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The geomorphic activity of forest roads and its dependencies in the Tatra Mountains

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ABSTRACT

Forest roads in mountain areas have a significant impact on the changes of water circulation and cause the development of numerous erosion and accumulation forms. The aim of the study was to investigate the magnitude of geomorphic changes within forest roads, determine the factors influencing it, and assess the rate of erosion/accumulation within these roads. Geomorphological mapping of forest roads (6.2 km) was conducted. Roads were divided into homogeneous morphogenetic sections, and a set of parameters was measured for each of them. In order to determine the main factors responsible for relief changes within the roads, the Principal Component Analysis was used. The *t*-test for two independent samples was also used to check the influence of the bedrock type on the geomorphic changes within roads. Repeated cross-sectional profile measurements were conducted to determine the intensity of erosion and accumulation processes. Our results show that the magnitude of geomorphic changes within forest roads mostly depends on the presence of subsurface flow interception from the cutslope, which in most cases occurs when a road is constructed across a convergent slope area. The strength of the bedrock also has a significant impact on relief transformations, which is expressed in the higher amount of accumulation and erosion features, and higher dissection depths within weaker rocks. The highest annual rate of road deepening is 10 cm yr^{-1}.

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Forest roads; relief transformations; mountains

1. Introduction

Forest roads in mountain areas are intensely used in the course of forest management, especially during the transport of tree trunks (Dudziak 1974; Kasprzak 2005; Wałdykowski and Krzemień 2013; Łukasik et al. 2016). Constructing new roads and skid trails is frequent in windthrow areas, while roads are necessary for the transport of wood during salvage logging operations (Parzóch 2001, 2002; Rojan and Wałdykowski 2007). In such a case, road density may increase even fourfold; however, most of the roads, after some period of time, become overgrown with vegetation, which was shown by the research conducted in the Slovak part of the High Tatra Mountains (Rojan 2010). The most intense erosion occurs in the period immediately after influencing the slope structure by the construction of a road (Luce and Black 2001; Byblyuk et al. 2010). Most of the changes in the relief of slope within which logging operations are conducted depend on the type and technique of the transport of tree trunks on the slope surface (Modrý and Hubený 2003; Dudek 2011).

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Forest roads disproportionately affect slope processes such as runoff production and erosion, given the area of land they occupy (Luce and Wemple 2001). In protected mountain areas, intense geomorphic changes within roads occur in the vicinity of conservation areas, where economic land use is allowed (Wałdykowski 2006; Wałdykowski and Krzemień 2013).

Forest roads in mountain areas cause significant changes in the functioning of slopes, which was shown, e.g. in the Olympic Mountains (Reid et al. 1981), Mont-Dore (Krzemień 1997), the Cascade Range (Wemple et al. 2001), and Spitsbergen (Buchwał 2008). Many works underline the impact of roads on changes in the surface runoff and sediment transport on the slope (Reid et al. 1981; Madej 2001; Sidle et al. 2006; Mirus et al. 2007; Thomaz and Peretto 2016). Roads frequently intercept subsurface flow, which causes significant changes in surface hydrology and intensity of geomorphic processes (Dutton et al. 2005; Sidle et al. 2006; Mirus et al. 2007; Ziegler et al. 2007; Negishi et al. 2008). Roads contribute to intense sediment transport to valley floors or directly to channels (Froehlich and Słupik 1980, 1986; Reid et al. 1981; Reid and Dunne 1984; Megahan et al. 2001; Sidle et al. 2004, Ramos-Scharrón and MacDonald 2005).

As a result of transporting wood within roads, deep ruts are created, which are later deepened by the erosion processes during rain storms and forestry operations. This leads to sediment transport and the deepening of the whole road surface. Intense logging during one season may lead to the development of 1.5 m deep erosion dissections (Kasprzak 2005). A system of evorsion kettles and accumulation steps may develop within road surfaces (Gorczyca and Krzemień 2010), whereas within cutslopes and fillslopes, sediment is systematically transported by landsliding (Imaizumi et al. 2008), especially in the periods of high ground saturation (Kłapa 1980, Montgomery 1994). Roads may also cause a break in the continuity of landforms, which is particularly possible in the middle part of a slope during intense rainfall (Wemple et al. 2001).

Roads and skid trails set out for the purposes of short-term forestry works should be protected against erosion (Łukasik et al. 2016). Roads may remain geomorphically active even after abandonment (Kroczak 2010; Dąbek et al. 2014). In such a case, an important factor contributing to the geomorphic activity of roads is the presence of surface water (Ziegler et al. 2007; Bajrić et al. 2013). However, the research of Reid and Dunne (1984) showed that sediment transport within intensely used forest roads is 130 times higher than within roads excluded from use.

