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Water Harvesting Pits on Forest Roads – Perspectives? A Case Study in the Czech Republic

Jan Deutscher, Petr Kupec, Karel Zlatuška, Tomáš Vichta, Martin Duchan, Ivana Tomášková, Ondřej Hemr

Abstract

Given the ongoing climate warming that can lead to water scarcity, water retention has been on the forefront of forest ecosystem services. Water harvesting pits on forest roads are one of the possible engineering measures that can help mitigate some of the negative impacts forest roads have on the hydrological regime of the forest ecosystem. The aim of the research is to inform the scientific and professional public about the function and potential of water harvesting pits under forest road culverts and to offer insight into the significance of expected benefits of these objects for water retention and improvement of forest stand hydrological conditions. In this study, standard engineering methods were used to design and build water harvesting pits connected and not connected to culvert mouths and to equip the whole surrounding area with soil moisture and water level sensors. During the two-year study period, a number of irrigation experiments were also performed. The goal was to observe and evaluate the distribution of water from the pits to the surrounding soil and forest stands. Even though water harvesting pits and similar water retention objects on the forest road network seem very beneficial on paper, data from our research does not fully support it. According to our results, the benefits obtained seem much smaller than originally expected to a point that the viability of such measures is probably very low both from the forest stand and water management standpoint. More research is definitely needed in a wider variety of conditions and with a longer time frame.

Keywords: catchment hydrology, water retention, water distribution, Rational method, cross-correlation analysis, irrigation experiments

1. Introduction

In temperate forest environments, surface runoff occurs only sporadically, and the main source of surface runoff is the forest transport network (Ramos-Scharrón and LaFevor 2015). This has a negative effect in areas affected by climate warming where water needs to be retained. The construction of water harvesting, seepage or retention objects on forest roads, is aimed to address the reduction of surface runoff concentrated in forest road ditches and to allow water retention in the soil and bedrock environment. However, it is currently not known what the effectiveness of the seepage objects is and whether it is practical and cost-effective to design them on a widespread basis in the forestry sector.

Direct (surface runoff) off the receiving channel can occur in temperate forests under certain conditions. When the intensity of the rain exceeds the infiltration capacity of the soil, we speak of the so-called excess overland flow (Horton 1933). Saturation overland flow can arise from direct precipitation on the saturated land-surface areas or from return flow of subsurface water to the surface in the saturated areas (Dunne and Black 1970). In variable source-area concept, streamflow is generated on saturated surface areas called »source areas«, which occur in places where the water table rises to the land surface because of infiltration of precipitation into the soil and down to the saturated surface zone, and the subsequent downslope movement of water in the saturated subsurface zone (Wolock 1993).

The construction of forest roads can play a significant role in altering the hydrological response of a watershed and accelerating erosion processes (Ziegler and Giambelluca 2001). The main manifestations of altering the hydrological response can be broadly defined as follows:

⇒ occurrence of surface runoff on heavily compacted areas (Ziegler and Giambelluca 2001)

⇒ capture of subsurface runoff and its conversion to surface runoff (Jones and Grant 1996)

⇒ accelerated conveyance of subsurface and surface runoff through ditches and culverts into stream channels (Jones and Grant 1996)

⇒ formation of erosion gullies by concentrated runoff from forest road culverts (Wemple et al. 1996)

⇒ ditches, culverts and erosion gullies increase the density of the river network (Jones and Grant 1996).

As such, roads can be considered active source areas (Ambroise 2004) with lower rainfall thresholds for runoff initiation than those of undisturbed soils (Ziegler and Giambelluca 2001). In addition, roads may increase hillslope – stream connectivity by intercepting subsurface flows at cutslopes (Negishi et al. 2008) and by concentrating large quantities of runoff and sediment to distinct drainage locations (Thomaz et al. 2014). Notably, forest road density also has a great impact on increased runoff especially during storms (Kastridis 2020). This can be very relevant for both the flood mitigation and water retention ecosystem services provided by forest ecosystems.

In general, water harvesting objects are designed to capture and infiltrate surface runoff into the nearby soil environment and groundwater. These are most commonly shallow basins filled with filter media (rocks, gravel, etc.), usually wrapped with geotextiles to prevent fine soil particles from infiltrating and clogging the filter media (Gold Coast City Council 2005). Water can move out of the reservoir either through infiltration, evaporation or through a safety overflow device when the reservoir is filled (Beecham 2003). Water harvesting objects can also have a flood control function – they reduce the maximum flood wave volumes and thereby flatten and lengthen the shape of the hydrograph (Dechesne et al. 2005). Detention facilities of this type are now commonly used to manage storm water in urban environments as a flood control measure. Water harvesting objects similar to those used in urban environments are hardly used in forestry practice. In fact, there are no scientific records of their implementation, function and effectiveness. For example, among dozens of documents of the so-called Forestry Best Management Practices, of the USA (Forestry Best Management Practices; Cristan et al. 2016), not one mentions infiltration devices along forest roads. Water harvesting objects on forest roads are implemented individually and spontaneously without contextual knowledge of their long-term impacts and overall function.

Objects on forest roads are usually designed using a limited number of standardized engineering methods, most notably the Rational Method in the case of the Czech Republic. The Rational Method is one of the simplest and oldest methods in estimating peak runoff. It depends on predetermined values for land use and land surfaces based on the runoff coefficient represented by »C« (Dooge 2010). The rational method is widely used to estimate the maximum runoff of small catchments up to this day (Sabzevari 2022). It is one of the most commonly used design tools for urban runoff calculations, where the runoff is found as a function of the area times the rainfall intensity times a runoff coefficient. The runoff coefficient is given as the relationship between precipitation and runoff. It can be calculated either by the ratio between the intensities of the peaks or the volumes (Schärer et al. 2020). The rational method allows for modeling of different scenarios according to how extreme driving precipitation values are used. For this purpose, the return period concept is usually used. The return period is an average time or an estimated average time between events; in hydrology for instance rains (Thorndahl and Willems 2008), floods (Kumari et al. 2019), avalanches (Mesesan et al. 2018) or droughts (Alencar a Paton 2024). The design rainfall intensity in the rational formula can be obtained by regional Intensity–Duration–Frequency (IDF) curves (Madsen et al. 2009). In the case of the Czech Republic, according to the national technical standards, the rational method is compulsorily used for the dimensioning of water harvesting objects (Czech technical standard ČSN 75 9010). The technical standard offers a table with expected runoff coefficients according to soil conditions, slope and land cover and serves as a pre-calibration for the runoff coefficients according to which the size of the object is calculated. For the experimental design of this study, we therefore intentionally used the Rational Method and return period concept as a basis for the construction of the water harvesting pits to simulate standard engineering and construction processes. Even though there are more precise and more robust scientific modeling approaches to estimate runoff in small catchments, the goal here was to use current engineering methods. This way we were able to perform an operational experiment and simulate realistic and practical procedure that would be used in practice, which offers an important outcome of the results of this study.

