoring activity employs repeated UAV-LiDAR acquisitions and the Lidaretto System to promote the understanding of digital elevation model uncertainties and integrate the gained understanding in an erosion monitoring approach. Monitoring aims to capture the shape of the terrain on the specific date of the measurements. The dates were selected to capture the terrain before and after the tourist season and after that. So, the measurements are performed twice a year.

### EQUIPMENT AND TOOLS USED

- **Lidaretto System** applied on UAS (DJI Matrice 300) carrier: LiDAR technology (data collection), GNSS receiver (positioning), IMU unit (orientation of the whole system), 360° Camera (capturing of real textures).
- The **LiDAR technology applied to a UAS carrier** was used for data collection. GNSS principles were used for the georeferencing of the measuring system by measuring the position and determination of a UAS trajectory. The whole system captures the real terrain geometry in the form of a georeferenced point cloud to which the real texture from the 360° camera may be aligned. The collected data must be post-processed using the pre-set methodology to obtain georeferenced high-quality dense point clouds with real texture.
- **LiDAR360, Inertial Explorer, and Lidaretto Creator** were used for the whole post-processing from raw data to the georeferenced point cloud with real texture. The point cloud is used for vector and raster analysis to determine the changes in the terrain and to clarify the presence of deformations in the form of soil erosion caused by various factors.
- The data post-processing revealed certain shortcomings in the robust data collection, such as point cloud noise and shadow site measurements. To address this issue, additional software tools (3D Survey and Matlab) were used. In Matlab, scripts were created to remove the mentioned noise, to eliminate errors from the epoch point clouds' overlap, and to reduce the data for more effective analysis.
- We also involved a group of students from the University of Žilina in **participatory monitoring**. We aimed to introduce the public to new ways of collecting, processing, and analyzing data using remote sensing data acquisition procedures.

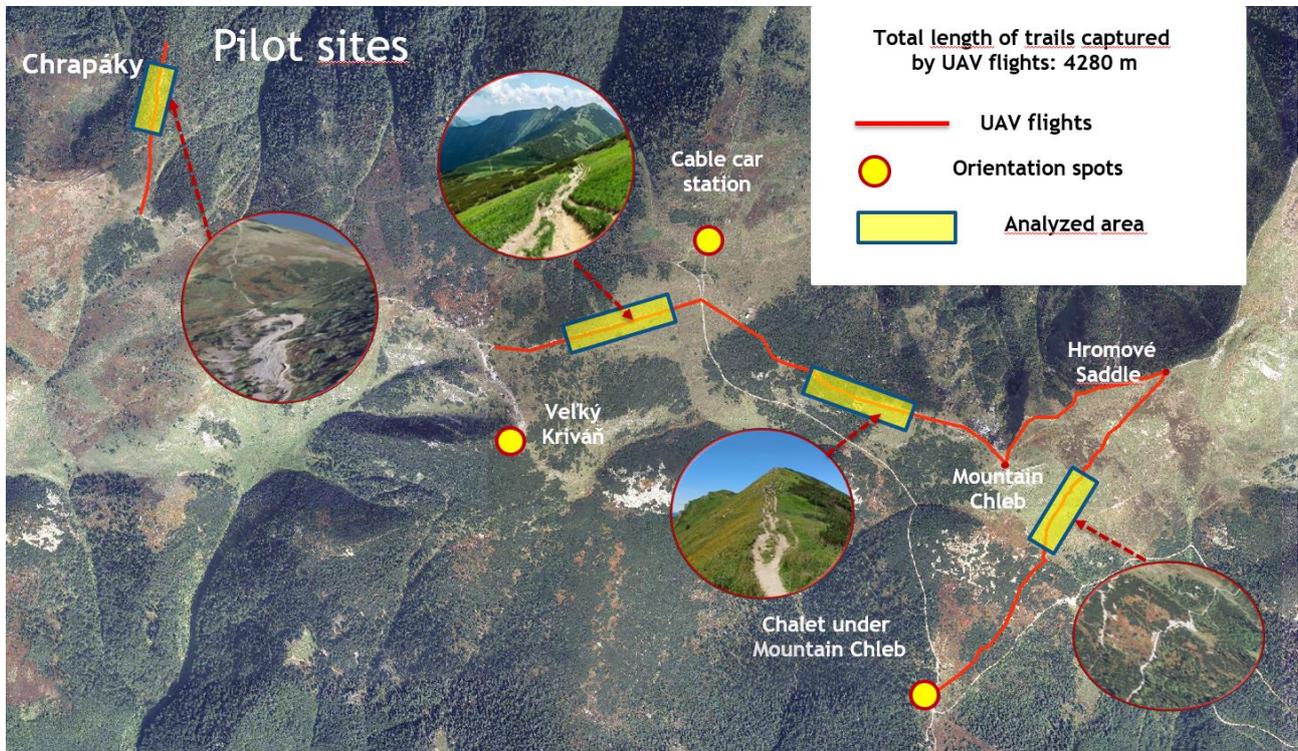


Fig. 18 Pilot sites monitored

## 4.2. RESULTS AND OBSERVATIONS

So far, all four pilot sites (Fig. 18) were monitored three times (09/2023, 05/2024, 09/2024). The first measurement is used as a reference terrain course (reference epoch). In regard to this reference epoch, until now the data from 05/2024 were compared. The results illustrate the changes between the individual epochs, but we still do not have enough data that leads to the final erosion state interpretation. Further measurements are necessary. However, it seems that laser scanning can be an effective erosion monitoring technique due to its high precision in 3D measurements. Using UAV techniques for sloping field erosion monitoring can be interesting, enabling the production of highly dense point clouds. If such point clouds are available for more epochs, it is possible to detect topographic changes in a spatially explicit way. The changes in terrain are visible between epochs. We can also see the changes in the branching of the trails, the creation of new paths, etc. The impact of tourists on trails is evident at all pilot sites. Figures as follows present the first results and different ways of their interpretation.

Additional measurements were carried out on 09/2025. The course of post-processing led to several results. The boundaries of the studied sites, on which further research is being conducted, were clearly defined. The processing of multiple epoch measurements showed that it is necessary to attempt to reduce georeferencing error as much as possible. Point clouds and their georeferencing accuracy are determined by the georeferencing of the drone's trajectory, with the manufacturer declaring an accuracy of 3 cm. When comparing multiple point clouds, this error can be mitigated by calculating a proper transformation, which reduces the influence of georeferencing. The challenge of this calculation lies in the relative flatness of the data, which presents another programming challenge.

Another challenge is the correct reclassification of the data so that existing vegetation is not captured, as it may lead to data misinterpretation. It is important to find a threshold that is thick enough to eliminate errors caused by vegetation, but sensitive enough not to reduce the quality of the captured data. So far, a value of 4 cm appears to be optimal.



Up to now, point clouds from all four epochs have been processed and created, with the first three epochs (09/23; 05/24; 09/24) processed and compared with each other, and the 09/25 epoch also processed.

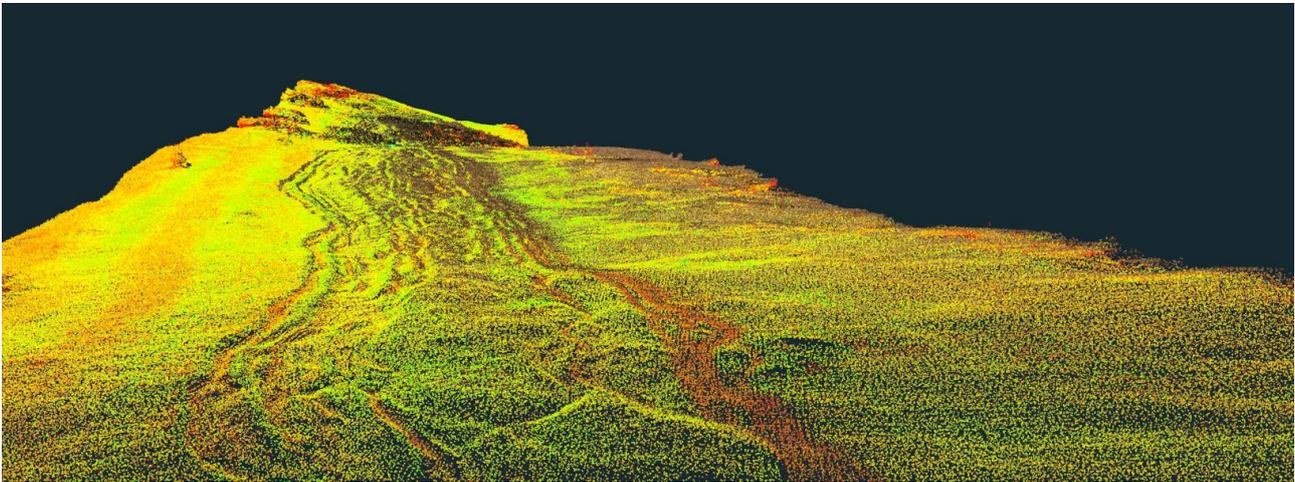


Fig. 19 The comparison of three previous measurements as point clouds (Velký Kriváň)

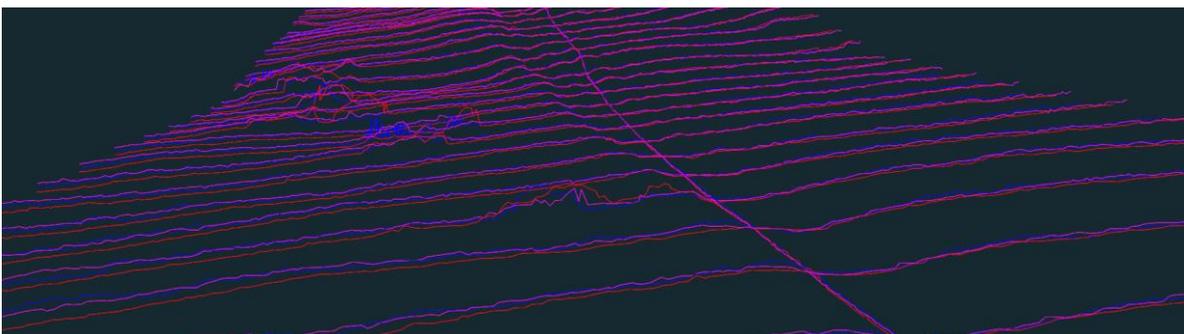


Fig. 20 The comparison of three previous measurements with each other using profile sections (Velký Kriváň)

