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Hydraulic sizing of forest road pipe culverts

Karel Zlatuška[1], *Petr Kupec*[2], *Martin Duchan*[1]*, *Alena Tichá*[1], *Jan Deutscher*[2]

[1]*Department of Forestry Technologies and Construction, Faculty of Forestry and Wood Sciences, Czech University of Life Sciences Prague, Prague, Czech Republic*

[2]*Department of Landscape Management, Faculty of Forestry and Wood Technology, Mendel University in Brno, Brno, Czech Republic*

**Corresponding author: duchan@fld.czu.cz*

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Abstract: This article presents guidelines for assessing the optimal dimensions of forest road pipe culverts, based on input of actual and experimental data to standard engineering techniques. In doing so, we assess the need for (*i*) changes in the parametrisation of inputs (i.e. culvert micro-catchment dimensions, rainfall and resultant culvert flow, and culvert flow rates during culvert hydraulic dimensioning), and (*ii*) the need to redesign culvert outlets in relation to flow speed. Our results demonstrate that values for most inputs presently used under current technical practice for forest road pipe culvert sizing are significantly higher than those achieved under experimental conditions. The data on outlet flow velocities strongly suggests that strengthening of culvert outlet aprons will be crucial for their future operation.

Keywords: culvert dimension precipitation parameters; culvert flow velocity; forest culvert catchment area; outflow strengthening

From a hydrological perspective, all roadways in the landscape represent obstacles to surface runoff from catchment areas (Montgomery 1994), concentrating surface, shallow subsurface, and some groundwater runoff into road ditches (Jacobson, Primm 1997; Ziegler, Gambelluca 1997; Lohnes et al. 2001; Soulis et al. 2015). To maintain earthwork stability and limit erosion, it is essential that this concentrated runoff is diverted across roads at suitable locations (Motayed et al. 1982; Lagasse et al. 1995; Kastridis 2020), with bridges and culverts designed according to the design category of the roadway and its significance (U.S. Department of Transportation, Federal Highway Administration 2003; Czech technical standard ČSN 73 6101: 2024). While on a much smaller scale, the same situation applies to Czech forest roads (Czech technical standard ČSN 73 6108: 2018; Zlatuška et al. 2020). Forest roads, according to Czech Decree No. 146/2024 Coll., are purpose-built roadways for the operation of road vehicle combinations with special trailers and semi-trailers essential for forest management, recreational use of forests, access to rescue services, and national defence. In individual cases, fords may also be considered for forest roads (Lydecker 1973; Motayed et al. 1982; Taylor et al. 1999).

The most commonly used by-pass systems are pipe culverts with a circular cross-section (Sereda 1982; Keller, Sherar 2003; Tomek et al. 2012).

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In the Czech Republic, forest road pipe culverts are defined as structural objects with a vertical clear opening diameter ranging from 0.51 m to 2.00 m, used to convey surface water flow across the body of the forest road (Czech Decree No. 146/2024 Coll.). These connect with other forest road drainage structures, and eventually to adjacent watercourse channels, terrain depressions, ponds or other retention or infiltration spaces (U.S. Department of Transportation, Federal Highway Administration 1983; Zuna 2008). Most are located outside permanent watercourses and serve only for occasional flow caused by catchment precipitation and, to a lesser degree, precipitation concentrated on the forest road itself, and to convey the runoff concentrated by road ditches (Keller, Sherar 2003; Hanák et al. 2008; Vokurka, Zlatuška 2020).

Czech forest road pipe culverts are designed according to Czech technical standard ČSN 73 6108: 2018, which specifies pipes with an internal diameter of 510 mm or 600 mm, with larger diameters also employed in rare cases. Culvert length is usually based on the width of the forest road, typically 5 m, though the length can increase up to 10 m, depending on longitudinal slope, installation depth and angle of intersection with the forest road axis. In exceptional cases, longer culverts (up to 10 m) may be installed where local conditions are especially complex. In general, the pipe longitudinal slope ranges from 0.5% to 5% as higher longitudinal slopes result in challenging construction issues and higher maintenance requirements. The most common materials presently used for such pipes are concrete or reinforced concrete, followed by smooth (spirally welded) steel and corrugated plastic. More recently, however, prefabricated pipes made of corrugated sheet metal have also been used. The pipes are usually installed in a concrete or gravel bed or on specialised transverse concrete beams. Newer culverts, and those for year-round operation on forest roads, are generally fitted with end caps on both ends or with an outlet end cap and inlet sump (Figure 1).