Following current understanding of the effects of forest road infrastructure on runoff processes (Kastridis

2020), there seems to be potential of water harvesting objects on forest roads to mitigate some of their main negative impacts on the water regime, in particular the reduction of surface runoff (by its transformation into subsurface runoff), the reduction of accelerated runoff from forest land (by increasing water retention in the soil) and the reduction of the risk of forest soil erosion (by capturing storm runoff in the retention space). At the same time, there is an ongoing debate about their usefulness as means of contributing to the mitigation of the negative effects of climate change on forestry.

To offer insight into the significance of expected benefits of these objects for both water retention and improvement of forest stand hydrological conditions, our focus was directed on these three follow-up questions:

⇒ What is the role of the culverts under forest roads in hydro-climatic conditions altered by the global climate change? Specifically, how much water does actually flow through the culverts?

⇒ If the water from a culvert is retained in a water harvesting pit, how does the water redistribute to surrounding forest stand?

⇒ Does the surrounding forest stand benefit from the retained water? If so, what area is actually positively affected?

To offer real results as close to practice as possible, we performed an operational experiment using the existing concurrently valid engineering standards and evaluated it using modern scientific approaches. The main aim of the research is to inform the scientific and professional public about the observed functioning and potential of water harvesting pits under forest road culverts in the conditions of this case study and see if some general conclusions could be drawn.

2. Materials and Methods

2.1 Water Harvesting Pits (WHP)

Experimental verification of the Water Harvesting Pits (WHP) was carried out on selected sections of two forest roads on the property of two university training

Fig. 1 Localization of experimental sites

forest enterprises at ČZU near Kostelec municipality and MENDELU near Krtiny municipality (Fig. 1). At each site, two WHPs were built in March 2022, a paired design with the same retention volume. One of the pits is always located below the mouth of a pipe culvert whose flow is diverted into the pit (WHPcu). A control pit is located approximately 30 m away with no connection to the culvert or any other source of concentrated inflow (WHPco). It is intended to serve as a reference for capturing non-concentrated surface runoff over the roadway crown and shallow subsurface runoff through the road embankment so that the effect of the culverts could be evaluated. The water source areas (catchments) above the culverts were both completely forested with the exception of the forest road itself. The length of the road inside the Krtiny catchment reaches ca. 450 m and in Kostelec ca. 150 m.

The WHPs were constructed as a hole under the terrain with trapezoidal cross-section with dimensions as follows (Table 1): length at the bottom 3.5 m; width at the bottom 2.0 m; wall slope 2:1 and retention depth 1.5 m. The volume of the pits without filling was approx. 18 m^3. The banks of the pits were covered with a separation geotextile of 350 g/m^2 (approx. 40 m^2). The pits were filled with backfill stone with an assumed gap density of m=35%. The assumed retention volume of the pits (when the gaps between the stones are filled) is approx. 6.5 m^3.

Table 1 WHPs

Locality	ČZU	MENDELU
Coordinates of the center of WHPcu below the culvert, WGS84	N 49.963732° E 14.793732°	N 49.308205° E 16.698821°
Altitude of the pit beneath the culvert, m a. s. l.	438.10	434.25
Catchment area, ha	12.64	4.21
The area of the catchment with a slope of up to 5%, ha	1.80	0.77
The area of the catchment with a slope over 5%, ha	10.84	3.44
Runoff coefficient for the whole catchment	0.09	0.09

2.2 Culvert Measurement Design

Thomson spillways were connected to the mouths of the pipe culverts. At the spillway, the water level was measured with the ultrasonic sensor US1200 connected to a data logger H7-G-TA4-SZ (both instruments Fiedler AMS, České Budějovice, Czech Republic), and was converted to streamflow via a rating curve pre-set by the manufactor of the sensors calibrated to the installed Thomson weir. Climatic data were obtained from our own in situ network of local meteorological stations (AMET, Velké Bílovice, Czech Republic).

2.3 Groundwater Measurement Design

Pipe shafts (WHP) were drilled and stabilized in the summer 2022 in the center of the WHPs to a depth of about 2 m (0.5 m bellow the pit bottom, 2 m below the terrain). Submersible pressure level gauges (TSH37, Fiedler AMS, České Budějovice, CR) were installed in the shafts to continuously monitor the water level. These main shafts were supplemented by additional fifteen pipe shafts, five in three transects in the left (L1–5) and right (R1–5) directions along the contour and in the downslope direction (D1–5) each with 5 monitoring points at 3 m intervals, see Fig. 2. The intention was to monitor the infiltration to the WHP and subsequent distribution of water through the soil in either transect.

2.4 Soil Water Measurement Design

At each site, 33 standard soil profiles were opened to describe the soil conditions and subsequent installation of soil moisture sensors. They mimicked the locations of the groundwater pipe shafts. In this manner 15 soil profiles were located in transects near both the culvert and control WHPs as well as three undisturbed soil profiles as references.

At the Krtiny site, the soil was classified as well-drained eutric Cambisol (WRB 2014), with a high-coarse fragment volume in the soil profile (>50% vol.) The bedrock consisted of limestone, which was overlain by a relatively homogeneous mixture of hornstone and Quaternary slope deposits. The soil texture ranges from silt-loam in the topsoil to loamy-sand in the subsoil, which is spatially very homogeneous across the site. During the monitoring period, soil moisture reached lower values at most of the monitoring locations on this site, hence the term »dry« variant.

On the other hand, both dry and waterlogged soils have been described at the Kostelec site, which influences the spatial variability of soil properties in the vicinity of the WHPs. However, the main soils of the site were hydromorphic gleyic Stagnosols and Gleysols (WRB 2014). Sandy-clay soils were dominant in texture, with clay and dusty subsoils, which was thus less permeable to soil water in places. The bedrock consisted of acidic granites, which in places protruded

