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The geomorphic impacts of culverts at paved forest roads: Examples from Carpathian headwater channels, Czech Republic

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ABSTRACT

Road-stream crossings constructed with culverts have the potential to alter geomorphic processes in adjacent stream channels. We examined changes in channel geometry and bed sediments in longitudinal profiles related to culverts at five paved forest road crossings with perennial headwater streams and two gullies initiated by point releases of water through ditches. A dendrogeomorphic approach was used for dating of exposed tree roots and estimation of bank erosion rates in incised cross-sections downstream of road crossings. The studied forest road crossings concentrate surface runoff from the road net, act as stabilizing elements in stream longitudinal profiles and decelerate bedload transport in the case of culvert clogging, which caused notable upstream and downstream changes in fluvial processes. Notable fining of the coarsest fraction in upstream cross-sections was observed only for two culverts with the highest depositional tendencies. Much lower width-depth ratios (< 4) and typically higher channel slopes were measured in channel reaches downstream of the culverts, compared with upstream cross-sections. Two road-induced gullies typically had very low width/depth ratios close to 2. At five of a total of seven studied culverts, the highest documented erosion rates occurred immediately downstream of these structures. The mean annual erosion rates reconstructed from cross-sections at the positions of individual tree root samples ranged from 0.2 to 6.5 cm·year^{-1}, and the erosion occurred over 2–5 year intervals, depending on the studied location. The highest number of observed changes in cross-sectional geometry caused by channel erosion were connected with relatively high-magnitude flow events (with recurrence intervals $>$ 10 years; specific discharge $>$ 1500 l·s·km^{-2}), whereas more frequent flows (with recurrence intervals of 2–10 years) were not always recorded by exposed tree roots.

1. Introduction

Road building in mountainous terrain alters the hydrologic and erosional processes operating in a basin by changing of drainage patterns and runoff generation (Montgomery, 1994). In general, forest roads affect geomorphic processes by following primary mechanisms: (i) accelerated erosion from the unpaved road surface and prism itself by erosion processes, (ii) destabilization of side-cast material and hillslope downside the road, (iii) altered surface flow paths, leading to extension of channels onto previously unchannelized portions of the landscape, and finally (iv) channel structure and geometry is directly affected by road crossings or anti-erosive works when road is constructed parallel with the stream channel (Montgomery, 1994; Gucinski et al., 2000; Wemple et al., 2001; Martín Duque et al., 2011). As a consequence, the establishment of artificial drains and increased catchment area by roads may lead to the extensive gullying (Montgomery, 1994; Wemple et al., 1996; Nyssen et al., 2002). Moreover, the erosion rates from road surfaces and road-related landslides are many times greater than from undisturbed slopes, which turn into increased sediment supply to the adjacent stream channels (Beschta, 1978; Bilby et al., 1989; Wemple et al., 2001).

The geometry and morphology of stream channels is adjusted to the energy acting on the stream bed and banks via the transport capacity, which depends on the discharge and the valley slope, the character of the sediment supply (its frequency, magnitude, and grain size) and the presence of living or dead vegetation, which can stabilize the stream banks or increase the flow resistance (Montgomery and Buffington, 1998). This relationship can be simplified by the classic Lane (1955) balance equation after omitting the vegetation effect:

$$Q \cdot S \approx Q_s \cdot D_{50} \quad (1)$$

where Q is the discharge, S is the channel slope, Q_s is the sediment supply and D_{50} is the median size of the bed material. The discharge can also be expressed as a function of the flow velocity and the channel cross-sectional area (i.e., the product of the flow width and flow depth):

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$$Q = v \cdot w \cdot d \quad (2)$$

and the modified balance equation results:

$$v \cdot w \cdot d \cdot S \approx Q_s \cdot D_{50} \quad (3)$$

where v is the flow velocity, w is the wetted channel width and d is the mean wetted channel depth at a given discharge. A change in a single variable will lead to changes (adjustments) in the remaining variables. A typical example of the disturbance of the river continuum via alterations in discharge or sediment supply is the construction of more or less water- and sediment-permeable barriers in channels, such as dams, weirs, grade-control structures or road culverts (Croke and Mockler, 2001; Petts and Gurnell, 2005; Conesa-García et al., 2007; Eekhout et al., 2015).

Culverts are constructed for the safe transfer of water through a road network. They often do not account for the effects of bedload transport or instream wood, which can produce clogging of culverts during flood events, especially in forested mountainous areas. Therefore, increased sediment deposition can be observed upstream of culverts. On the other hand, the effect of 'hungry water' causes channel incision downstream of these structures because of the sediment supply deficit (Castro, 2003). These downstream processes can be compared with general channel evolution models after a disturbance (i.e., the placing of a culvert that disconnects the sediment supply from upstream), where incision occurs until the critical bank stability height is reached. At the same time, channel degradation flattens the channel slope and consequently reduces the available transport capacity. Later, channel widening occurs due to bank collapses after the critical bank stability height is exceeded (Schumm et al., 1986; Simon, 1989; Simon and Rinaldi, 2006). However, culverts act as stabilizing elements in stream longitudinal profiles; they prevent the upstream migration of knickpoints and related decreases in channel slopes. Therefore, the aggradation of sediments, which occurs during the last phases of channel evolution models, usually cannot occur immediately downstream of these structures, and the enlargement of gullies in the downslope direction has often been documented (Moeyersons, 1991; Moges and Holden, 2008). An additional important aspect of culverts is the concentration of surface runoff by the road network, which increases discharge at the point where water is released from ditches to the channel. As a consequence, the increased discharge contributes to incision downstream of culverts, and gully-like systems can even develop downstream of the points where water is released from a road (Croke and Mockler, 2001; Nyssen et al., 2002; Takken et al., 2008; Katz et al., 2014). Culverts also have serious consequences for aquatic macroinvertebrates and fish species and their migration, and their replacement with more ecologically friendly structures is recommended in river restoration projects (Ward et al., 2008; Bouska et al., 2010; Bouska and Paukert, 2010; Suvendu, 2013; Eekhout et al., 2015; Olson et al., 2017).