Most forest culverts are designed to convey a twenty-year flow (Q_{20}) consistent with longitudinal ditches (Czech technical standard ČSN 75 1400: 2014). In both Czech and international literature, similar principles are used to classify culverts according to local hydraulic regimes; however, specific categories are defined differently

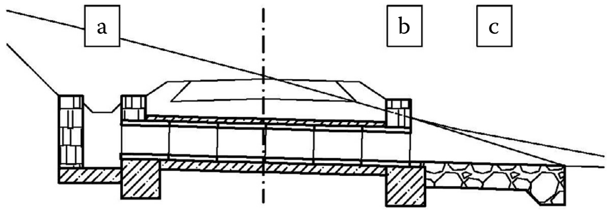

Figure 1. Diagram of a typical forest road pipe culvert with an inlet sump (a), outlet end cap (b) and apron (c), adapted and modified from Zlatuška et al. (2020)

(Normann et al. 1985; Schall et al. 2001; Tomek et al. 2012). The basic classification comprises two categories:

(*i*) Culverts with inlet control. For these culverts, the amount of water and flow rate is influenced by the capacity and hydraulic efficiency of the inlet, which will be less than the capacity of the culvert due to its structural design and hydraulic characteristics. This category is predominantly found on forest roads.

(*ii*) Culverts with outlet control. For these culverts, the amount of water flowing through the culvert is influenced by the flow capacity and hydraulic efficiency of the culvert itself or its outlet section. This category is less common on forest roads due to the high risk of clogging by sediment deposition, which frequently occurs in forest road drainages (Gillespie et al. 2014; Truhlar et al. 2020; Zlatuška et al. 2020).

Also of importance is the damping of flow energy at the outlet of the pipe culvert. For pipe culverts discharging into a watercourse channel, the flow energy must be dampened to levels corresponding with the technical parameters of the channel below the culvert (Schall et al. 2001; Zuna 2008; Tomek et al. 2012; Mattas 2014), usually achieved through the use of aprons (energy damping through effective roughness) or stilling basins (energy damping using a hydraulic jump), in the same way as with drop structures (U.S. Department of Transportation, Federal Highway Administration 1983; Schall et al. 2001; Zuna 2008; Vokurka, Zlatuška 2020). According to the Czech technical standard ČSN 73 6108: 2018, the recommended apron length for a pipe diameter of 600 mm is 3.0 m, 6.0 m for a pipe diameter of 800 mm, and 10 m for a pipe diameter of 1 000 mm. On forest roads, however, pipe culverts without water energy damping at the outlet tend to be more common, resulting in erosion at the culvert outlet from concentrated

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surface runoff (Mukherjee et al. 2015; Vokurka, Zlatuška 2020).

The volume of water entering a pipe culvert depends on many factors. In the case of forest road pipe culverts outside permanent watercourses (i.e. in forested catchment areas), the most important factor will be catchment area size as other factors will not vary significantly over the relatively small contributing area (usually up to 100 ha) adjacent to the culvert. To calculate the inflow from a small catchment area without a developed water network, Kavka et al. (2023) and Horský and Dvořák (2014) suggest using a simple method based on the design rainfall (Method A according to the Czech technical standard ČSN 75 6101: 2012), see Equation (1):

$$Q_{dim} = A_{red} \times q_s \quad (1)$$

where:

Q_{dim} – rainfall runoff flow for culvert design ($L \cdot s^{-1}$);

q_s – intensity of the design rainfall for the periodicity considered (in $L \cdot s^{-1} \cdot ha^{-1}$); for forest roads, the most commonly used values are 15-min rainfall with a periodicity of $P = 0.05$ ($N = 20$ years) (Crhová et al. 2024), though values according to Kavka et al. (2023) or Šamaj et al. (1985) are also used;

A_{red} – reduced catchment area (ha), followed by Equation (2):

$$A_{red} = \sum_{i=1}^{n} A_i \times \psi_i \quad (2)$$

where:

A_i – area of sub-basine with specific runoff coefficient ψ;

n – number of sub-basines in the catchment area;

ψ – runoff coefficient ($\psi = 0.05$ for forests with a slope of 1–5%, $\psi = 0.10$ for fields with a slope of 1–5% and forests > 5%; $\psi = 0.15$ for fields with a slope > 5%).