The type of bedrock, road inclination, and road length were shown as the most important factors controlling the magnitude of relief changes within roads (Fransen et al. 2001; Megahan et al. 2001; Agherkakli et al. 2010; Nasiri et al. 2012; Akbarimehr and Jalilvand 2013). The research of Bajrić et al. (2013) showed higher erosion intensity within roads located on flysch rocks than those located on limestone. The location within a slope and protection against erosion also play an important role (Tague and Band 2001; Wemple et al. 2001). One of the most important protection treatments is the proper water drainage by creating numerous drainage channels preventing the concentration of surface runoff (Burroughs and King 1989; Akbarimehr and Naghdi 2012; Łukasik et al. 2016). Copstead et al. (1998) presented the principles of using drainage channels (types, distances between channels) within forest roads, including different site conditions (slope inclination, type of bedrock). The research of Nasiri and Hosseini (2012) showed that anti-erosion treatments significantly decrease the magnitude of erosion within forest roads.

The issue of the gully erosion risk connected with constructing new roads was also raised in the research conducted in Kenya and Ethiopia (Jungerius et al. 2002; Nyssen et al. 2002). The authors point out that little attention is paid to the analysis of the location of a road in relation to the terrain topography, which should precede the construction of a new road (Jungerius et al. 2002). Thus, the road construction, especially in places susceptible to erosion, should be subject to prior procedures, which would incorporate the environmental impacts analysis (Caliskan 2013).

In this work, we explore the geomorphic consequences of using and constructing new forest roads on an example of the Tatra Mountains, where the windthrow event in 2013 was followed by intense salvage logging operations. We show the most important factors which influenced the magnitude of geomorphic changes within researched roads, and present the impact of terrain morphology on its distribution. We also assess the rate of erosion/accumulation within the researched roads based on the repeated road profile measurements.

2. Study area

The researched roads are located in the Western Tatra Mountains, in the Lejowa, Jaroniec, and Kościeliska valleys, in the Tatra National Park (Figure 1). All of the roads are located in a montane belt.

The analyzed roads are located within sedimentary rocks, mainly dolomite, limestone, dolomitic breccia, dolomitic sandstone, conglomerate, shale, and quaternary deposits (Szczegółowa mapa geologiczna Tatr, 2011). The area has a typical fluvial-denudation relief (Klimaszewski 1988), and is dominated by Cambic Rendzic Leptosols, Rendzic Leptosols, and Haplic Cambisols (Eutric) (Skiba et al. 2015).

The mean annual precipitation in the research area is 1200–1600 mm. The mean precipitation for the summer period (June–August) is 530–680 mm for the altitude range of 1150–1550 m a.s.l. (Hess 1974). The mean annual temperature is 2–6°C. The number of days with snow cover ranges between 100 and 140 (Niedźwiedź 1992; Ustrnul et al. 2015). In 2014, the precipitation sum for the summer period (June–August) was 603.5 mm, in 2015, 274 mm, and in 2016, 657 mm (data obtained from the Institute of Meteorology and Water Management).

The study area is dominated by fluvial processes, sheet wash, gully erosion, creep, and windthrow denudation (Kotarba 2002). There are frequent occurrences of strong foehn winds, the velocities of which may reach 60 m s^{-1} (Hess 1974; Niedźwiedź 1992). This often results in the damage of large forest areas (Kotarba 1970; Minar et al. 2008; Dąbrowska 2009; Strzyżowski et al. 2016). In December of 2013, a foehn wind, the maximum hourly average velocity of which reached 29 m s^{-1} (data obtained from the Institute of Meteorology and Water Management), caused significant damage in the forests of the Western Tatra Mountains. In 2014 and 2015, intense salvage logging operations were conducted. In the Lejowa and Jaroniec valleys, tree trunks were transported mainly via forest roads. In the Kościeliska Valley, cable-crane logging was applied; however, one side of trunks was in contact with the slope surface, and thus several linear erosion scars were created.

The research areas in the Lejowa Valley and the Jaroniec Valley are located in the landscape protection zone of the Tatra National Park, where economic use of forests is allowed and realized by the Community of 8 Villages in Witów. The research area in the Kościeliska Valley is located in the active protection zone of the Tatra National Park, where protective procedures preclude the economic use of forests.