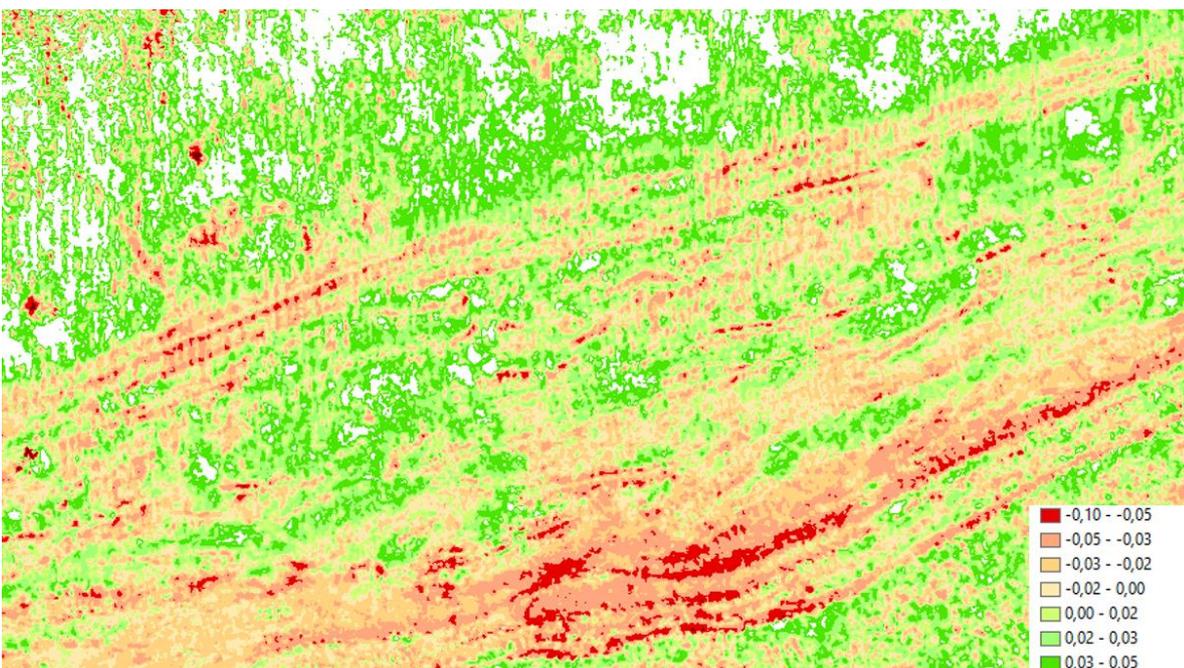


Fig. 21 Example of the erosion of the tourist path (compared measurements in 2024 - 09/24 to 05/24), legend is in cm



### 4.3. PROBLEMS AND OBSTACLES

- Data collection is complicated by unfavorable weather conditions, especially in heavy rain or wind. Tourists present on trails are recorded in the collected data. Therefore, it is better to manage their presence on trails while monitoring. They are sometimes not willing to wait till the measurement ends.
- It is quite difficult to carry monitoring equipment because it is big, heavy, and quite fragile. At the same time, monitoring sites are very often remote, or access to them is complicated.
- More people are necessary to perform measurements. It is sometimes difficult to manage the presence of the whole team.
- Permits for flying in protected areas can be problematic.
- In the 2024 summer season, there were several flash floods or heavy rain events in the area of Malá Fatra NP. It caused strong erosion on the trails. It will not be possible to calculate the contribution of tourists to the erosion process in this season (Fig. 22).
- The differences between epochs consist of two aspects: systematic and random; the systematic error component is caused by the accuracy of the measuring system (its interpretation as erosion is imprecise, so it is necessary to find a “hack” to eliminate this component; although the magnitude is not large, detection and removal will improve the interpretation of the final deformation), the difference after reducing the systematic impact will better explain the erosion effect.
- It is necessary to improve the possibilities of terrain classification and remove the presence of the point cloud noise, which is basic in this type of measurement.



Fig. 22 Erosion on the trail - pilot site Chrapaky

### 4.4. FUTURE DEVELOPMENTS

A larger dataset revealed challenges related to georeferencing individual epoch measurements. These are georeferenced with an accuracy of less than 5 cm, but transforming epoch measurements to the zero epoch can reduce this effect. The main challenge is to find code for calculating the transformation parameters needed to align individual point clouds in order to eliminate this error. It is also necessary to improve the process of data reclassification to completely remove the influence of vegetation on measurement results. The most recent epoch measurements, which have only been processed so far, will also be compared. As part of the next measurement, the behavior of the reconstructed section of the hiking trail will be monitored, and epoch 09/2025 will become the new reference epoch for the Kopiská section.

We will continue our measurements to obtain a bigger amount of data and try to precisely define the triggers of soil erosion and their contribution to this process. The idea is to find the formula or the relation between



soil erosion and the subsoil character, number of tourists, terrain slope, orientation, etc. The plan is to increase the effectiveness of measurement processing without losing the precision criteria.

#### 4.5. RECOMMENDATIONS

- Verify the legislative procedures and the need for permits required before measurements. Different countries and localities have different specifications.
- The measuring device should measure all necessary values with the required accuracy.
- The choice of a suitable carrier to carry the measuring device such as UAS, car or backpack form is important (site access, measured parameters, equipment capabilities, etc. must be taken into account).
- Individual carriers have their constraints that affect the measurement (car- accessibility, traffic constraints; UAS- weather conditions, access, vegetation, etc.).
- The data acquisition process needs to be adapted to the actual outdoor conditions - temperature, rain/snow, etc. Proper choice of time and conditions for data acquisition are essential for the required quality of output data.

#### 4.6. REMEDIATION MEASURES ON THE TRAIL

Detailed analysis was provided at the pilot site Hromove sedlo - Chata pod Chlebom to define erosion and accumulation processes on the trail, as well as surface runoff analysis to identify areas that require special attention for remediation measures on this trail in 2025 (Fig 23).

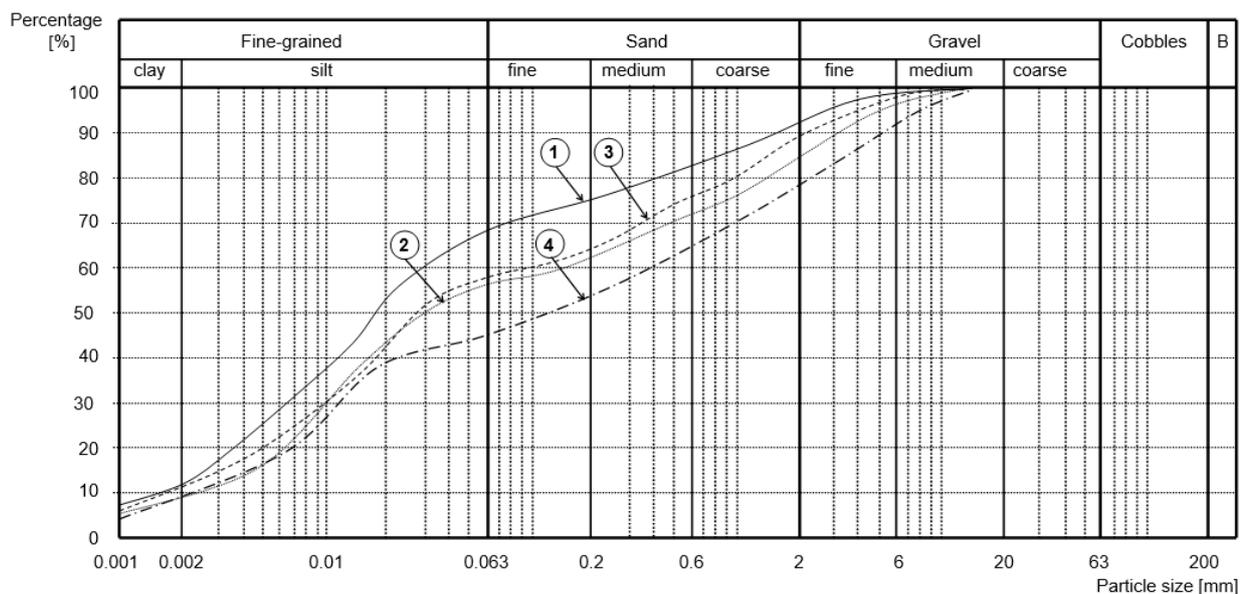


Fig. 23 GIS Runoff analysis on the section of the trail at pilot site Hromove sedlo - Chata pod Chlebom



Fig. 24 Soil samples locations at pilot site Hromove sedlo - Chata pod Chlebom

Analysis of soil grain size distribution from 4 locations (Fig. 24) was done to determine the proportions of different particle sizes (such as sand, silt, and clay) within a soil samples. This information is important for ecology and restoration projects, because soil structure affects plant growth and also soil erosion processes.



Grain-size distribution curves of soils from the trail ~~Kopiska~~. Soil classification: sample 1 (MI); sample 2 (CS); sample 3 (MS) and sample 4 (CS)

Table ... Soil properties from location ~~Chleb~~

Soil parameters	Sample 1	Sample 2	Sample 3	Sample 4
Water contents (%)	25.34	26.69	22.09	24.45
Plastic limit (%)	30.75	26.71	28.34	25.67
Liquid limit (%)	45.08	45.32	43.20	44.11
Plasticity index (%)	14.33	18.60	14.86	18.44
Soil classification acc. to STN 731001	MI	CS	MS	CS

Fig.25 Grain size distribution curves for 4 samples.

A grain size distribution curve is a graphical representation of the proportions of different grain sizes in soil samples (Fig. 25).



In the summer 2025 we implemented remediation measures on tourist trails with the aim to prevent erosion, ensure visitor safety, and protect the surrounding natural environment. These measures were used on the trail exposed to high foot traffic, weathering, and steep slopes at pilot site Hromove sedlo - Chata pod Chlebom. We implemented remediation measures as follows:

- Trail surface stabilization to prevent soil erosion and improve traction for hikers. We used crushed limestone surfacing to harden the trail and improve drainage.
- Water drainage to divert water away from the trail to prevent washouts and soil loss. We used water bars (stones, wood) to redirect surface runoff in areas with regular water flow.
- Reinforcement on steep slope to reduce trail damage and improve hiker safety on inclines. We used steps made of stone, and especially wood.
- Vegetation restoration to restore damaged areas and prevent further degradation. We used biodegradable erosion control ropes from sheep wool to stabilize the soil during plant recovery.