The application of this method for forest roads is further elaborated by Zlatuška et al. (2020). For forested catchment areas with an established drainage network, the use of certified data from the Czech Hydrometeorological Institute (CHMI) is assumed, based on the Czech technical standard ČSN 75 1400: 2014.

The procedures for designing culverts without inlet modifications, with a free water surface, with a free inlet or with a free outlet, i.e. without the influence of a lowered water table, have been widely published and outlined in numerous textbooks (Kunštátský 1956; Krešl 1973; Balkham et al. 2010; Schall et al. 2012; Tomek et al. 2012), and will not be discussed in detail here. More recently, however, culvert design has also been made possible using specialised software, such as HEC-RAS (Version 6.4, 2024) and HydroCAD (Version 10.2, 2024), or through specialised online calculators such as Autodesk CIVIL 3D (Version 2024, 2024), Online Culvert (Version 150914, 2024) or Diameter Velocity & Flow Rate (2024).

Generally speaking, in the case of a culvert with a concrete/reinforced concrete pipe of standard quality, it is recommended to use the simplified calculation according to Zlatuška et al. (2020), see Equation (3):

$$Q_d = 24 \times DN^{\frac{8}{3}} \times \sqrt{I_0} \quad (3)$$

where:

Q_d – capacity flow rate under free-flow conditions ($m^3 \cdot s^{-1}$);

DN – pipe diameter (m);

I_0 – bed slope.

In contrast to the detailed procedures for designing culvert pipes, published procedures for the section beneath the culvert, prior to connecting to the 'downstream' channel [Figure 1, (c)], are rare. For road and highway culverts, this issue is addressed with a stilling basin (see above; Tomek et al. 2012); however, this method is not typical for forest road culverts outside of permanent watercourses. Furthermore, the professional literature fails to provide specialised procedures for assessing the dimensions (i.e. length) of the apron and design size of the stone, important for minimising erosion in the lower channel while simultaneously optimising structure size.

Following on from the results of Departmental Research Project NAZV QK 22020146 – 'Technical Recommendations for Water Management in Forest Transportation Networks', and in the face of recent changes in the techno-economic requirements for such water management structures, this study seeks to address three fundamental hypotheses regarding the optimal dimensions for forest road pipe culverts, i.e.:

(*i*) Inflow from partial catchment areas into pipe culverts could be significantly lower in practice

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than indicated by current culvert dimensioning methodologies.

(*ii*) When constructing pipe culverts, it should be feasible to use pipes with considerably smaller diameters than those specified by current technical standards.

(*iii*) Currently specified apron lengths beneath pipe culverts, based on the longitudinal gradient of the culvert pipe and the gradient of the apron and the downstream channel, may be inadequate.

The outcomes of these hypotheses could initiate a potential change in the extent of intervention into forest lands due to the construction of forest roads and their drainage, as well as the optimisation of the scope of structural elements. This could subsequently lead to reduced costs for the construction and maintenance of forest roads, as well as a decrease in the consumption of construction materials from non-renewable sources (cement, steel, aggregate).

MATERIAL AND METHODS

Location. Experimental verification was carried out on two forest road culverts (and their micro-catchments) within the Kostelec nad Černými lesy Forest Enterprise of the Czech University of Life Sciences Prague (Lesy ČZU Kostelec) and Masaryk Forest Křtiny School Enterprise (ŠLP Křtiny) of Mendel University Brno, herein termed Jevany and Habrůvka sites, respectively, based on the name of the closest urban habitation (Figure 2). Both locations form part of the National Agricultural Research Agency Project QK 22020146 'Technical Recommendations for Water Management within the Forest Transportation Networks' project field experiment. Basic technical and hydrological data for both culverts are provided in Table 1.

The Jevany site is situated within the Svojetice forest section and has an above-culvert micro-catchment area of 12.32 ha with a terrain slope > 5%. The site is 100% forested and is characterised by notable soil heterogeneity, with the exclusive presence of semi-hydromorphic and hydromorphic soil types (pseudogley, stagnogley, gley and their subtypes). The geological substrate consists of Říčany type granites from the Moldanubian zone, overlain by varying depths (potentially several metres) of slope debris and polygenetic clays, with a notably bouldery soil surface.