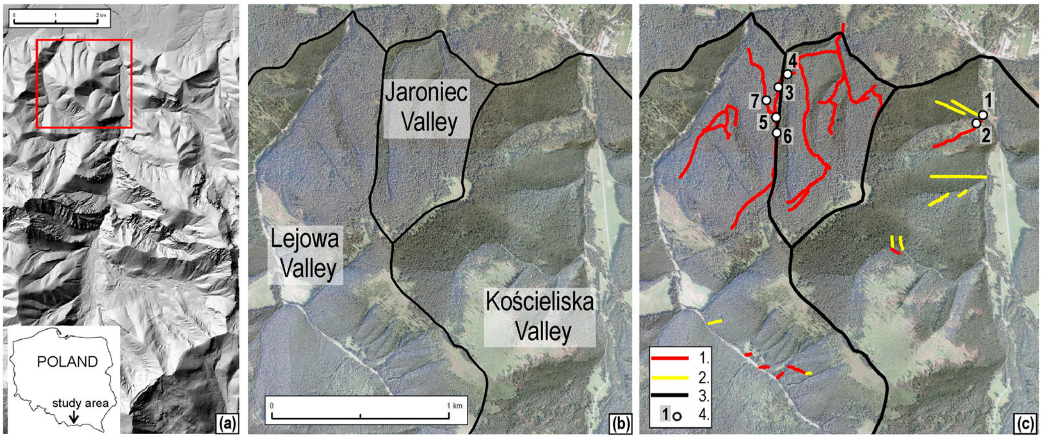

Figure 1. Location of the study area on the DEM (a). Studied valleys (b). Location of mapped forest roads and linear erosion scars (c). Map (c) shows: mapped forest roads (1), mapped linear erosion scars (2), catchment boundaries (3), locations and numbering of measured road cross profiles (4).

3. Methods

The mapping of the roads was conducted in the summer season of 2016. The roads were mapped by dividing them into morphologically homogenous sections. A new road section was distinguished, if any of the following road parameters changed significantly: the amount of dissections within a road, depth of a road, or inclination of a road. A set of a parameters was measured within each section of a road, i.e. its average width (WIDTH), average depth (DEPTH), average dissection depth (DISSECTION), average road inclination (INCLINATION), number of accumulation steps and evorsion kettles (STEPS_KETTLES), the number of micro-scale landslides (LANDSLIDES) within the cutslope, and the number of intercepted subsurface flow features (ISSF) within the cutslope (Figure 2). For the latter, we considered all places where water flowing from the cutslope was observed during the field work, and all places where no signs of flowing water were observed at the time of the field work, but the scars in the cutslope relief indicated evidently that water was flowing from it during/after the rainfall. In such a case, each single scar was counted. Next, for each section, the ratio of accumulated steps and evorsion kettles (SK_RATIO) was calculated by dividing STEPS_KETTLES by the length of a given road section, and then by dividing it by the amount of dissections within a given road section, if there was more than one dissection. The ratio of landslides (L_RATIO), and the ratio of subsurface flow interception features (ISSF_RATIO) were calculated by dividing LANDSLIDES, and ISSF by the length of a given road section. Also, for each road section, the cumulative length (CUMUL_LENGTH), i.e. distance from the upper part of a road, was calculated, and the bedrock type was assigned. Also, all the linear erosion scars created by logs transported using cable crane logging were mapped. Width, depth, and inclination were measured for each of them.

In order to find relationships between the measured road parameters (WIDTH, DEPTH, DISSECTION, INCLINATION, SK_RATIO, L_RATIO, ISSF_RATIO, CUMUL_LENGTH), the Principal Component Analysis (PCA) was used. The most important factors were identified based on

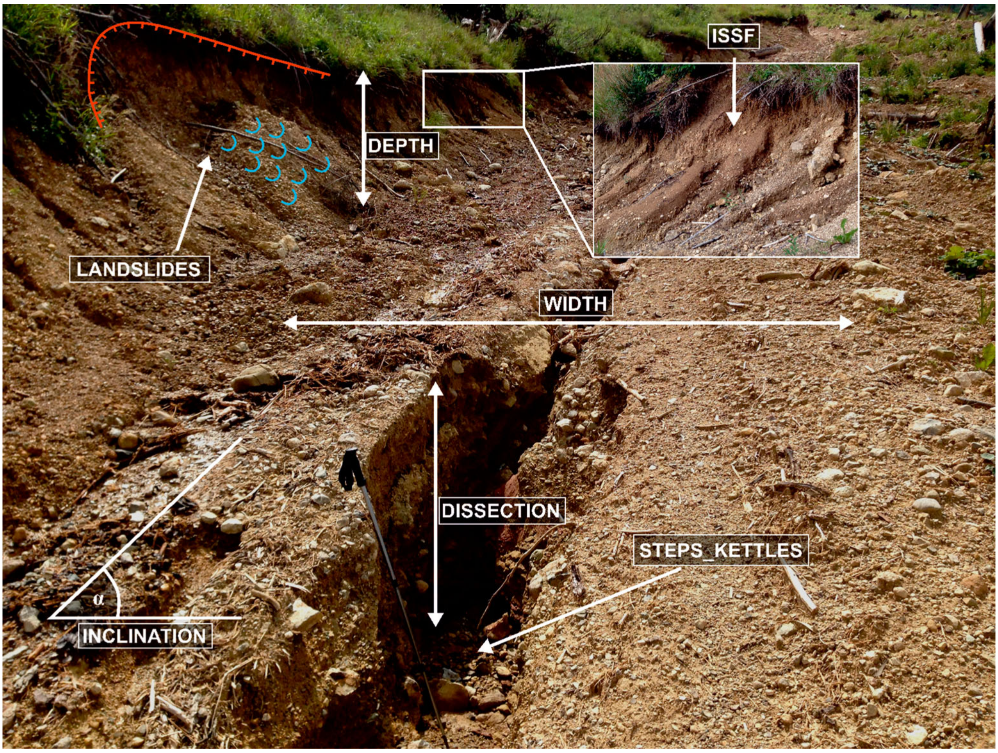

Figure 2. Parameters measured in each road section.