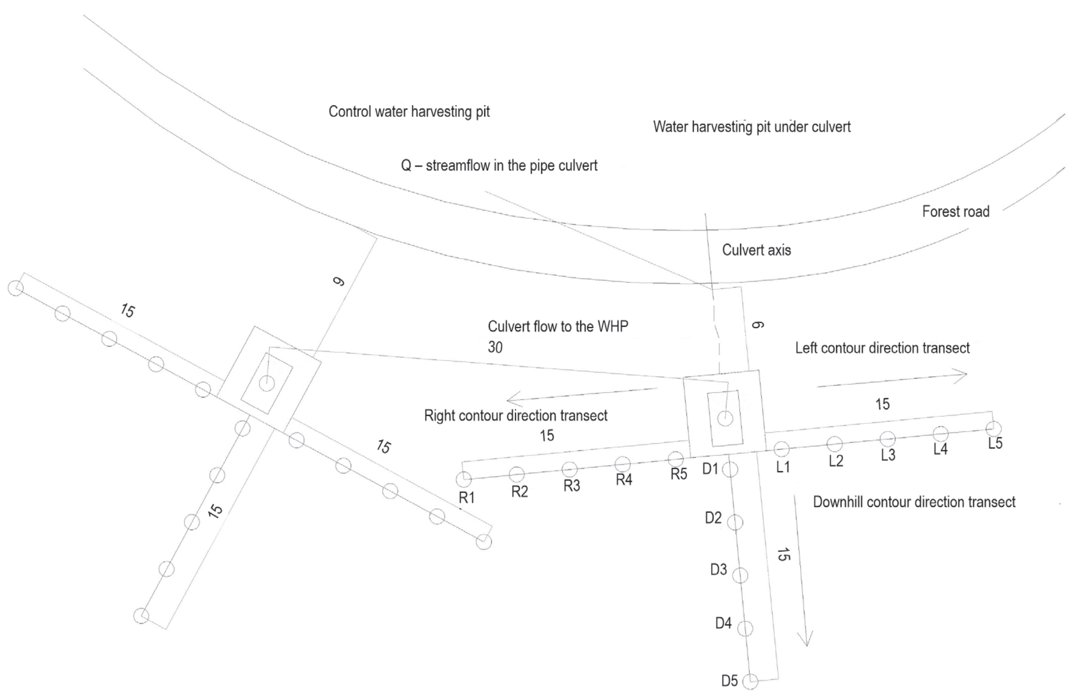

Fig. 2 Schematic experiment design

to the soil surface as partially weathered boulders through varying thicknesses of Quaternary slope deposits. Soil moisture levels were consistently high throughout the year at the site, especially in winter. The site is therefore referred to as the »wet« variant.

Soil moisture at all soil profiles was monitored uniformly at depths of 0.1, 0.3, and 0.6 m on the above described three transects, two on either side (L=left; R=right) along the contour and one down the slope (D=downslope). SMT-100 soil moisture and temperature sensors (Truebner GmbH, Neustadt, Germany; SWC range 0 to 60%, accuracy ±3%) were used to monitor soil moisture. Measurements at both sites were taken automatically every hour and data were then sent using a GreyBox N2N data logger (EMS Company, Brno, CR) to the technology supplier's internet cloud. However, similar to the groundwater level measurements, complete measurements were not performed during some experiments: on 20 April 2023 (pit with pipe, position L1, depth 0.3 m) and 21 June 2024 (pit with pipe, position L3, L4 and L5, depth 0.1 m) at the Krtiny site.

2.5 Forest Stand Description

The forest stands on both localities are dominated by European beech (*Fagus sylvatica* L.). At each site, six representative trees were selected based on height, crown area, and diameter at breast height. Two trees were located in the vicinity of the culvert WHP, two near the control WHP and two at an undisturbed site. On these trees, sap flow sensors (EMS 81, EMS Brno, Czech Republic) were installed utilizing the trunk heat balance method (Čermák et al. 1973, Tatarinov et al. 2005). The sap flow rates were measured from April 2022 to October 2024.

2.6 Irrigation Experiments

Throughout the measurement periods li occurred from October 1, 2022 to August 31 2024, a total of five irrigation experiments were organized on both localities. During the irrigation experiments, water was poured to the pipe culvert and directly to the control WHP. Local firefighting tanker was used at both Kostelec and Krtiny sites. The water was poured with streamflow of approx. 3 liters per second and the volume reached between 8–10 m^3 (the firefighting tanker had to be emptied each time) per irrigation. The goal of the irrigation experiments was to simulate intensive runoff events of known properties and to closely monitor the subsequent distribution of water from the WHP to the surrounding forest stand. The timing of the irrigation was aimed at several days lasting precipitation-free periods.

2.7 Data Evaluation and Time-Lag Response

Monitoring of groundwater level (GW) and soil moisture content (SWC) was performed on hourly data at the same UTC+1 time offset. The hydrographs for both Kostelec and Krtiny culverts were created with indication of timing of the irrigation experiments (Fig. 3 and 4). The irrigation experiments were analyzed in more detail. Additionally, two periods of natural precipitation that caused the highest streamflow in the culverts were separately evaluated as well.

In this paper, the results of the analysis of the five irrigation experiments are presented as well as the two most significant natural precipitation events that occurred throughout the measurement period. The periods (irrigation experiments as well as natural precipitation events) were analyzed from the maximum peak observed in GW level in the WHP caused by the irrigation/rainfall until either a second peak occurred (caused by natural precipitation), or for a period of 96 hours, i.e., 4 days. After four days, we considered that the effect of irrigation water would be minimal. The values of both GW level in mm and SWC at 0.1, 0.3, 0.6 m in % were rounded to whole units.

For each period, cross-correlation (CC) analysis was used to identify the response of GW and SWC at different distances (points along transects) from the WHPs to the initial rise in values at the WHPs. These responses were analyzed both on a horizontal scale along monitoring transects – e.g., along the L1 to L5 line – and simultaneously on a vertical scale along the bedrock/subsoil/topsoil gradient – from the GW level up to the SWC level at 0.1 m.

Lag indicates the delay (lag unit=1 h) between the maximum peak reached at WHP and the subsequent maximum peaks observed in every position along the transect and each depth. The goal was to identify how far would the irrigation water from WHP reach and to what depths. The response indicators (of whether the water reached the location and depth) were considered to be:

- ⇒ a combination of positive correlation and positive lag corresponding to a fast response of GW or SWC to a fast increase in water level at WHP or
- ⇒ a combination of negative correlation and negative lag corresponding to a slow response of GW or SWC to a fast increase in water level at WHP (see Fig. 6 and Discussion Chapter).

A significant lag correlation »*r*« was considered for $p<0.05$. CC analysis was performed using the »stats« package, version 4.2.1, in R software (R version v.4.2.1 GUI 1.79 High Sierra build and RStudio v.2022.07.2 + 576; R Core Team 2022).

3. Results

3.1 Long-Term Culvert Dynamics

The streamflow in the culvert happened only sporadically (Fig. 3 and 4). Streamflow occurred in total during 176 and 16 days out of 701 days at Kostelec and Krtiny, respectively. Maximum streamflow reached 19.86 and 6.07 liters/s at Kostelec and Krtiny, respectively. At the »wet« Kostelec locality, minimal but continuous streamflow at the culvert was observed in the spring time lasting several months. This indicated that the culvert is located in a spring area and that the road drainage sometimes acted as an ephemeral stream. The total runoff through the culvert reached 924,611 and 7118 liters at Kostelec and Krtiny, respectively, which corresponds to a runoff coefficient of only 0.67% and 0.011%. This is a very different amount compared to the expected 9% obtained via the rational method.