Fig. 26 Remediation measures on the trail



## 5. SOIL BIODIVERSITY MONITORING

### STARTING DATE

June 5, 2023

### 5.1. METHODOLOGY DESCRIPTION

Soil is a key factor in evaluating the sustainability of land use, as it contributes to both the conservation of natural resources and the maintenance of ecosystem biodiversity. Recent research has underlined the importance of mites in biomonitoring, identifying them as valuable soil bioindicators. Since mite communities are highly sensitive to different types of soil disturbance, our study aims to determine whether the diversity and abundance of soil mites found along tourist trails and in their surroundings reflect the impact of human activity on the landscape and whether mites can be effectively used in regular monitoring programs. To this end, four pilot sites were selected in the Malá Fatra National Park, and one additional site in the TANAP was chosen for a blind experiment.



Fig. 27 Tullgren funnel and adult soil mite of the genus Oribatida

Samples were collected manually twice a year (6/2023, 6/2024, 9/2024, 6/2025 and 9/2025) before and after the main tourist season. Three samples were collected at each pilot site, directly on the trail, at ecotone, and near the trail at the unaffected place. Samples from 2025 have not been evaluated yet.



## 5.2. RESULTS AND OBSERVATIONS

A total of 542 soil mites were found in 2023 and 2024. They were identified into four groups - Oribatida, Mesostigmata, Astigmata, and others. As part of the project, three main indicators of biodiversity were analyzed:

- Number of individuals
- Density (individuals per 375 cm<sup>3</sup> of soil)
- Simpson's Diversity Index (D)

The Simpson's Index (D) is one of the most widely used measures of biodiversity in ecology. It expresses the probability that two randomly selected individuals from a given sample will belong to the same species. All data were normalized using min-max scaling (0-1), which allowed for direct comparison of variables across years (2023 vs. 2024), seasons (before and after the tourist season), and sampling site types. The results were visualized using boxplots and interpreted in the following three categories:

### 1. Yearly Comparison - 2023 vs. 2024

Although the number of individuals in 2024 showed a decline, this difference is not statistically significant. The same applies to both density and Simpson's index (Fig. 28). However, the results may suggest a slight deterioration of environmental conditions in 2024 – possibly due to lower precipitation, increased human disturbance, or other external factors. Biodiversity, and particularly the Simpson's Index, is a sensitive ecological indicator. A decrease in diversity often reflects a decline in ecological stability or overall environmental health.

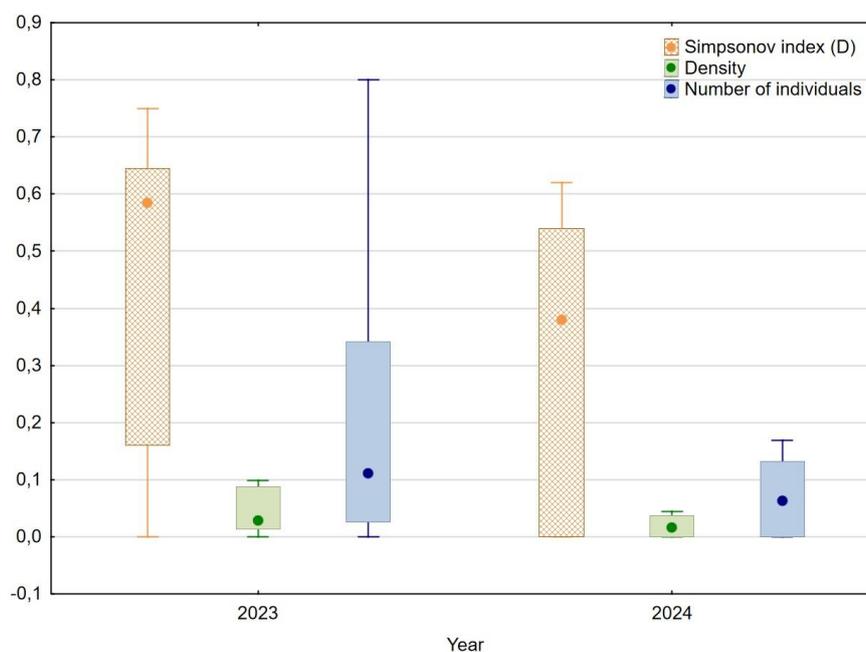


Fig. 28 Graph shows results of non-parametric tests for years - Simpson's index: M-W U (2;36) = 90.50,  $p = 0.07$ ; density: M-W U (1;30) = 86.00,  $p = 0.35$ ; number of individuals: M-W U (1; 30) = 81.00,  $p = 0.25$ ; results not significant.



## 2. Seasonal Comparison - Before vs. After Tourist Season

The number of individuals and density remained relatively stable across the two periods (Fig. 29), with no significant differences observed. Interestingly, Simpson's index increased after the tourist season, indicating a higher species diversity. This suggests that seasonal change had minimal or no effect on the number of individuals and density, but may have promoted the appearance or establishment of new species.

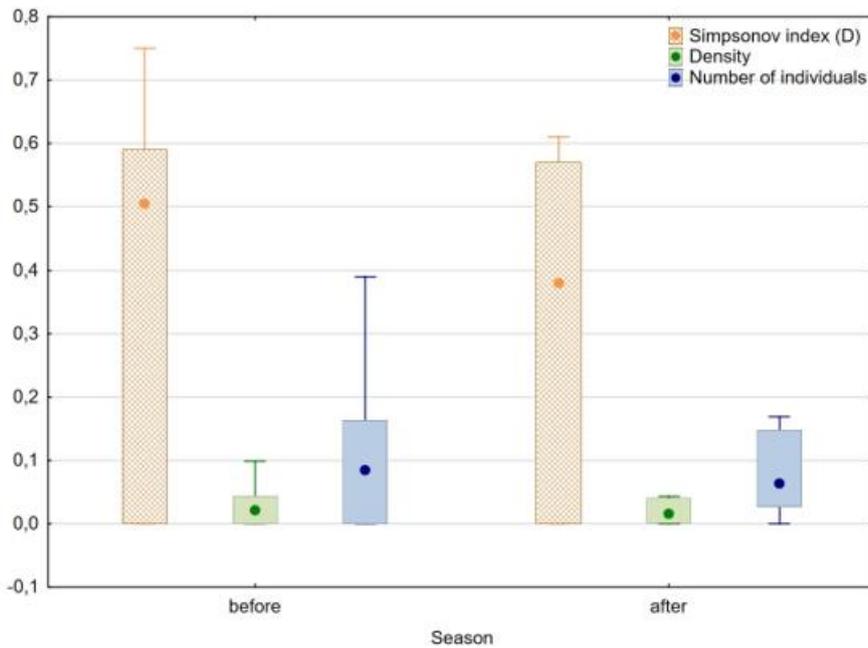


Fig. 29 Graph shows results of non-parametric tests for seasons - Simpson's index:  $M-W U (1;30) = 69.50$ ,  $p = 0.16$ ; density and number of individuals:  $M-W U (1;30) = 90.00$ ,  $p = 0.84$ ; results not significant.

## 3. Sampling Site Type

Samples taken from natural grassy areas near trails (control sites) showed the highest number of individuals, accompanied by a large variance, and also exhibited the highest density and diversity (Simpson's Index) of all locations. The transition sites had lower values across all indicators when compared to the control sites, but still higher than the trail samples. At the trail sites, all biodiversity indicators were close to zero (Fig. 30), indicating highly degraded or disturbed conditions. The results underscore the ecological importance of ecotone zones as key areas for biodiversity conservation. At the same time, the observed trends may signal potential negative developments in species diversity in 2024. Regular monitoring and effective management of these ecosystems are essential to maintain ecological balance and long-term habitat health.

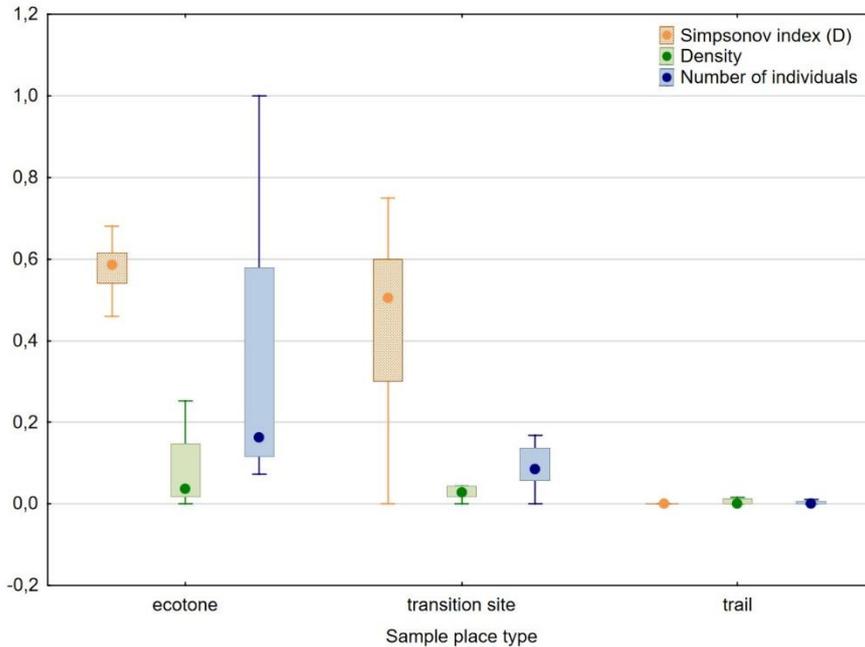


Fig. 30 Graph shows results of non-parametric tests for sampling site types - Simpson's index: K-W H (2;36) = 23.109,  $p = 0.0001$ ; density: K-W H (2;36) = 24.55,  $p < 0.0001$ ; number of individuals: K-W H (2;36) = 24.07,  $p < 0.00001$ ; results are significant.