The Habrůvka site is situated within the Habrůvka forest district and has an above-culvert micro-catchment area of 9.65 ha with a terrain slope > 5%. The site is also 100% forested and is characterised by homogeneous soil conditions with a single soil type, cambisol, predominating, primarily in its modal subtype. The site has a complex geological structure primarily composed of siliceous sediments (cherts) of the Rudice layers, mixed with loess clays, in contact with the limestone bedrock of the Moravian Karst.

Data collection and processing. Both culvert pipes are lined and fitted with flumes equipped with sharp-edged Thomson overflows allowing outlet flow to be measured continuously. At the overflow, the water level is monitored and converted into flow rate using a US1200 ultrasonic sensor fitted with an H7-G-TA4-SZ data logger (Fiedler AMS, Czech Republic), with the recording interval set at 10 minutes (see Kupec et al. 2023). Climatic data was obtained from the national network of meteorological stations operated by Amet (Velké Bílovice), with data for the Jevany site obtained from the Tuchorazy station, and data from the Útok 6 station for the Habrůvka site.

As part of the QK22020145 research project, data from both culverts were evaluated for approximately two years, i.e. from October 1, 2022, to August 31, 2024. Episodes in which measurable flow was recorded at both culverts, along with the corresponding six-hour rainfall initiating the flow, are listed in Table 2.

The flow data were then compared with the concurrent hydrological data (Kavka et al. 2023; Crhová et al. 2024) with a periodicity of P = 0.5. Values for precipitation total and precipitation intensity were further refined using the appropriate (common) localisation coefficient (k_l), calculated according to Equation (4):

$$k_l = \frac{H_1}{H_2} \tag{4}$$

where:

H_1 – precipitation total for six-hour rain of given periodicity, Kavka et al. (2023);

H_2 – precipitation total for six-hour rain of given periodicity, Crhová et al. (2024).

The localised value for precipitation total H_1 was then calculated as the product of the value for precipitation total H_2 according to Crhová et al. (2024)

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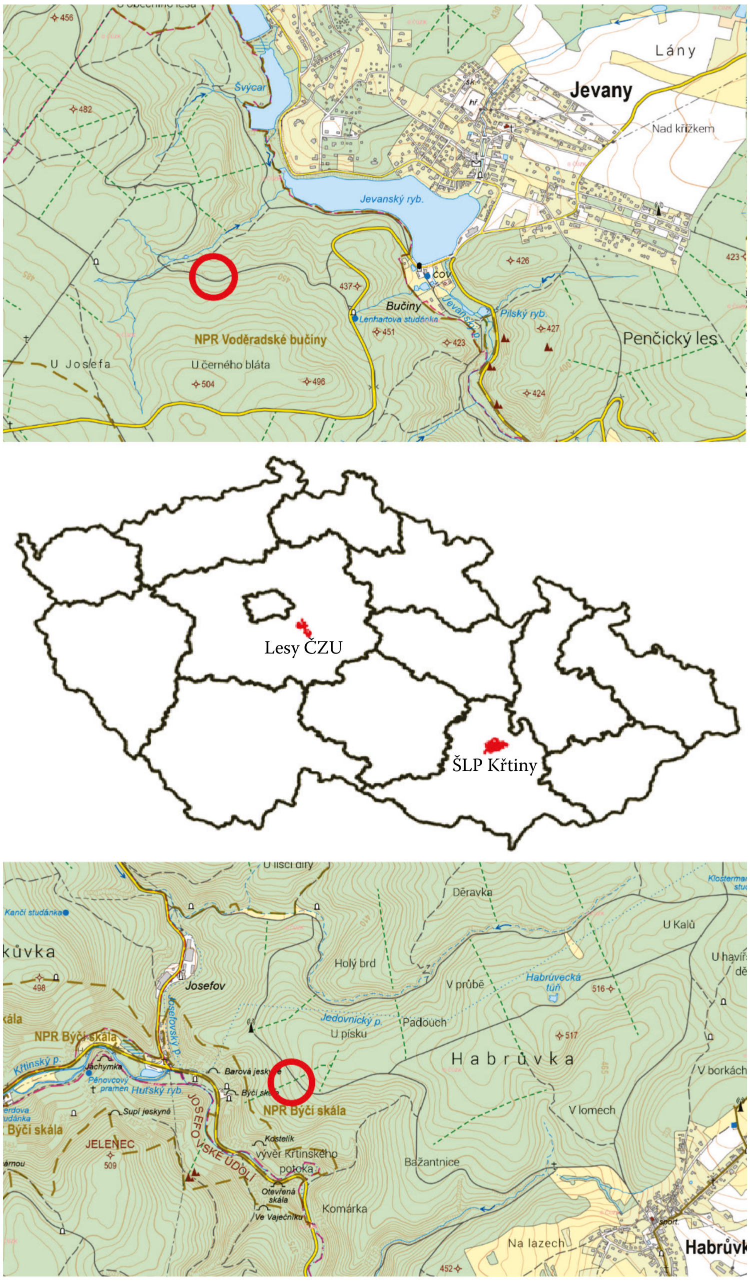