The temporal and spatial reconstruction or monitoring of geomorphic processes related to culverts is quite rare. Lachance et al. (2008) monitored and quantified particle-size changes in surface and subsurface bed layers related to newly constructed culverts. They observed the peak changes in sedimentary patterns one year after the culverts were constructed, and this effect decreased 2–3 years after construction. The increased accumulation of fine sediments, which seriously affect fish-spawning habitats, was documented in the downstream reaches, up to several hundred meters from these structures; this fine sediment most likely originated from construction sand or road erosion. On the other hand, Wellman et al. (2000) documented that, although culverts increased the deposition of fine sediment (silt and clay), this was not sufficient to impact local fish communities. Katz et al. (2014) used cesium-137 dating of valley deposits to establish annual rates of erosion for gullies developed downstream of culverts and to reconstruct the cross-sectional geometry prior to the road construction. Dendrogeomorphology can be applied for reconstruction of changes in channel cross-section geometry and bank erosion rates over time scales ranging up to decades via analyses of exposed tree root systems, which provides results with annual resolution (Stoffel et al., 2013). By investigating exposed roots, Šilhán and Galia (2015) documented a high sediment deficit in the sedimentary budget of a headwater stream due to the crossing of a road by a completely clogged culvert, which disconnected the sediment supply from upstream steep reaches. A similar approach has also been used to examine the dynamics of gully sheet erosion in loess (Šilhán et al., 2016b), sand (Bodoque et al., 2011) and unconsolidated Quaternary deposits (Vandekerckhove et al., 2001). Exposed roots are also used for annual dating of bank erosion caused by hydro-geomorphic events, such as debris flows or flash floods, that occur in steep mountain streams, and they thus provide valuable data on natural hazards in ungauged basins (Malik and Owczarek, 2007; Malik and Matyja, 2008;Tichavský and Šilhán, 2015).

The aim of this paper is to describe the geomorphic responses of perennial headwater streams and the development of gullies in flysch lithologies, using as examples seven road culverts constructed during the years between 1976 and 1980. We examined the cross-sectional channel geometries upstream and downstream of the culverts, together with changes in the coarsest fraction of bed sediments. Dating of exposed roots was applied to reconstruct the intensity of channel erosion rates downstream of the studied culverts. In addition, we compared the years with dated erosion events with gauge records from a small experimental basin to determine the critical specific discharges responsible for channel cross-section geometry changes and gullies development.

2. Study sites

We investigated the crossings of five perennial headwater channels with paved forest roads (Lub1, Lub2, Msp, Ver1, and Ver3) (Fig. 1; Table 1). To allow scale comparisons of studied parameters between individual sites, we selected road crossings with similar contributing basin areas upstream ($0.2 < A < 0.5\ \mathrm{km}^2$) and the same bedrock lithology (soft shale-dominated flysch). In addition, the study was extended to two nearby intermittent gullies (Lub3 and Ver2) that developed as the direct consequence of the concentration of surface runoff by the road net and the point release of water through ditches by culverts. The studied channel reaches were located on the northern, windward slope of the Moravskoslezské Beskydy Mountains, the Czech part of the flysch belt of the Western Carpathians (Fig. 1). These culverts were excavated in low-resistance flysch bedrock of the Silesian Nappe that is dominated by shales (the Lhoty and Veřovice Members) and colluvial Quaternary unconsolidated deposits (Menčík and Tyráček, 1985). Some cross-sections downstream of the Msp, Lub1 and Ver1 culverts were incised into soft well-erodible shales. Such lithological conditions play an important role, not only in the accelerated propagation of incision in local channels, but also in the delivery of relatively fine particles into fluvial systems and intensive bedload transport and morphological changes during flood events (Galia et al., 2015; Galia and Škarpich, 2016; Šilhán et al., 2016a). In addition, the Moravskoslezské Beskydy Mountains represent one of the most landslide-affected areas in Central Europe, where small debris-flows have also been documented in the steepest parts of the valleys (Pánek et al., 2013; Šilhán, 2014). High yearly precipitation amounts in the context of Central Europe (up to 1800 mm in the windward parts) also increase the intensity of hillslope and fluvial processes within the study area (Tolasz et al., 2007). Local flood events that are responsible for morphological changes in headwater stream channels are usually related to cyclonic activity or are flash floods from convective storms during the warm part of the year; floods caused by melting snow are rare (Bíba, 2006; Šilhán, 2015).

The paved forest roads, together with the studied culverts, were built in 1976–1980 (Lub1, Lub2, Lub3, Msp) and 1979 (Ver1, Ver2, Ver3) (Fig. 1). However, former road crossings that may have