### 5.3. FUTURE DEVELOPMENTS

We will process the latest samples taken in September 2025 and then evaluate the data for the entire period. We will evaluate the occurrence and abundance of soil mites in relation to years, tourist seasons, and the type of sampling site. It is important to monitor soil mites biodiversity because soil organisms (e.g., microbes, fungi, invertebrates) play essential roles in:

- Nutrient cycling
- Organic matter decomposition
- Soil structure maintenance
- Plant growth and resilience

Trail erosion can lead to:

- Soil compaction
- Loss of topsoil
- Reduced organic matter
- Altered water infiltration
- Displacement or loss of soil organisms



## 6. WATER MONITORING

### STARTING DATE

August 2024, older data available from a bachelor's thesis from March 2022 to December 2023.

### 6.1. METHODOLOGY DESCRIPTION

Water pollution can be caused in several ways. The cumulative impact of different human activities can degrade water quality in rivers in Malá Fatra NP. Research emphasized the need for sustainable management practices to mitigate these adverse effects. Tourists can contribute to water pollution through the improper disposal of solid waste, including plastics, packaging materials, and other non-biodegradable items. Studies emphasize the need for awareness campaigns and the implementation of responsible tourism practices to address this aspect of water pollution. Accommodation facilities can also cause problems if they do not have proper waste and wastewater management. The sampling points were selected to detect potential water pollution originating from these sources.

This monitoring aims to confirm or rule out the possible impact of human recreational activities on the water quality in the Varínka river basin (Vrátna Valley) and the Stohový stream, which flows through the Štefanová settlement, an important tourist center in Malá Fatra National Park. Water samples were collected at bi-weekly intervals from four sampling points (Fig. 31).

#### 1. Sampling point: Varínka 1 (below Chata Vrátna)

- **Location:** The Varínka river, downstream from Chata Vrátna.
- **Characteristics:** This is a reference point for the mainstream of the Varínka. This location is considered the least affected by human activity within the monitored area, which allows for the collection of data on the baseline water quality in the upper part of the valley before its confluence with tributaries from tourist centers.

#### 2. Sampling point: Stohový potok 1 (near Chata Vyhnaná)

- **Location:** The Stohový stream, in the vicinity of Chata Vyhnaná.
- **Characteristics:** This serves as a reference point for the Stohový stream catchment area. As it is situated above the main part of the Štefanová settlement, it is considered the point least affected by human activity in this sub-catchment. Samples from this location serve as a direct comparative baseline for point no. 3.

#### 3. Sampling point: Stohový potok 2 (below the Štefanová settlement)

- **Location:** The Stohový stream, downstream from the built-up area of the Štefanová settlement.
- **Characteristics:** This location serves as the key site for assessing the impact of the settlement. Its location allows for the direct capture and measurement of the potential cumulative impact of the entire Štefanová settlement, including accommodation facilities and their waste management, on water quality. By comparing the results with point no. 2, the extent of this impact can be quantified.

#### 4. Sampling point: Varínka 2 (Tiesňavy)

- **Location:** The Varínka river in the Tiesňavy area, after the confluence of all major tributaries from Vrátna Valley.
- **Characteristics:** This is the final, summary point. Samples from this location represent the overall quality of the water leaving the Vrátna Valley catchment. It allows for the evaluation of how local impacts (including those from the Štefanová settlement) manifest in the main stream after being diluted and how they affect the broader Varínka river basin.

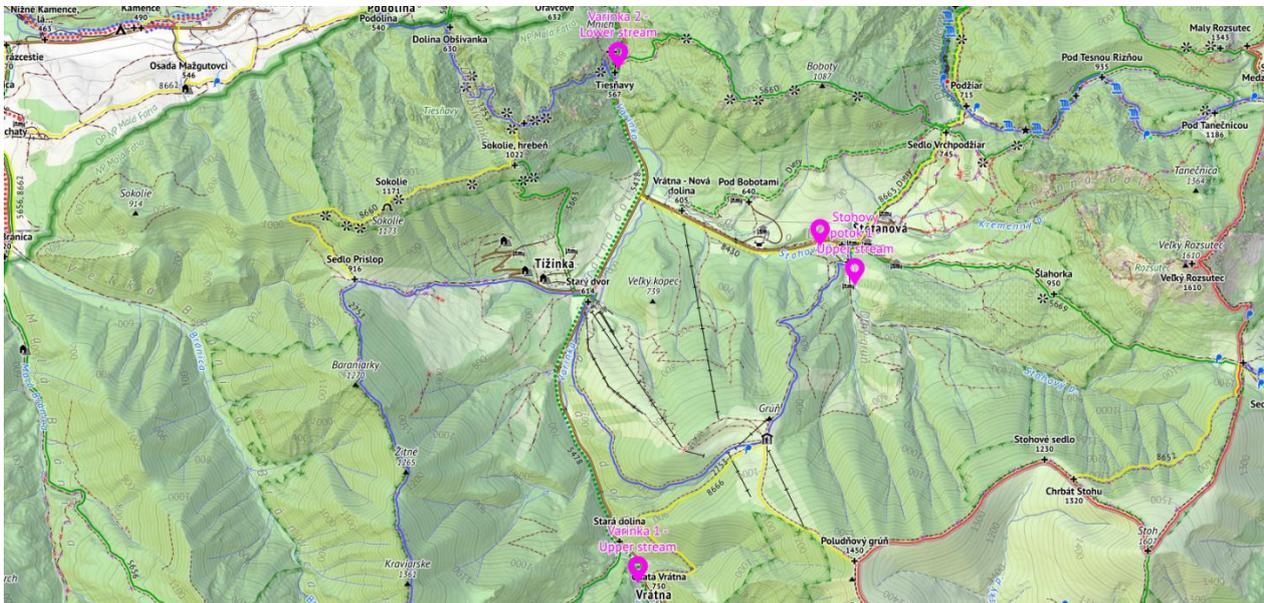


Fig. 31 Sampling points

During laboratory water analysis, various quality indicators such as chemical oxygen demand (COD), physical water parameters, pH, and basic chemical analysis (nitrates, ammonium nitrogen, total hardness, phosphates, chlorides, sulfates) are determined. The COD analysis is performed using a standardized manganometry titration method. Chemical analysis is performed by spectrophotometry using the Novel Palintest method with a YSI 9500 Photometer. Physical properties and pH are measured with a WTW Multi 3430 multimeter. To determine the turbidity in the sample, the nephelometric method is used, which consists of comparing absorbed and transmitted light through the liquid. The YSI Turb® 430 T device is used for this measurement.

After a significant period of data collection and validation, the data are subjected to evaluation using statistical methods. The seasonal rate of visitors to the area and weather conditions are also considered.

## 6.2. RESULTS AND OBSERVATIONS

### Data preparation and descriptive statistical analysis

#### Methodology

The initial step of the data analysis involved the processing and preliminary examination of the water quality dataset, covering the period from August 2024 to August 2025. The primary objective was to derive a foundational understanding of the central tendency and variability of key water quality parameters at the four designated sampling points.

The procedure was executed as follows:

1. **Data loading and validation:** The raw dataset was loaded and systematically inspected for completeness, format consistency, and potential outliers. All numerical values were standardized to a consistent data type to ensure computational accuracy.
2. **Selection of key Indicators:** Based on the project's objective to assess anthropogenic impacts from recreational activities, a subset of key indicators was selected for detailed analysis. These parameters are widely recognized as robust indicators of municipal wastewater and human-induced pollution:
  - **Chemical Oxygen Demand (COD):** An aggregate measure of organic pollution.



- **Conductivity:** A proxy for the total dissolved solids, indicative of inorganic and ionic pollutants.
- **Ammonium ions (NH<sub>4</sub><sup>+</sup>):** A primary indicator of recent sewage or wastewater contamination.
- **Nitrates (NO<sub>3</sub><sup>-</sup>):** An indicator of older, more oxidized organic pollution or septic system leachate.
- **Phosphates (PO<sub>4</sub><sup>3-</sup>):** A critical indicator of contamination from detergents and domestic wastewater.
- **Turbidity:** A measure of water clarity affected by suspended solids, which can be linked to runoff and pollution events.

3. **Calculation of descriptive statistics:** For each key indicator at every sampling point (Varínka 1, Varínka 2, Stohový potok 1, Stohový potok 2), a comprehensive set of descriptive statistics was computed. This included the number of observations (n), mean, median, standard deviation, minimum, and maximum values.

## Results

Table 1 provides a summary of the descriptive statistics for the selected water quality parameters across the four sampling locations.

Parameter	Sampling Point	n	Mean	Median	Std. Dev.	Min	Max
COD [mg/l]	Varínka 1	26	0,76	0,69	0,51	0,14	2,24
	Stohový potok 1	24	1,26	1,14	0,49	0,27	2,67
	Stohový potok 2	24	02,01	1,93	0,50	1,32	3,19
	Varínka 2	26	1,25	1,23	0,40	0,29	2,15
Conductivity [µS/cm]	Varínka 1	26	288,7	288,0	12,8	258	307
	Stohový potok 1	24	341,5	342,0	16,6	300	388
	Stohový potok 2	24	349,3	354,5	19,8	312	391
	Varínka 2	26	360,7	363,0	18,2	327	398
NH <sub>4</sub> <sup>+</sup> [mg/l]	Varínka 1	26	0,04	0,03	0,02	0,00	0,09
	Stohový potok 1	24	0,02	0,03	0,01	0,01	0,04
	Stohový potok 2	24	0,28	0,14	0,31	0,01	1,04
	Varínka 2	26	0,08	0,06	0,07	0,00	0,25
NO <sub>3</sub> <sup>-</sup> [mg/l]	Varínka 1	26	9,29	9,28	1,94	6,38	17,44
	Stohový potok 1	24	8,12	7,85	2,21	5,84	17,53
	Stohový potok 2	24	8,92	8,83	1,35	5,58	11,51
	Varínka 2	26	8,24	8,17	1,87	6,20	14,08
PO <sub>4</sub> <sup>3-</sup> [mg/l]	Varínka 1	26	0,06	0,07	0,03	0,02	0,12
	Stohový potok 1	24	0,04	0,04	0,02	0,01	0,08
	Stohový potok 2	24	0,20	0,20	0,13	0,02	0,56
	Varínka 2	26	0,09	0,05	0,12	0,01	0,56



Turbidity [NTU]	Varínka 1	26	0,86	0,82	0,42	0,17	1,93
	<b>Stohový potok 1</b>	<b>24</b>	<b>1,22</b>	<b>0,99</b>	<b>0,86</b>	<b>0,32</b>	<b>4,51</b>
	<b>Stohový potok 2</b>	<b>24</b>	<b>2,32</b>	<b>2,27</b>	<b>0,78</b>	<b>0,73</b>	<b>4,29</b>
	Varínka 2	26	1,83	1,79	1,48	0,28	8,00

**Table 1.** Descriptive statistics of key water quality indicators for the monitoring period (August 2024 - August 2025).