Figure 2. Sites of the two experimental culverts – top: Jevany site [Kostelec nad Černými lesy Forest Enterprise of the Czech University of Life Sciences Prague (Lesy ČZU Kostelec)], bottom: Habrůvka site [Masaryk Forest Křtiny School Enterprise of Mendel University Brno (ŠLP Křtiny)]; background layer: State Administration of Surveying and Cadastral Registry, Basic Map of the Czech Republic 1 : 10 000

and the localisation coefficient k_l. The localised value for precipitation intensity q_{sl} was then calculated as the product of the value for precipitation intensity q_s according to Crhová et al. (2024) and the localisation coefficient k_l The values of Crhová et al. (2024) and Kavka et al. (2023), along with the appropriate localisation coefficients and localised values, are presented in Table 3.

Pipe outflow data were used to determine the maximum length of the apron under the culvert, obtained based on the method of Tomek et al. (2012) for individual lengths and using the following data:

– Water flow ($m^3 \cdot s^{-1}$) through the pipe at free surface, free inlet and free outlet (Q);
– Water height (m) in the pipe at the outlet (h);

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Table 1. Basic technical and hydrological data for the Jevany and Habrůvka experimental culverts

Location	Jevany	Habrůvka
Coordinates	49°57'50"N, 14°47'38"E	49°18'28"N, 16°41'56"E
Region	Central Bohemia	South Moravia
Diameter (*DN*, mm)	600	
Pipe length (m)	5.0	7.5
Pipe gradient (%)	5.2	3.2
Inlet elevation (m a.s.l.)	439.85	435.72
Pipe material	concrete	reinforced concrete
Inlet design	inlet headwall without adjustment	
Outlet design	outlet headwall without adjustment	
Impact of below-culvert water level on outlet	none	
Lower channel and apron gradient (%)	13.4	6.4
Apron/channel length with increased roughness (m)	13.16	2.19

Table 2. Episodes during which measurable flow occurred at the Jevany and Habrůvka culverts

No.	Date	Site	Max. hourly flow ($L \cdot s^{-1}$)	Six-hour precipitation (mm)
1	03.11.2023	Jevany	19.86	1.73
2	21.06.2024	Habrůvka	6.07	9.10
3	02.06.2024	Habrůvka	0.87	6.48
4	28.08.2023	Jevany	0.43	5.27
5	04.08.2024	Jevany	0.39	0.60
6	05.08.2023	Habrůvka	0.39	7.37
7	03.06.2024	Habrůvka	0.23	2.33
8	06.08.2023	Habrůvka	0.18	5.75
9	15.11.2023	Jevany	0.15	0.77
10	04.06.2023	Jevany	0.12	1.07
11	28.08.2023	Habrůvka	0.09	4.79
12	18.08.2024	Habrůvka	0.07	2.68
13	04.11.2022	Jevany	0.04	3.13

– Water flow velocity ($m \cdot s^{-1}$) at the pipe outlet (v);
– Energy height of the profile (m) at the culvert outlet (E).