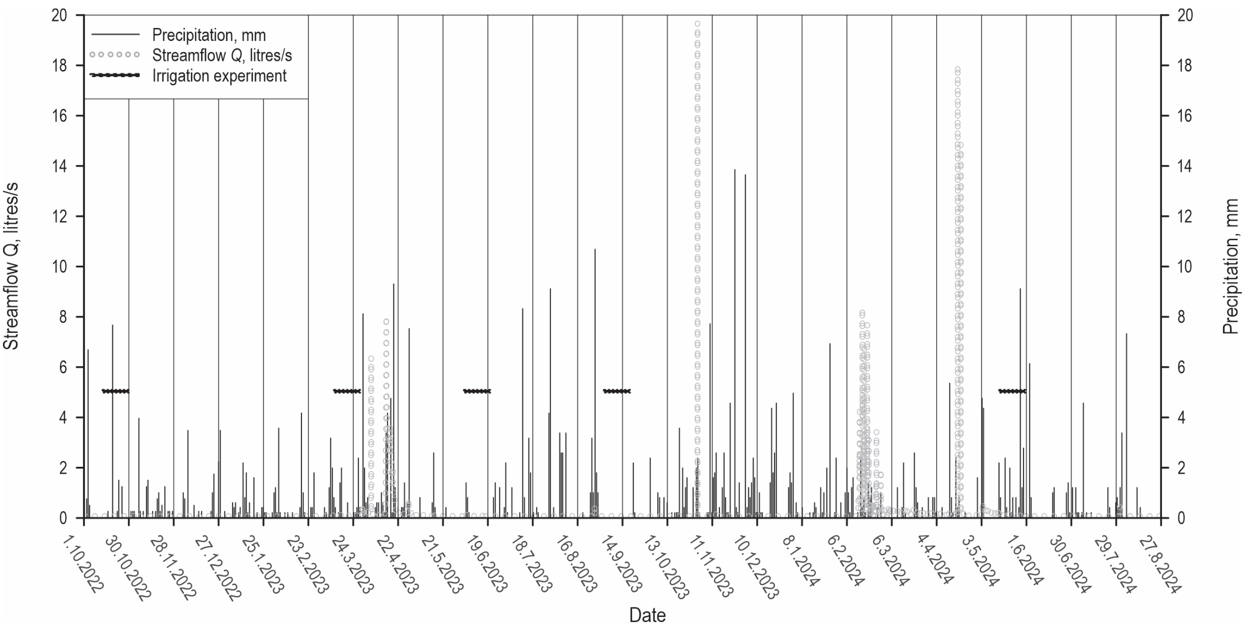

Fig. 3 Hydrograph of culvert streamflow in Kostelec, note different scaling compared to Fig. 4

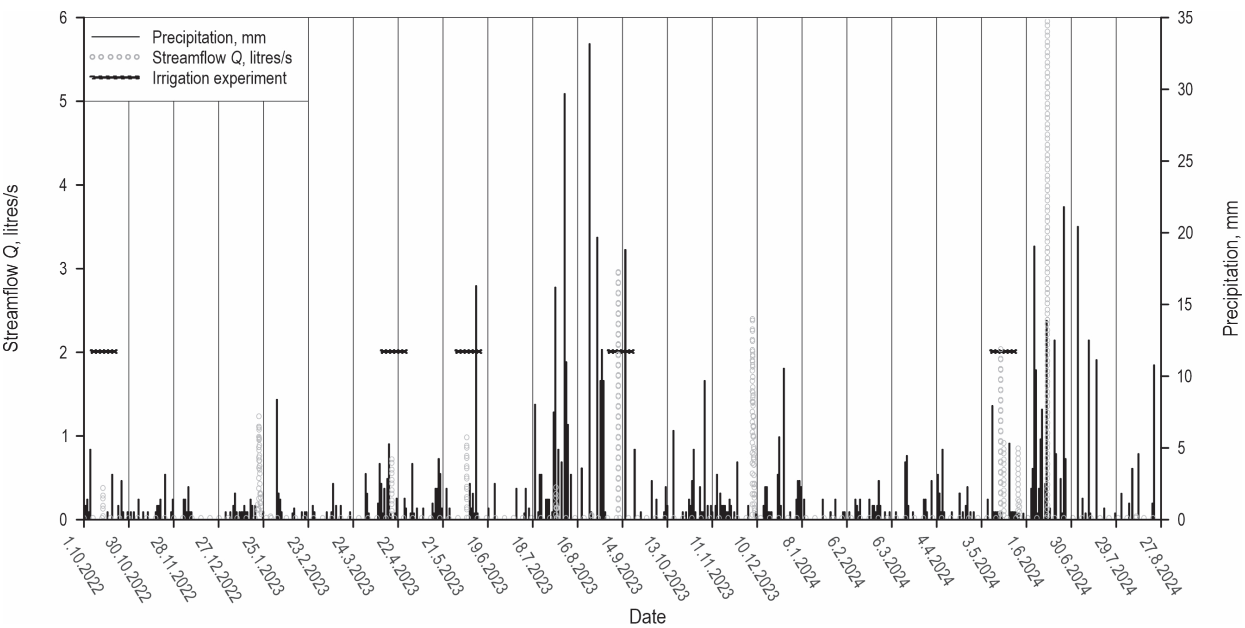

Fig. 4 Hydrograph of culvert streamflow in Krtiny, note different scaling compared to Fig. 3

Table 2 Statistically relevant distribution of water from WHPs after irrigation experiments