### Interpretation of Preliminary Results

This initial statistical summary provides compelling preliminary evidence that strongly supports the primary research hypothesis.

- 1. Comparison of Stohový potok 1 (Reference) vs. Stohový potok 2 (Impacted):** A consistent and marked increase in pollution indicators is observed after the stream flows through the Štefanová settlement.
  - **Phosphates ( $\text{PO}_4^{3-}$ ):** The mean concentration increases fivefold, from 0.04 mg/l to 0.20 mg/l, which is a powerful indicator of contamination from detergents and sewage.
  - **Ammonium Ions ( $\text{NH}_4^+$ ):** A more substantial increase is observed here, with the mean concentration rising 14-fold from 0.02 mg/l to 0.28 mg/l. The high standard deviation and maximum value (1.04 mg/l) at the Stohový potok 2 site are indicative of significant, episodic pollution events.
  - **COD & Turbidity:** Mean values for both parameters increase substantially (by approx. 60% and 90%, respectively), indicating an influx of both dissolved and suspended organic and inorganic matter.
  - **Conclusion:** The data strongly suggests that the stream segment between the Stohový potok 1 and Stohový potok 2 sampling points is subject to significant contamination, consistent with the impact of the Štefanová settlement.
- 2. Comparison of Varínka 1 vs. Varínka 2:**
  - The reference site Varínka 1 exhibits low concentrations for all pollution indicators, confirming the high water quality of the upper reaches of the river.
  - The downstream site Varínka 2, located after the confluence with Stohový potok, shows a discernible increase in the mean concentrations of most indicators (COD,  $\text{NH}_4^+$ ,  $\text{PO}_4^{3-}$ ) when compared to Varínka 1.
  - This increase, however, is substantially less pronounced than the contamination observed in Stohový potok itself. This pattern is suggestive of a **dilution effect**, whereby the larger volume of the Varínka river partially mitigates the pollution load. Nevertheless, the impact remains measurable.

This initial analysis has successfully established a quantitative baseline, revealing clear patterns in the data that align with the research hypotheses.

### Comparative analysis and hypothesis H1 testing (Impact of the Štefanová settlement)

#### Methodology

This phase of the analysis focused on a rigorous statistical comparison of the water quality of the Stohový potok stream, specifically contrasting the reference site located upstream of the Štefanová settlement



(Stohový potok 1) with the impacted site located downstream (Stohový potok 2). The primary objective was to statistically test Hypothesis H1: that recreational and residential activities within the settlement exert a significant, measurable impact on water quality.

The analytical workflow was structured as follows:

1. **Visual analysis via box plots:** To visually assess the differences in data distribution between the two sites, box plot diagrams were generated for the key pollution indicators (phosphates, ammonium ions, and COD). This graphical method is highly effective for comparing distributions, as it illustrates the median, interquartile range (IQR), and the full range of the data, thereby highlighting systematic shifts in concentration and variability.
2. **Quantification of impact:** The magnitude of the impact was quantified by calculating the percentage increase in the mean concentration of each indicator between the reference and impacted sites.
3. **Statistical significance testing:** To formally test the hypothesis, the **Mann-Whitney U test**, a non-parametric statistical test, was employed. This test was selected due to its robustness and suitability for environmental datasets, which often do not conform to a normal distribution. The test evaluates the null hypothesis ( $H_0$ ) against the alternative hypothesis ( $H_1$ ):
  - **$H_0$  (Null hypothesis):** There is no statistically significant difference in the median concentrations of the indicator between Stohový potok 1 and Stohový potok 2.
  - **$H_1$  (Alternative hypothesis):** The median concentration of the indicator at Stohový potok 2 is significantly higher than at Stohový potok 1. A **p-value** of less than 0.05 was adopted as the threshold for statistical significance.

## Results

### 1. Visual data comparison

The box plots for the key indicators provide a clear and compelling visual representation of the water quality degradation.

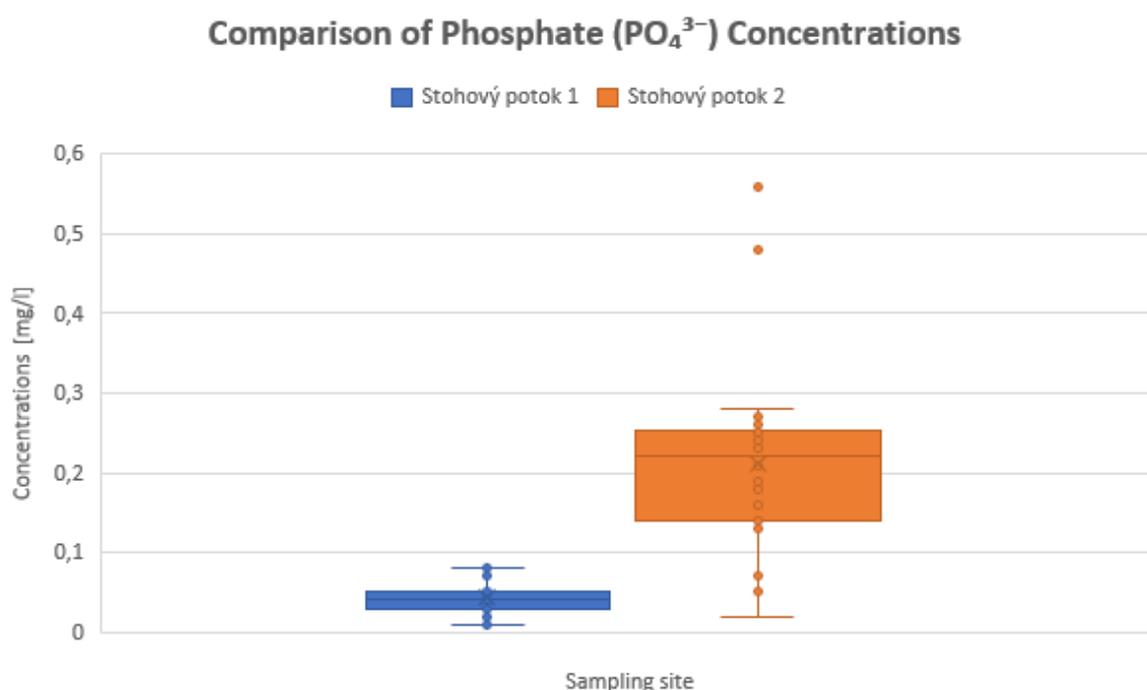


Fig.32 Comparison of phosphate ( $\text{PO}_4^{3-}$ ) concentrations



Fig.32 Illustrates a dramatic upward shift in phosphate concentrations. The entire data distribution for Stohový potok 2 is elevated significantly above that of Stohový potok 1, where concentrations remain consistently low. This visualization strongly suggests a substantial input of phosphate-containing pollutants between the two sites.

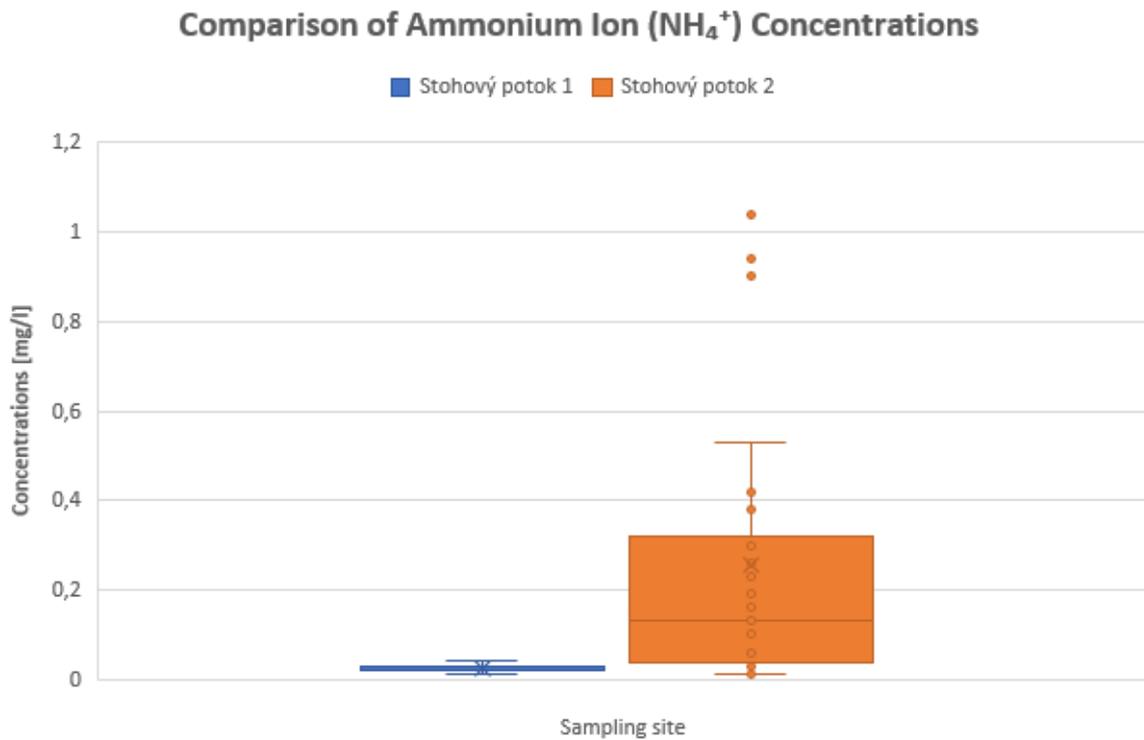


Fig. 33 Comparison of ammonium Ion (NH<sub>4</sub><sup>+</sup>) concentrations

The impact is even more pronounced for ammonium Fig. 32). The distribution for Stohový potok 1 is tightly clustered near zero, whereas Stohový potok 2 exhibits a markedly higher median and a wide data range, including several extreme outliers. This pattern is indicative of severe, intermittent pollution events.