The method of Zuna (2008) and Vokurka and Zlatuška (2020) was used to calculate the length of the direct (non-expanding) apron (L) according to Equation (5):

$$L = L_P + L_N \tag{5}$$

where:
L – length of direct fall (m);
L_N – effective length under the weir (m);
L_P – distance from the overflowing water jet point of impact to the weir wall (m), calculated according to Equation (6):

$$L_P = 2\sqrt{E_P \times \left[0.83 \times \left(s + L_P \times i_d\right) + 0.21 \times E_P\right]} \tag{6}$$

where:
E_P – height of the energy line of the overflow (m);
s – height of the structure (m) (for pipe culverts with an adjoining apron, the height of the structure is assumed to be ca. 0.2 m to prevent the influence of protruding stones in theapron on the outflow of water from the pipe);
i_d – longitudinal slope of the bed under the weir (m).

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Table 3. Hydrological data localised for the Jevany and Habrůvka experimental culverts

Location	Jevany	Habrůvka
Rainfall station [Crhová et al. (2024)]	Ondřejov 491 m a.s.l. 49°54'24"N, 14°47'06"E	Protivanov 675 m a.s.l. 49°28'40"N 16°49'52"E
Intensity of 15-minute rainfall ($L{\cdot}s^{-1}{\cdot}ha^{-1}$), periodicity $P = 0.05$ [Crhová et al. (2024)]	281.11	314.44
Ditto for periodicity $P = 0.5$ ($L{\cdot}s^{-1}{\cdot}ha^{-1}$)	148.89	165.56
Precipitation total of 15-minute rainfall (mm), periodicity $P = 0.05$ [Crhová et al. (2024)]	25.3	28.3
Ditto for periodicity $P = 0.5$ (mm)	13.4	14.9
Precipitation total of six-hour rainfall (mm), periodicity $P = 0.05$ [Crhová et al. (2024)]	55.7	61.8
Ditto for periodicity $P = 0.5$ (mm)	30.1	32.6
Sub-catchments used [according to Kavka et al. (2023)]	1-09-03-106	4-15-02-100
Precipitation total of six-hour rainfall (mm), periodicity $P = 0.05$ [Kavka et al. (2023)]	51.4	60.5
Ditto for periodicity $P = 0.5$ (mm)	29.1	30.0
Localisation coefficient k_l = ratio of six-hour precipitation total (mm), periodicity $P = 0.05$ [according to Kavka et al. (2023)], and the precipitation total or intensity of the same duration and periodicity of rainfall [according to Crhová et al. (2024); Equation (4)]	0.9228	0.9790
Ditto for periodicity $P = 0.5$ [Equation (4)]	0.9668	0.9202
Localised value for 15-minute rainfall intensity ($L{\cdot}s^{-1}{\cdot}ha^{-1}$), periodicity $P = 0.05$	259.41	307.84
Ditto for periodicity $P = 0.5$ ($L{\cdot}s^{-1}{\cdot}ha^{-1}$)	143.95	152.65
Localised value for total 15-minute rainfall, periodicity $P = 0.05$ (mm)	23.35	27.71
Ditto for periodicity $P = 0.5$ (mm)	12.96	13.74

The effective length of L_N under the weir is the section following the point of impact of the water jet, defined as the length over which the water depth at the point of impact y_s changes to the depth in the lower channel y_d, i.e. in the channel downstream of the apron. In the case of a steep longitudinal apron slope, this is considered subcritical flow.

A steady non-uniform flow is calculated over small sections using Bernoulli's equation. Where apron slopes are small, subcritical flow over the apron changes to super-critical flow, leading to the formation of a hydraulic jump over this section. In this case, the calculation must identify the location, length and height of the hydraulic jump, the second associated height of jump h_2 being considered equal to the depth of water in the lower channel y_d.

RESULTS AND DISCUSSION

Water flow rates through the Jevany and Habrůvka culverts were far below the anticipated rainfall totals and intensities (Tables 2 and 3). According to Tomek et al. (2012), the assumed maximum flow through culvert pipes without inlet modification, under free surface flow and free outflow conditions, should have been 0.407 $m^3{\cdot}s^{-1}$ in both cases. However, at the Jevany site, this maximum flow rate was only achieved once, with levels reaching approx. 5%, while at the Habrůvka site, highest utilisation reached 1.5%, though again, this only occurred once over the monitoring period. At both sites, all other flow utilisation rates were < 1%.