		L1	D1	D2	D3	D5	R1	R3			L1	D1	D2	D3	R1	R4
Kostelec, culvert	Depth, cm	lag	lag	lag	lag	lag	lag	lag	Krtiny, culvert	Depth, cm	lag	lag	lag	lag	lag	lag
Mean	IN:0.10	–	–	–	–	–	–	2.3	*Mean*	IN:0.10	1.4	1.2	1.0	–	0.8	13.0
	IN:0.30	–	1.0	–	–	–	0.5	1.0		IN:0.30	1.4	1.2	1.4	–	1.6	–
	IN:0.60	–	–0.7	–	–	–	–	–		IN:0.60	1.4	1.4	1.0	4.6	1.4	–
	IN:GW	–	–0.5	–0.3	0.0	–4.0	0.0	–		IN:GW	1.2	1.2	0.0	–	0.8	–
Count	IN:0.10	–	–	–	–	–	–	3	*Count*	IN:0.10	4	4	4	–	4	3
	IN:0.30	–	3	–	–	–	4	4		IN:0.30	4	4	4	–	4	–
	IN:0.60	–	3	–	–	–	–	–		IN:0.60	5	4	4	4	5	–
	IN:GW	–	5	3	4	3	5	–		IN:GW	5	5	5	–	5	–
Kostelec, control	Depth, cm	lag	lag	lag	lag	lag	lag	lag	Krtiny, control	Depth, cm	lag	lag	lag	lag	lag	lag
Mean	IN:0.10	–	–	–	–	–	–	–	*Mean*	IN:0.10	–0.75	–0.5	6.25	–1	–1.333	–
	IN:0.30	–	–	–	–	–1	3.25	–		IN:0.30	–	–	8	8.33	–	–
	IN:0.60	–	–	–	–	–	–	–		IN:0.60	14.67	2.33	–1	7.33	–1.5	–
	IN:GW	0.667	–2	–	–	–	–	–		IN:GW	0.25	0.75	0	–	–	–
Count	IN:0.10	–	–	–	–	–	–	–	*Count*	IN:0.10	3	3	4	3	3	–
	IN:0.30	–	–	–	–	4	4	–		IN:0.30			3	3	–	–
	IN:0.60	–	–	–	–	–	–	–		IN:0.60	4	4	3	4	3	–
	IN:GW	3	3	–	–	–	–	–		IN:GW	3	3	4	–	–	–

3.2 Distribution of Water from the Pit

3.2.1 Irrigation Experiments

Here, only the statistically relevant increases in soil moisture indicative of water distribution (Table 2) and the positively affected active wetted zone of its spatial impact are presented (Fig. 5a and b). Additionally only locations and depths where water distribution was observed in at least three out of five experiments are

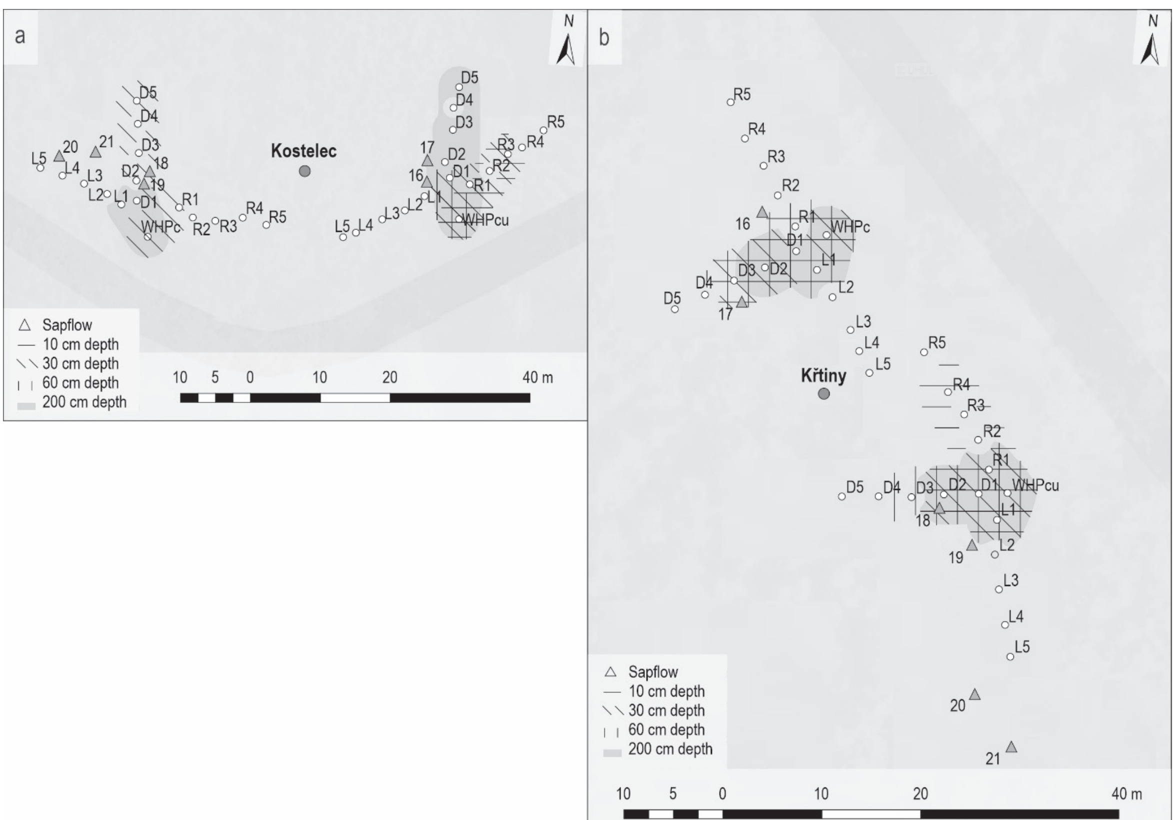

Fig. 5 Spatial distribution of irrigated water from WHPs used to identify the active wetted zone

Table 3 Statistically relevant distribution of water from WHPs after natural precipitation[2]