### Comparison of Chemical Oxygen Demand (COD)

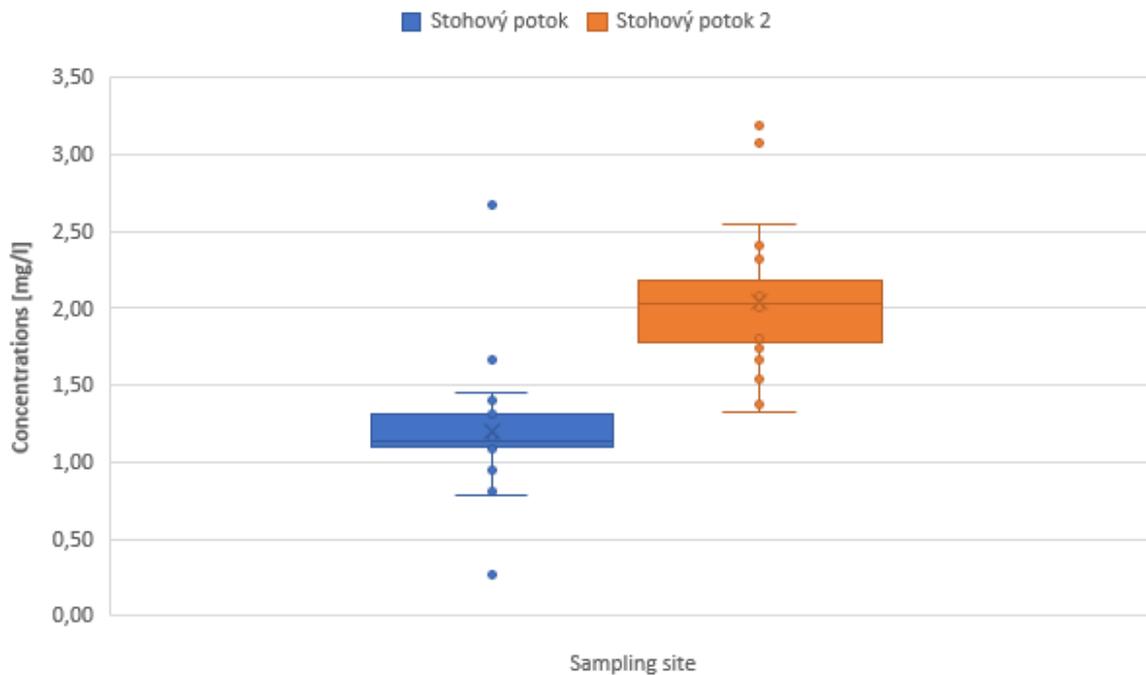


Fig. 34 Comparison of chemical oxygen demand (COD)

A clear and consistent increase in COD is observed. The box plot for Stohový potok 2 is entirely shifted to a higher range compared to Stohový potok 1, confirming a significant increase in organic pollution (Fig. 34)

## 2. Quantitative and Statistical Analysis

The numerical results, including the percentage increase and the outcome of the Mann-Whitney U test, are summarized in Table 2.

Parameter	Mean: Stohový potok 1 [mg/l]	Mean: Stohový potok 2 [mg/l]	Mean Increase	p-value	Statistical Significance
PO <sub>4</sub> <sup>3-</sup>	0,04	0,20	+400 %	< 0,001	Highly Significant
NH <sub>4</sub> <sup>+</sup>	0,02	0,28	+1300 %	< 0,001	Highly Significant
COD	1,26	2,01	+60 %	< 0,001	Highly Significant

Table 2. Summary of mean concentration increases and statistical significance testing between Stohový potok 1 and Stohový potok 2.

### Interpretation of Results

The evidence gathered in this step provides unequivocal support for **Hypothesis H1**.

1. **Confirmation of anthropogenic impact:** The visual and statistical analyses converge to demonstrate that the Štefanová settlement is a significant source of water pollution. The observed increases in pollutant concentrations are not attributable to random chance ( $p < 0.001$ ).
2. **Nature of pollution:** The specific chemical signature of the pollution—characterized by a dramatic rise in both **phosphates and ammonium ions**—is a classic indicator of contamination from municipal wastewater. This strongly points towards sources such as malfunctioning small-scale wastewater



treatment facilities, septic tank leakages, or direct discharge of sewage and detergent-rich greywater.

3. **Statistical certainty:** The extremely low p-values indicate that there is less than a 0.1% probability that the observed differences are coincidental. Therefore, we can conclude with a high degree of confidence that the source of contamination is located within the stream segment between the two sampling points.

**Conclusion:** Hypothesis H1, stating that pollutant concentrations are significantly higher at the Stohový potok 2 site compared to the Stohový potok 1 site, is conclusively confirmed.

### Analysis of downstream impact and Hypothesis H2 testing (dilution effect)

#### Methodology

This step was designed to evaluate the downstream propagation of the contaminant load from Stohový potok and its impact on the main Varínka river. The objective was to test Hypothesis H2, which posits that the pollution signature from the impacted tributary would be detectable in the main river channel post-confluence, but that its magnitude would be attenuated due to dilution.

The analytical procedure was as follows:

1. **Comprehensive visual analysis:** Box plot diagrams were generated for the key pollution indicators (phosphates, ammonium ions), this time incorporating all four sampling points. This allows for a complete visualization of the pollutant pathway, from the pristine reference conditions (Varínka 1 and Stohový potok 1), through the point-source contamination (Stohový potok 2), to the final receiving water body (Varínka 2).
2. **Statistical significance testing:** To ascertain whether the observed increase in pollutant concentrations in the main river was statistically significant, the dataset from the Varínka 1 (upstream reference) site was compared against the Varínka 2 (downstream impacted) site using the **Mann-Whitney U test**. This directly assesses the impact of the tributary's inflow on the river's water quality.

#### Results

##### 1. Visual data comparison

The box plots provide a clear graphical narrative of the pollutant dynamics within the catchment.



### Comparison of Phosphate ( $\text{PO}_4^{3-}$ ) Concentrations across All Sampling Sites

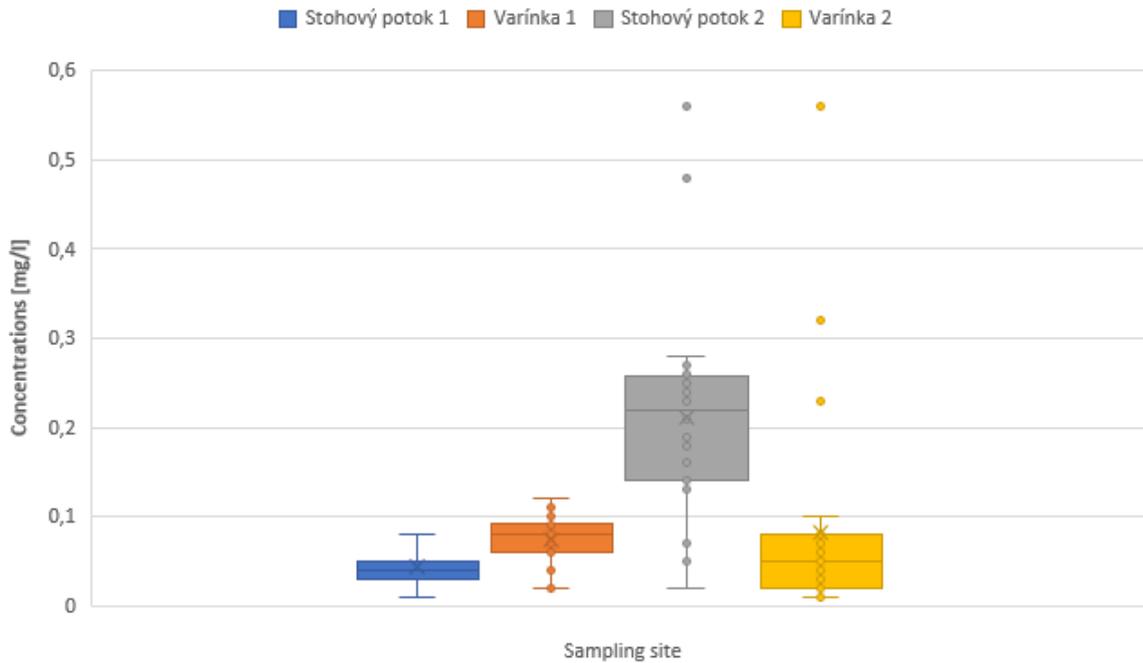


Fig. 35 Comparison of phosphate ( $\text{PO}_4^{3-}$ ) concentrations across all sampling sites interpretation

Fig. 35 effectively illustrates the complete process. The reference sites, Varínka 1 and Stohový potok 1, exhibit nearly identical and low phosphate distributions. A severe contamination event is evident at Stohový potok 2. Subsequently, the Varínka 2 site shows a slight but noticeable elevation in its median and interquartile range compared to Varínka 1, while remaining significantly lower than the extreme levels in the tributary. This provides a classic visual demonstration of the dilution effect.