Using Equation (1), inflow from the sub-catchment to the culvert for localised rainfall intensity

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($m^3 \cdot s^{-1}$) with a return period of P = 0.5 should have been 0.177 $m^3 \cdot s^{-1}$ at the Jevany site and 0.147 $m^3 \cdot s^{-1}$ at the Habrůvka site over the monitoring period. However, these expected inflow values were only achieved in approx. 11% and 4% of cases, respectively.

At both pipe culverts, six-hour rainfall totals were determined across the monitoring period and these values were compared with rainfall totals with a recurrence interval of P = 0.5 (Kavka et al. 2023) over the monitoring period. Even in this case, the maximum recorded values did not achieve expected levels, with the highest recorded instance at the Jevany site barely reaching 20% of total expected rainfall, while at the Habrůvka site, the figure was approx. 30%. Furthermore, at both locations, periods of maximum culvert flow failed to temporally coincide with periods of maximum six-hour rainfall total (Table 4).

As such, rainfall patterns expressed as maximum six-hour totals were significantly lower than expected over the ca. two-year observation period, reaching only 20% to 30% of values predicted by Kavka et al. (2023) and Crhová et al. (2024). This indicates that inflow into the culverts from the sub-catchments was, in reality, significantly lower than indicated by existing methodologies, thereby confirming our first question/hypothesis.

As in the studies of Keller and Sherar (2003), Hanák et al. (2008), and Vokurka and Zlatuška (2020), data from the two culverts only represented occasional flows caused by rainfall in the adjacent catchment area (and partially from the forest road crown), with runoff being concentrated into roadside ditches, possibly explaining the lower than expected values. The shortfall could also be explained by the maximum flows through the culverts being lower than values determined by localised rainfall intensities with a periodicity of P = 0.5. For example, maximum flows calculated using the so-called rational method (Horský, Dvořák 2014; Kavka 2023), represented by Equation (1) in our study, were approx. 20–50 times lower than the actual values achieved, indicating that the rainfall pattern over the observation period differed from expectations and did not generate rainfall totals capable of producing the predicted flows through the culverts.

From this perspective, the reduction in six-hour rainfall totals over the observation period to 20–30% of expected levels, along with the reduction in maximum flow to 2–5% of calculated levels, is striking. This suggests that the calculation method used, as described by the Czech technical standard ČSN 75 6101: 2012, [Equation (1) or the runoff coefficient ψ], is unsuitable for calculating runoff from forested catchments of ca. 10 ha. Technically, these results imply that it should be possible to reduce the number of culverts per unit length of forest road, i.e. compared to the number suggested by Beneš (1986).

The results clearly suggest that maximum measured flows could be handled by pipes with relatively small diameters, i.e. approximately 150 mm to 200 mm. However, using such small diameters for culverts would be inappropriate due to the amount of sediment and debris commonly transported to the culvert inlet. Additionally, designing pipes with an internal diameter of < 510 mm would contradict both legislative requirements (Czech Decree No. 146/2024 Coll.) and technical standards (ČSN 73 6108: 2018). From a hydrotechnical

Table 4. Comparison of measured and calculated parameters for the Jevany and Habrůvka culverts

Location	Jevany	Habrůvka
Maximum pipe flow ($m^3 \cdot s^{-1}$), without inlet modifications, free surface and free outlet (Tomek et al. 2012)	0.407	0.407
Percentage utilisation of pipe capacity (without inlet modifications, free surface and free outlet) at maximum recorded flow over the monitoring period (%)	4.88	1.50
Sub-catchment water inflow ($m^3 \cdot s^{-1}$) for localised rain intensity, recurrence interval P = 0.05	0.320	0.297
Ditto for recurrence interval P = 0.5 ($m^3 \cdot s^{-1}$)	0.177	0.147
Percentage of sub-catchment inflow value for localised rain intensity with recurrence interval P = 0.5 achieved during maximum recorded flow over the monitoring period (%)	11.22	4.13
Percentage of six-hour rainfall total with P = 0.5, Kavka et al. (2023), achieved during maximum recorded rainfall total over the monitoring period (%)	18.11	30.33

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Table 5. Recommended minimum apron length under a culvert pipe with an internal pipe diameter of 600 mm and length of 7.5 m