Natural rainfall		L1		L2		L3		L4		L5		D1		D2		D3		D4		D5		R1		R2		R3		R4		R5	
Kostelec culvert	Depth	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag
Mean	IN:0.10	0.9	1	1	1	1	0			–1	–22	–	–	0.7	2	–0	–4	–1	–9	–1	–9	0.8	0.5	–	–	1	1	1	1	1	5
	IN:0.30	0.9	2	–	–	–	–	–	–	–	–	–1	–19	–1	–15	0	–4	–0	–4	0	–4	0.7	11	–	–	–1	–21	1	9	0	–9
	IN:0.60	–	–	–	–	–	–	–	–	–	–	–1	–9	–1	–5	–0	–2	–1	–3	1	0	–	–	–	–	–1	–16	–1	–16	–	–
	IN:GW	0.8	2	1	0	1	12	–1	–9	–1	–20	1	1	0.9	0.5	1	0	1	2	1	0	0.9	0	0	–5	1	15	–1	–8	1	7
Count	IN:0.10	1	1	1	1	1	1	–	–	1	1	–	–	1	1	2	2	1	1	1	1	2	2	–	–	2	2	2	2	1	1
	IN:0.30	1	1	–	–	–	–	–	–	–	–	2	2	2	2	2	2	2	2	2	2	1	1	–	–	1	1	1	1	2	2
	IN:0.60	–	–	–	–	–	–	–	–	–	–	1	1	1	1	2	2	1	1	1	1	–	–	–	–	1	1	1	1	–	–
	IN:GW	1	1	1	1	2	2	1	1	1	1	2	2	2	2	2	2	2	2	2	2	1	1	2	2	1	1	1	1	1	1
Kostelec control	Depth	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag
Mean	IN:0.10	0.7	4.5	1	0	–	–	1	0	1	1	1	0	0.2	–6	–	–	–1	–12	–	–	0.2	–6	1	1	1	0	1	8	1	0
	IN:0.30	–1	–20	–0	–6	0	–11	1	9	1	0	1	0	–	–	–	–	–	–	–	–	0.7	0	1	18	–	–	1	12	0	–12
	IN:0.60	–0	–6	1	26	–0	7	1	3	–	–	–	–	–0	–10	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	IN:GW	–0	–2	0	–7	–0	–8	0	–8	1	6	0	–4	–1	–20	–1	–13	1	1	–1	–12	0.7	5	1	1	–1	–21	0	1.5	–1	–23
Count	IN:0.10	2	2	2	2	–	–	2	2	2	2	1	1	2	2	–	–	2	2	–	–	2	2	2	2	1	1	1	1	2	2
	IN:0.30	1	1	2	2	2	2	2	2	1	1	1	1	–	–	–	–	–	–	–	–	1	1	2	2	–	–	1	1	2	2
	IN:0.60	2	2	1	1	2	2	1	1	–	–	–	–	1	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	IN:GW	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	2	2	2	2	1	1	2	2	1	1
Natural rainfall		L1		L2		L3		L4		L5		D1		D2		D3		D4		D5		R1		R2		R3		R4		R5	
Krtiny culvert	Depth	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag
Mean	IN:0.10	–0	–1	1	1	–1	–3	–1	–3	–1	–4	0	–1	0.1	–1	0	–1	0	–2	1	7	0.7	6.5	1	6	1	11	0	–1.5	1	0
	IN:0.30	0.7	0.5	0	–1	–0	–1	1	1	0	–1	0	–1	0.1	–2	–1	–4	0	–2	1	4	0.7	4	1	1	1	1	0	–1.5	1	0
	IN:0.60	0.1	–1	0	–1	0	5	0	–2	1	1	0	–2	0.6	14	1	7	0	–1	–1	–3	0.1	–1	0	–2	0	–2	–0	–4	0	–1
	IN:GW	0.8	0	1	1	1	1	1	1	–1	–3	1	1	0.8	0	1	1	1	1	1	1	1	0	1	0	1	2	1	1	1	0
Count	IN:0.10	2	2	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	2	2	1	1
	IN:0.30	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	2	2	1	1
	IN:0.60	2	2	2	2	1	1	2	2	1	1	2	2	2	2	2	2	2	2	1	1	2	2	2	2	2	2	1	1	2	2
	IN:GW	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Krtiny control	Depth	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag	*r*	lag
Mean	IN:0.10	–	–	–0	–1	–1	–1	0	0	1	0	0	0	–0	–1	–1	–1	0	0	–	–	0.5	0.5	–0	–2	–1	–2	0	0	–0	–1
	IN:0.30	–0	–2	–0	2	–1	–2	1	1	–0	–1	–	–	–0	–1	1	0	–1	–1	–1	–2	0	0	1	0	–1	–1	–1	–1.5	–0	–1
	IN:0.60	–1	–1	0	–1	–0	–1	–0	–2	–0	–1	0	12	–0	–1	–0	–1	–0	1	–1	–1	–0	–2	–0	–2	–1	–1	–1	–1	–0	–1
	IN:GW	0.9	0	0	1	–	–	0	2	1	1	–	–	0.7	6	1	0	–	–	1	2	0.3	6	0	6	0	7	0	6	1	2
Count	IN:0.10	–	–	2	2	1	1	2	2	2	2	2	2	2	2	1	1	1	1	–	–	2	2	1	1	2	2	1	1	2	2
	IN:0.30	1	1	2	2	2	2	2	2	2	2	–	–	2	2	2	2	1	1	2	2	2	2	1	1	2	2	2	2	2	2
	IN:0.60	2	2	2	2	2	2	1	1	2	2	1	1	2	2	2	2	2	2	2	2	1	1	1	1	2	2	2	2	2	2
	IN:GW	2	2	2	2	–	–	1	1	1	1	–	–	1	1	1	1	–	–	1	1	1	1	1	1	1	1	1	1	1	1

[2]only locations and depths where water distribution was observed in one out of two precipitation events are shown

shown. Complete data of the statistical analysis is available in the supplement (as Supplementary Tables 1 to 4).

The distribution of irrigated water from the WHPs in the lateral transects along the contour occurred only in a very distinct area closest to the pit (L1 and R1), with some exceptions indicating probably some form of preferential pathways (R4 and R3 in random depths). Spatially most significant water distribution occurred in the downslope transect reaching from D1 down to D3, which corresponds to roughly 9 meters from the WHP itself. The WHPs located under culverts performed better compared to the control ones. The most reliable water distribution was observed in the deepest groundwater horizon (ca. 2 m deep). The response to irrigation was usually very fast in under two hours as indicated by the lags.

3.2.2 Natural Precipitation Events

As a comparison, two biggest streamflow events that occurred on the culverts throughout the study period after natural precipitation were also evaluated in more detail (Table 3). The response times are also very fast, similar to the artificial irrigation events. However, the effect of the WHPs is less pronounced and water is distributed evenly in all transects as a result of non-concentrated surface infiltration. In the »wet« variant in Kostelec, water reached the topmost soil layer and deepest groundwater pipe shafts bypassing the transition zone (30–60cm) in many cases. This was not observed at the »dry« Krtiny locality.

3.3 Transpiration Dynamics of Nearby Trees

The sap flow measurements indicated no evidence of relative increase in transpiration over the study period (Table 4). Some of the trees exhibited stable relative transpiration rates (Culvert II and Control II in Krtiny, most of the trees in Kostelec). Most trees in Krtiny and some in Kostelec, however, exhibited significant decrease in the interannual comparison probably indicating some damage during the construction of the pits (most notably Culvert I and NO II in Krtiny and Culvert II in Kostelec). Most positive changes were observed on trees in the control plots with no relation to the pits or irrigation experiments.

4. Discussion

In this study, operational experiments were performed in real conditions on two currently operated forest roads. Applicable Czech technical standards were followed to simulate regular management and approaches to the dimensioning and construction of the WHPs and to analyze the source areas and expected runoff through two culverts under two forest roads (Kumari et al. 2019, Sabzevari 2022). The whole surrounding area was then equipped with soil moisture, water level and sapflow sensors to scientifically evaluate the effectivity of water harvesting pits on retention and redistribution of water and its supposed beneficial effects on the surrounding forest stands.