### Comparison of Ammonium Ion ( $\text{NH}_4^+$ ) Concentrations across All Sampling Sites

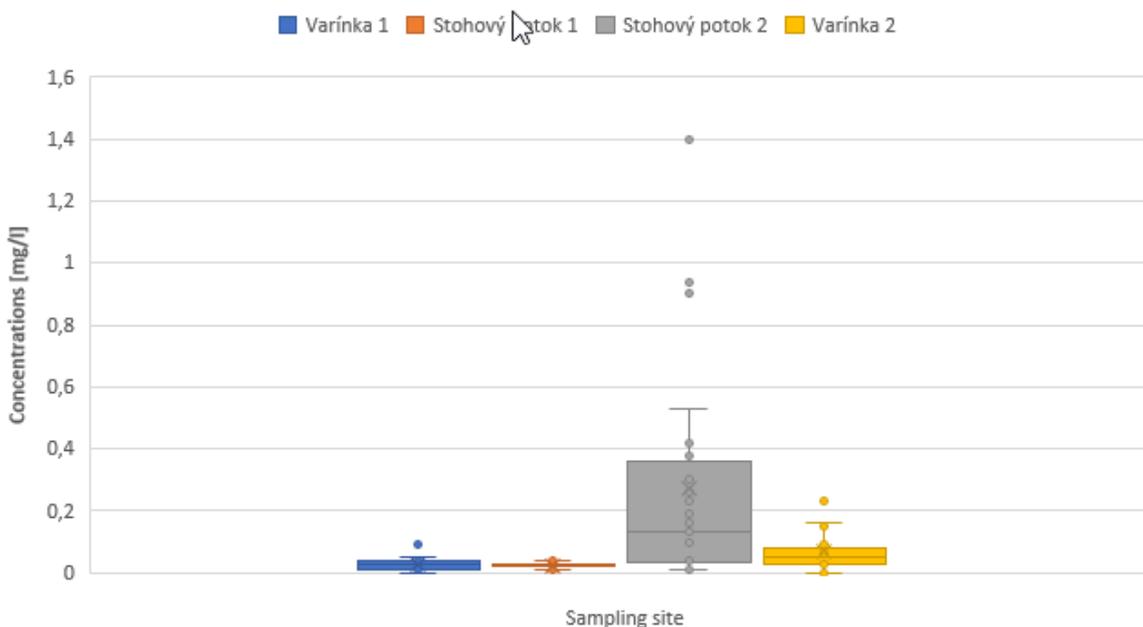


Fig. 36 Comparison of ammonium ion ( $\text{NH}_4^+$ ) concentrations across all sampling sites interpretation



A similar pattern is observed for ammonium (Fig 36). Following the extreme spike in concentration at Stohový potok 2, the levels at Varínka 2 are only marginally higher than the baseline concentrations at Varínka 1. This confirms that the substantial pollution load of ammonium is also effectively diluted by the greater volume of the main river.

## 2. Statistical analysis (Varínka 1 vs. Varínka 2)

The statistical comparison between the upstream and downstream sites on the Varínka river is presented in Table 3.

Parameter	Mean: Varínka 1 [mg/l]	Mean: Varínka 2 [mg/l]	p-value	Statistical Significance
PO <sub>4</sub> <sup>3-</sup>	0,06	0,09	0,048	Significant
NH <sub>4</sub> <sup>+</sup>	0,04	0,08	0,015	Significant
COD	0,76	1,25	< 0,001	Highly Significant

**Table 3.** Statistical comparison of water quality indicators in the Varínka river, upstream (Varínka 1) and downstream (Varínka 2) of the confluence with Stohový potok.

### Interpretation of results

The findings from this step robustly support **Hypothesis H2**.

1. **Downstream impact is statistically significant:** The Mann-Whitney U test confirms that the increases in phosphate, ammonium, and COD concentrations at the Varínka 2 site are statistically significant. This demonstrates that the contaminant load originating from the Stohový potok is substantial enough to degrade the water quality of the larger Varínka river.
2. **Dilution effect is confirmed:** While the impact is statistically significant, both the visual and numerical data show that the concentrations at Varínka 2 are considerably lower than those at Stohový potok 2. For instance, the mean phosphate concentration in the Varínka river increases by only 0.03 mg/l, despite receiving inflow from a tributary with a mean concentration of 0.20 mg/l. This confirms that the larger discharge of the Varínka river effectively dilutes and attenuates the incoming pollution.

**Conclusion:** Hypothesis H2, which states that the pollution load from Stohový potok 2 is detectable at the downstream Varínka 2 site but is attenuated by dilution, is **confirmed**. The analysis shows that while the ecosystem of the Varínka river has the capacity to dilute the pollutants, it is still subjected to a continuous and statistically significant input of anthropogenic contaminants.

## Time series analysis and seasonality assessment (Hypothesis H3)

### Methodology

This step investigates the temporal dynamics of the pollution load to test Hypothesis H3, which posits that pollutant concentrations will correlate with periods of high tourist activity.

The procedure involved:

1. **Generation of time series plots:** Line graphs were created for the primary pollution indicators (phosphates and ammonium ions), plotting their concentrations against the sampling date. Each of the four sampling sites was represented by a distinct colored line, facilitating direct comparison of their temporal behavior throughout the monitoring period (August 2024 - August 2025).
2. **Visual trend and peak analysis:** The resulting graphs were visually inspected to identify significant temporal patterns, particularly pollution peaks at the impacted Stohový potok 2 site. These peaks



were then contextualized with respect to expected tourist seasons, such as the summer holiday periods (August 2024, July-August 2025) and the winter season (December 2024 - February 2025).

## Results

### 1. Graphical representation of temporal trends

The following figures illustrate the concentration changes over time for the key pollutants.

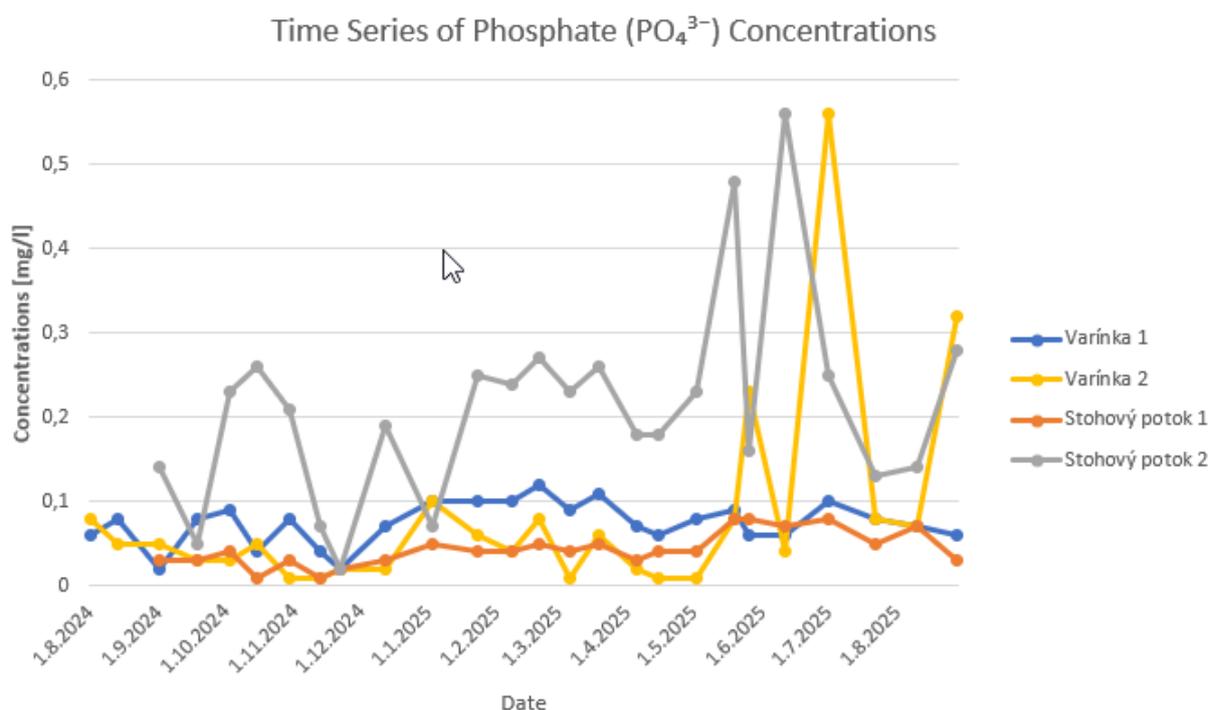


Fig. 37: Time series of phosphate ( $\text{PO}_4^{3-}$ ) concentrations

#### Interpretation:

The lines representing the reference sites, Varínka 1 (blue) and Stohový potok 1 (orange), remain consistently low throughout the entire year, establishing a stable baseline.

- In stark contrast, the line for Stohový potok 2 (gray) is significantly elevated across all seasons, confirming the continuous nature of the pollution.
- Notable peaks in phosphate concentration are observed in **October 2024** and again during the **May-June 2025** period. Concentrations appear somewhat lower, though still highly elevated, during the winter months.

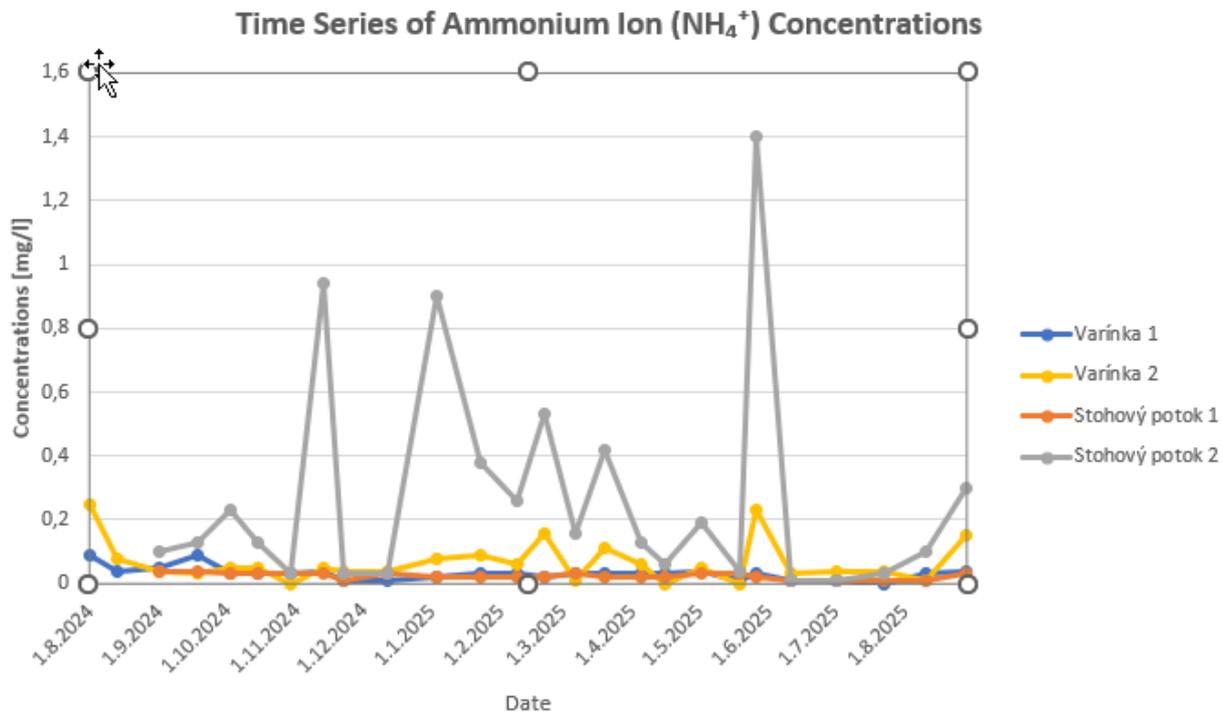


Fig. 38 Time series of ammonium ion ( $\text{NH}_4^+$ ) concentrations

#### Interpretation:

- The time series for ammonium ions reveals a more episodic pollution pattern, characterized by sharp, intermittent concentration peaks.
- The reference sites remain near the detection limit.
- The Stohový potok 2 site exhibits several extreme concentration peaks, most notably in **November 2024**, during the **January-February 2025** period, and again in **May-June 2025**. These sharp peaks are indicative of acute, high-intensity discharge events.