Grade under the culvert (%)	MAT	Length of the parallel fallout shelter (m)																												
		3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	17.5
2.0% to 4.5%	0.2	–	×	×	×	×	×	×	×	×	×	×	×	×	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	0.5	–	×	×	×	×	×	×	×	×	×	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Above 5.0%	0.2	–	–	–	–	–	–	×	×	×	×	×	×	×	×	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	0.5	–	–	–	–	×	×	×	×	×	×	×	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	0.5+	–	–	–	–	×	×	×	×	×	×	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–

(–) – unacceptable apron length; (×) – acceptable apron length; MAT – materials; 0.2 – stone bed with stones 80 kg to 200 kg and middle grain 0.45 m; 0.5 – stone bed with stones 200 kg to 500 kg and middle grain 0.60 m; 0.5+ – stone bed with stones above 500 kg and middle grain 0.75 m

perspective, therefore, while question/hypothesis (*ii*) is confirmed, implementation would be impractical and inapplicable in practice.

For both culverts at our monitoring sites, the recommended minimum apron length was determined according to Tomek et al. (2012), with input data for the calculation including a requirement for maximum flow rate with unmodified inlet (0.407 $m^3 \cdot s^{-1}$ in both cases), free flow within the pipe and a free outlet (see also geometric parameters listed in Table 2). At the Jevany site, the recommended minimum apron length was 8.7 m, while at the Habrůvka site it was 7.7 m (Table 5). In both cases, this assumes the use of a stone bed or stone surface composed of stones weighing between 80 kg and 200 kg.

A comparison of the calculated values with the requirements of the Czech technical standard ČSN 73 6108: 2018 indicates that the required apron length of 3.0 m for a pipe with an internal diameter of 600 mm is entirely insufficient. This means that question/hypothesis (*iii*), stating that values currently provided for apron length under pipe culverts are adequate, considering the longitudinal slope of the culvert pipe, the longitudinal slope of the apron and the lower channel, has not been confirmed. In the future, this value should account for the longitudinal slope of the pipe, the longitudinal slope of the apron and the lower channel, as well as the material used for the apron itself (see Table 5).

While the actual apron length under the Jevany pipe culvert would appear to be sufficient, that at Habrůvka is completely inadequate, reaching only 30% of the recommended minimum length for the quarry stone used (ranging from 80 kg to 200 kg). Note, however, that the calculation of apron length for the actual maximum flow values over the monitored period (Table 3) was not performed. Based on further analysis of the input data, it was concluded that the expected flow pattern would not occur, and that water flow was so low that the flow height would not exceed any protrusions on the quarry stone used for the lining.

CONCLUSION

This study addresses issues related to the hydraulic sizing of forest road culverts through a comparison of results of standard engineering

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methods, achieved using both standardised and experimental input data. The study introduced three hypotheses, based on both the results of the National Agricultural Research Agency Project QK 22020146 'Technical Recommendations for Water Management on Forest Transportation Networks' and the long-term operational experience of the authors. These three hypotheses focussed on input parameters for assessing the dimensions of forest road culverts, actual pipe dimensions and the need for protective aprons as an integral part of the culvert structure.

The results of the study indicated that:

(*i*) Input values used in present methods for assessing the dimensions of forest road pipe culverts are rarely achieved under current field conditions. This effectively means that larger sub-catchments could be considered for individual culverts, and the number of pipe culverts per unit length of forest road could theoretically be reduced.

(*ii*) The calculated flow velocities suggest that the diameter of pipes commonly used to construct pipe culverts could be reduced. However, this solution would likely lead to clogging of the culverts and, moreover, it would not comply with current technical standards or relevant legislation.

(*iii*) The data indicate that fortified aprons of adequate length must become an integral part of the forest road pipe culvert structures in future. This follows from both the calculated flow velocities at the culvert outlets (e.g. in the context of reducing their number per unit length of forest road) and from the requirement for control of forest soil erosion, as well as from a broader need to retain water within forests (surface runoff retardation). Importantly, current literature fails to describe any specialised procedure for dimensioning apron length and assessing the size of stone needed to minimise erosion damage while simultaneously optimising construction size.

In conclusion, while we are aware that this study has only 'cracked open' the issue of hydraulic design parameterisation for forest road culverts at a time of dramatically changing climatic and socio-economic conditions, we believe that it is highly desirable to continue addressing this issue and to verify the results obtained over a broader range of natural conditions.

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