4.1 Functioning of Culverts

An interesting result of the field measurements was the significant discrepancy in the results obtained

Table 4 Comparison of changes in transpiration of individual trees

Krtiny	Season	Culvert I	Culvert II	NO I	NO II	Control I	Control II
Daily mean, mm	2022	1.27	1.29	1.05	1.18	1.07	0.68
Daily mean, mm	2023	1.39	1.76	1.52	1.04	0.86	1.53
Daily mean, mm	2024	1.31	2.34	1.05	0.35	–	1.47
Relative change	2022	99%	100%	81%	92%	83%	53%
Relative change	2023	79%	100%	87%	59%	49%	87%
Relative change	2024	56%	100%	45%	15%	–	63%
Kostelec	Season	Culvert I	Culvert II	NO I	NO II	Control I	Control II
Daily mean, mm	2022	1.93	1.35	1.22	1.01	1.45	1.38
Daily mean, mm	2023	2.07	1.25	1.38	0.95	1.72	1.54
Daily mean, mm	2024	2.50	1.23	1.92	1.31	1.98	2.17
Relative change	2022	100%	70%	63%	52%	75%	71%
Relative change	2023	100%	60%	67%	46%	83%	74%
Relative change	2024	100%	49%	77%	52%	79%	87%

by the rational method and streamflow measurements at the culvert mouths. According to the results of the rational method, the capacity of the WHPs pits located under the culverts should be filled by precipitation reaching 0.5 mm in Kostelec (catchment area over 12 ha) and under 2 mm in Krtiny (catchment area 4 ha), which we never observed as a result of natural precipitation. Notably, the runoff coefficient for both of the catchment areas obtained by the rational method was 9% as compared to the measured runoff coefficient that was more than 13 times lower for Kostelec 0.67% and more than 800 times lower for Krtiny 0.011%. This finding highlights the fact that runoff coefficients in engineering practice (at least in the conditions of CR) are primarily set for urban environments and thus do not reflect the complexity of the forest ecosystem and perhaps other natural ecosystems, which may reduce their relevance (e.g. Tolland et al. 2007). It appears that over the ca. two year-long study period, surface runoff was virtually non-existent. We believe that the main reason for the observed discrepancy comes from the fact that, according to the Czech technological standard, runoff coefficients were configured to represent hydro-climatological conditions preceding global climate change. Currently, forest stands in the upland regions in central Europe experience long-term water deficit (Kupec et al. 2021) that might cause the forest soils to have larger water retention capacity. At the same time, the highest rainfalls came during the full growing season when trees exhibit the highest transpiration rate as well as the highest interception rate capable of retaining up to 5 mm of rainfall in the beech stands (Novosadová et al. 2023), thus greatly limiting the effective precipitation. At the same time, it is also possible that some of the water captured by the roadside ditch bypasses the culvert through the road embankment body. This phenomena was not included in this study and more research is needed in this case. Our findings highlight the need for the forestry engineering practice to adapt and perform more complex runoff calibrations for the optimal sizing of culverts and other water management structures.

4.2 Redistribution of Water Retained from WHPs

CC analysis was used as a means to identify if water from the WHPs reached individual soil depths at specific locations along the three transects. We evaluated the CC analysis similarly to Juřička et al. (2022), where positive lag and positive statistically significant correlation was considered evidence that water indeed reached the soil around the evaluated sensor. In addition, we also included periods where both negative lag and negative statistically significant correlation was observed. The reasoning was that in some cases, water from the irrigation experiment would reach some spots earlier, before the peak in WHP was reached. By not including these types of events, signals of significant water distribution would potentially be lost. The results of the CC analysis reached four different outcomes interpreted as described below (Fig. 6):

+/+ quick water distribution: the most obvious water distribution best indicating the effect of irrigation. This indicates quick water flow through preferential flow paths (macropores, dikes, burrows, etc.; Valtera et al. 2017).

–/– slow water distribution: water distribution occurs, but at a much slower rate. Most often observed in the soil horizons (10–60) as opposed to GW. It is indicative of water flow through the soil matrix (Spencer et al. 2016).

–/+ and +/– water distribution does not occur. The CC analysis likely captures natural soil processes that are not significantly affected by irrigation. For example, there is a spontaneous intraday fluctuation of soil moisture or long-term decrease due to natural processes more significant than the effect of irrigation/rainfall. These events were not evaluated.

4.3 Beneficial Effects of Redistributed Water for Surrounding Trees

As one of the potential positive effects of the WHPs, we expected a relative increase in the transpiration rate of trees affected by the distribution of additional water from the pits. This effect was expected to be more significant in the »dry« Krtiny variant, where the growth of beech forests stands is limited throughout the year by available water resources (Martinez et al. 2022). Our results indicate that the positively affected wetted zone was rather small (Figs. 5a and b), and no clear evidence of a relative increase in transpiration could be observed over the study period. More so, the impact of the construction of the pits led to the destruction of some of the roots, which resulted in a sever decrease in transpiration for a number of affected trees nearest to the WPHs (Table 4). Fine roots should regenerate relatively quickly over the course of ca. 200 days (one season, Weemstra et al. 2020). It is still possible that the roots will regenerate over time and an increase in transpiration will occur; however, over the two growing seasons after the initial impact, no improvement could be observed in the transpiration data (Table 4). In the short-term, the negative impact of the construction seems to be more prevalent than any possible benefits of additional water for the surrounding trees.