#### Results

The time series analysis provides a nuanced perspective on **Hypothesis H3**.

1. **Chronic vs. acute pollution:** The data clearly indicates that the pollution at Stohový potok 2 is a **chronic, year-round issue**. Superimposed upon this baseline level of contamination are acute, high-magnitude events.
2. **Correlation with tourism seasons:** A plausible correlation with tourism activity can be inferred.
  - The pronounced ammonium peaks during **January and February 2025** align well with the high winter tourist season.
  - The elevated levels of both indicators in **May and June 2025** coincide with the onset of the summer season, a period of increased visitor traffic.
  - The data, however, also presents complexities. The relatively lower concentrations during the main summer holiday month of August 2025 and the high phosphate peak in the off-season month of October 2024 suggest that other variables are also influencing the results. These could include specific discharge events from accommodation facilities or meteorological factors, such as heavy rainfall which may cause septic system overflows.



3. **Need for corroborative data:** To establish a definitive causal link between tourism and pollution peaks, it would be beneficial to correlate these water quality data with ancillary data, such as visitor numbers, accommodation occupancy rates, and daily precipitation records.

**Conclusion:** Hypothesis H3, regarding the influence of seasonality, is **partially confirmed**. While the pollution is a persistent, year-round problem, there is evidence of exacerbation during periods corresponding to high tourist seasons. The overall pattern suggests that the existing wastewater infrastructure is continuously inadequate and is further overwhelmed during periods of increased load.

## Synthesis and overall conclusions

### Summary of analytical approach

A systematic statistical analysis was conducted on a water quality dataset from the Varínka catchment, collected over a one-year period from August 2024 to August 2025. The core objective was to quantitatively assess the impact of human recreational activities originating from the Štefanová settlement on the aquatic environment. The study employed a comparative approach, contrasting data from two reference (upstream) sampling sites with two impacted (downstream) sites. A combination of descriptive statistics, graphical analysis (box plots, time series plots), and non-parametric hypothesis testing (Mann-Whitney U test) was utilized to rigorously evaluate three a priori hypotheses.

### Key findings and hypothesis evaluation

The analysis has yielded clear, statistically robust conclusions regarding the research questions.

#### 1. Hypothesis H1: Impact of the Štefanová Settlement - **CONCLUSIVELY CONFIRMED**

- The analysis unequivocally demonstrated a severe and statistically significant degradation of water quality in the Stohový potok as it passes through the Štefanová settlement. The study documented an extreme increase in key pollution indicators downstream of the settlement:
  - **Phosphate ( $\text{PO}_4^{3-}$ ):** Mean concentration increased by **400%**.
  - **Ammonium ions ( $\text{NH}_4^+$ ):** Mean concentration increased by **1300%**.
  - **Chemical Oxygen Demand (COD):** Mean concentration increased by **60%**.
- **Interpretation:** The specific chemical signature of the pollution, particularly the high concentrations of phosphates and ammonium, provides definitive evidence of **contamination from municipal wastewater**. The most probable sources include effluent from inefficient small-scale wastewater treatment plants, leakage from septic systems, and/or direct discharge from accommodation and recreational facilities within the settlement.

#### 2. Hypothesis H2: Dilution effect in the main river channel - **CONFIRMED**

- The contaminant load originating from Stohový potok was found to be substantial enough to cause a **measurable and statistically significant deterioration** of water quality in the main Varínka river, as observed at the Varínka 2 site post-confluence.
- Simultaneously, a strong **dilution effect** was confirmed. While the impact is significant, the concentrations of pollutants in the Varínka river are substantially lower than the extreme levels recorded in the Stohový potok tributary.
- **Interpretation:** The greater discharge of the Varínka river provides significant dilution capacity, which attenuates the incoming pollution load. Nonetheless, the ecosystem is subjected to a continuous, quantifiable influx of anthropogenic nutrients and organic matter that would not naturally occur.



### 3. Hypothesis H3: Influence of seasonality - PARTIALLY CONFIRMED

- The time series analysis revealed that the pollution from Štefanová is a **chronic, year-round phenomenon**, not merely an intermittent one.
- Superimposed on this persistent baseline pollution are **seasonal and episodic peaks**. Elevated concentrations, especially of ammonium, were observed during periods that correlate with peak tourist seasons (winter and the beginning of summer).
- **Interpretation:** It is highly probable that the existing wastewater management infrastructure is operating at or beyond its capacity year-round and becomes critically overloaded during periods of high visitor numbers, leading to more severe discharge events. The overall pattern is complex, however, and some anomalous peaks may be attributable to other factors, such as precipitation-induced overflow events.

#### Overall Conclusion

This statistical evaluation of the monitoring data provides conclusive evidence that the recreational settlement of Štefanová acts as a **significant point source of pollution, severely degrading the water quality of Stohový potok and measurably impacting the main Varínka river within the Malá Fatra National Park**. The problem is chronic and is further exacerbated during peak tourist seasons. These results also align with data from a 2022-2023 bachelor's thesis study, confirming identical pollution patterns.

### 6.3. Recommendations

- **Targeted regulatory action:** The results of this study provide a robust, evidence-based foundation for environmental protection and water management authorities to conduct targeted inspections of wastewater management practices at all commercial and residential properties within the Štefanová settlement.
- **Enhanced monitoring:** To further resolve the relationship between tourism intensity and pollution events, the monitoring program could be enhanced by integrating it with data on tourist numbers and accommodation occupancy rates.
- **Infrastructure improvement:** The findings clearly indicate that the current wastewater infrastructure is inadequate. A long-term, systemic solution is required to mitigate the ongoing pollution and protect the sensitive aquatic ecosystem of the national park.

This concludes our collaborative analysis. The process has yielded clear and actionable results.



Fig. 39 water sampling

## 6.4. FUTURE DEVELOPMENTS

The results presented in this study provide conclusive evidence of significant water quality degradation in the Stohový potok, with measurable impacts on the Varínka river, originating from the Štefanová settlement. While the primary research questions have been addressed, the findings open new avenues for more detailed investigation and a transition towards data-driven environmental management. Future work will be structured around four key pillars: continuation and enhancement of the core monitoring program, high-resolution source apportionment, integration with ancillary datasets for predictive modeling, and the translation of scientific findings into management action.

### 1. Continuation and enhancement of core monitoring

The established bi-weekly sampling protocol will continue as planned until autumn 2025. This will yield a robust, multi-year dataset, essential for understanding long-term trends and inter-annual variability. To enhance the diagnostic power of the monitoring program, the following additions are proposed:

- **Microbiological analysis:** The current physio-chemical analysis should be augmented with microbiological testing. Specifically, quantification of fecal indicator bacteria, such as *Escherichia coli* (*E. coli*), should be incorporated at all four sampling sites. This will provide direct, irrefutable evidence of fecal contamination and allow for a more comprehensive assessment of the potential public health risks.
- **Analysis of anthropogenic tracers:** To differentiate sources more effectively, future analyses should include specific anthropogenic tracers. The analysis of Pharmaceuticals and Personal Care Products, such as caffeine, carbamazepine, and specific surfactants found in detergents, can serve as highly specific markers for untreated or inadequately treated domestic wastewater.



## 2. High-Resolution source apportionment

The current monitoring design successfully identified the Štefanová settlement as the primary pollution hotspot. The next logical step is to narrow down the specific sources within the settlement.

- **Targeted synoptic sampling:** A series of high-intensity, synoptic sampling campaigns should be designed. These will involve establishing several temporary sampling points within the settlement along Stohový potok and on minor tributaries that drain different sections of the village. Conducting these campaigns during both a baseline (low-tourism) and a peak (high-tourism) period will help to spatially resolve the primary contaminant entry points into the stream.

## 3. Integration with ancillary data for predictive modeling

To move beyond correlation towards causation and predictive capability, the water quality dataset will be integrated with external datasets:

- **Tourism and occupancy data:** A concerted effort will be made to acquire anonymized data on visitor numbers from the Malá Fatra National Park administration and/or occupancy rates from the major accommodation providers in Štefanová. This will enable a quantitative statistical analysis (e.g., regression analysis) to model the direct relationship between human load and pollutant concentration.
- **High-resolution meteorological data:** Data from the nearest Slovak Hydrometeorological Institute (SHMÚ) climate station will be integrated to analyze the influence of precipitation events on pollutant discharge. This is critical for distinguishing between pollution peaks driven by infrastructure overload versus those driven by storm-induced surface runoff or septic system flushing.

## 4. Translating research into management action

The ultimate goal of this research is to provide actionable intelligence for the protection of the aquatic ecosystem.

- **Stakeholder engagement:** The conclusive findings of this study will be compiled into a technical report and formally presented to key stakeholders, including the Malá Fatra National Park Administration, the Slovak Water Management Enterprise (Slovenský vodohospodársky podnik, š.p.), and the relevant municipal authorities.
- **Effectiveness assessment of mitigation measures:** The continuation of the monitoring program will serve as a crucial tool for evaluating the effectiveness of any future mitigation strategies. Should remedial actions be implemented by property owners or authorities (e.g., upgrading a wastewater treatment facility, connecting properties to a centralized system), the ongoing data collection will provide a quantitative measure of their success in reducing the pollution load on the Stohový potok and Varínka river.