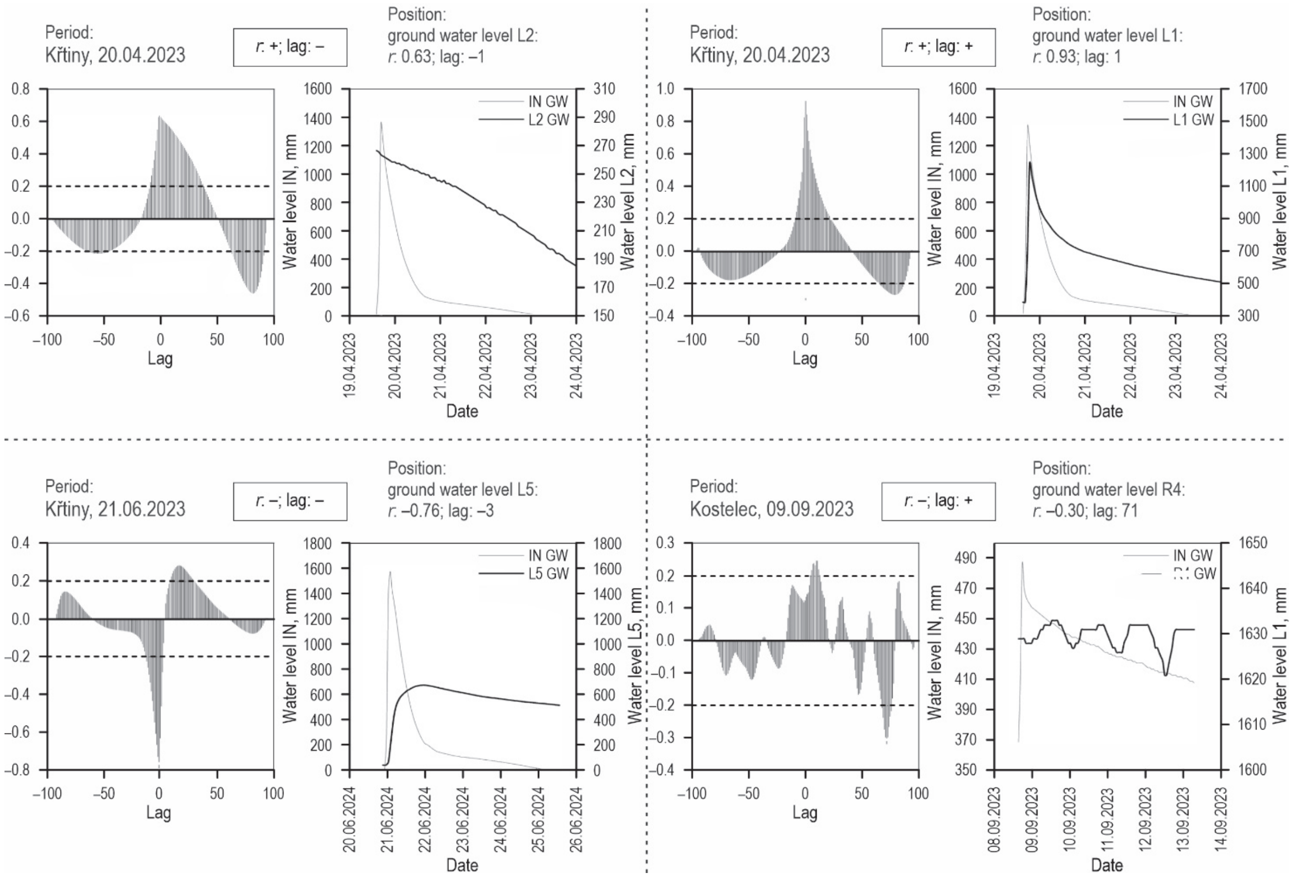

Fig. 6 Example results of the cross-correlation analysis indicating different water distribution

5. Conclusions

Given the ongoing climate warming that can lead to water scarcity, water retention has been on the forefront of forest ecosystem services for more than a decade (Ojea et al. 2012). Forest ecosystems, in particular, are very sensitive not only to increasing annual temperatures because of the prolonged growing seasons (Kupec et al. 2018) but also towards changes in the distribution of precipitation such as less summer precipitation, more intense rainfall and longer precipitation-free periods, which are projected and already reported from Central Europe (Dubrovský et al. 2015). Water harvesting pits on forest roads are one of the possible engineering measures that can help mitigate some of the negative impacts forest roads have on the hydrological regime of the forest ecosystem. According to our results though, their function and benefits to the forest stands are more complicated than initially anticipated. There are a number of factors that affect the delivery of the possible benefits.

First, the current forest engineering practice and widely used supporting methodologies for forest roads (at least in the CR) seem outdated and not sufficiently accurate for the quickly changing forest environment in the temperate zone (Kupec et al. 2021). Our results indicated a significant discrepancy between the design runoff data from the Rational Method and data measured in the culverts. The measured runoff was lower in the order of tens and hundreds in the wet and dry variant, respectively. For adequate design of water harvesting objects, there is a need for more accurate engineering runoff modeling methods specifically suited for the forest environment.

Secondly, in the study conditions (temperate upland forests) according to our irrigation experiments, the distribution of water from the pit to surrounding soils and forest stand was very limited. Basically, the distribution occurred only in the closest vicinity of the water harvesting pit itself (in the order of meters). The distribution was most significant in the downhill transect, where it reached ca. 10 meters downslope from the pit. The rather small size of the active wetted area, as a result of irrigation experiments, indicates poor hydrological connectivity and is one of the important limits against a wider use of similar water harvesting objects.

Lastly, during the two complete growing seasons captured by sap flow measurements during the study period, there was no observable increase in the transpiration of trees growing inside the actively wetted zone defined by the irrigation experiments. More importantly, the roots of trees growing close to the pit were probably damaged during the construction works, which resulted in an opposite trend. The roots are expected to regenerate during the first growing season after the construction and increase transpiration rate in the second growing season as a result of better vitality and more available water. Our data do not confirm that, it is possible that more time is needed for full regeneration.

Even though water harvesting pits and similar water retention objects on the forest road network seem very beneficial on paper, data from our research does not fully support it. The benefits obtained seem much smaller than originally expected to a point that the viability of such measures is probably very low both from the forest stand and water management standpoint. More research is definitely needed in a wider variety of conditions and with a longer time frame. However, at this point, it seems that water harvesting pits should not be designed as »hard« civil engineering construction operations on the forest roads but rather in a simplistic more nature-friendly way as a basic part of forest management.

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Conflicts of Interest

The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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Authors' addresses:

Jan Deutscher, PhD *
e-mail: jan.deutscher@mendelu.cz
Assist. prof. Petr Kupec, PhD
e-mail: petr.kupec@mendelu.cz
Onřej Hemr, PhD
e-mail: ondrej.hemr@mendelu.cz
Mendel University in Brno
Faculty of Forestry and Wood Technology
Department of Landscape Management
Zemědělská 1
613 00, Brno
CZECH REPUBLIC

Assist. prof. Karel Zlatuška, CSc
e-mail: zlatuska@fld.czu.cz
Martin Duchan, MSc
e-mail: duchan@fld.czu.cz
Czech University of Life Sciences Prague
Faculty of Forestry and Wood Sciences
Department of Forestry Technologies and Construction
Kamýcká 129
165 00, Praha – Suchdol
CZECH REPUBLIC

Tomáš Vichta, MSc
e-mail: tomas.vichta@mendelu.cz
Mendel University in Brno
Faculty of Forestry and Wood Technology
Department of Geology and Pedology
Zemědělská 1
613 00, Brno
CZECH REPUBLIC

Assist. prof. Ivana Tomášková, PhD
e-mail: tomaskova@fld.czu.cz
Czech University of Life Sciences Prague
Faculty of Forestry and Wood Sciences
Department of Genetics and Physiology of Forest Trees
Kamýcká 129
165 00, Praha – Suchdol
CZECH REPUBLIC

* Corresponding author

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