Keiser's criterion (factor eigenvalues greater than 1). The spatial distribution of the PCA results was analyzed basing on the map of flow convergence (*Convergence Index*) generated in SAGA GIS 2.2.0 to search for the impact of terrain morphology on the magnitude of geomorphic changes within roads.

To verify whether the magnitude of changes within the roads is influenced by the bedrock type, the t-test for two independent samples was used. For the purpose of this analysis, the rocks occurring in the study area were divided into two groups according to their strength. The first group (strong rocks) included dolomite, limestone, dolomitic breccia, and dolomitic sandstone. The second group (weak rocks) included conglomerate, shales, and quaternary deposits. The mean values of road parameters (DISSECTION, SK_RATIO) were compared between those groups to check them for significant differences ($p = 0.05$).

For the purpose of statistical analysis, all of the variables containing 0 values (SK_RATIO, L_RATIO, ISSF_RATIO) were re-scaled by adding 1 to all values of a given variable. Next, all variables were prepared to fit normal distribution. First, the Lilliefors test was applied, and all of the variables which did not have normal distribution were transformed using the logarithm ($\log_{10}$). If the variables still did not present normal distribution, variables presenting more symmetrical distribution (skewness coefficient closer to 0) were used for further analysis. The analyses were conducted using the Statistica 12 software.

Additionally, seven road profiles were measured on the 7th and 21st of July, and on the 18th of August 2016. The measurements were repeated on the 28th and 29th of September 2016. The profile measurements and calculations of erosion/accumulation were conducted using the Cross-Section Area (CSA) method proposed by Cole (1983) (Figure 3). A tape was mounted and tautened above the dissection at fixed points, and a series of vertical measurements (V) at fixed intervals ($L = 5$ cm) were taken. The CSA (in cm^2) was calculated according to the formula shown below (based on Cole 1983):

$$A = \left(\frac{(V_1 + 2V_2 + \cdots + 2V_n + V_{n+1})}{2} \right) L \tag{1}$$

where A is the cross-section area, $V_1 \ldots V_{n+1}$ is vertical distance measurements, starting at V_1 as the first fixed point and ending at V_{n+1} as the last measurement, and L is the constant interval between the vertical measurements.

Next, the CSA of the first measurement was subtracted from the CSA of the second measurement. By dividing this by the given road profile length, we obtained the thickness of eroded/accumulated soil layer (in cm). Subsequently, basing on time elapsed between the first and second measurements, we assessed the net annual erosion/accumulation (in cm yr^{-1}) within a road profile.

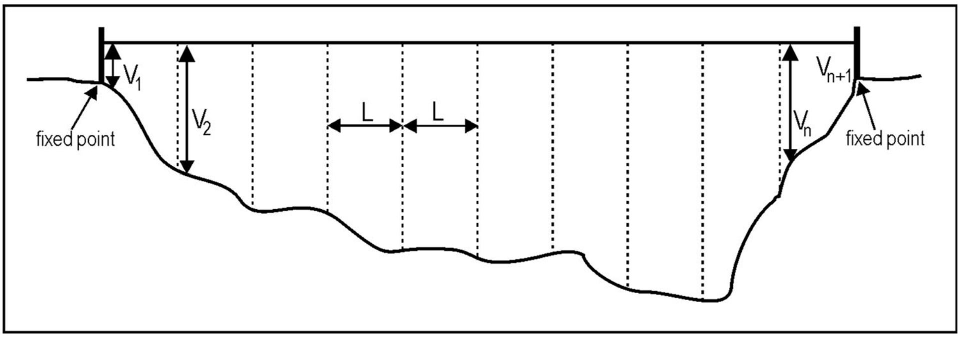

Figure 3. Example of cross-section profile measurements conducted within road profiles (based on Cole 1983).

Unfortunately, the CSA method calculates only the net change within a road, and does not show the magnitude of erosion and accumulation separately. To provide this distinction, we used ArcGIS. The coordinates x and y, representing road length (cumulative L values) and road depth (V values) respectively, were saved as an .xls file, and inserted into ArcGIS. Then, basing on those coordinates, points were created using the '*Display XY data*'. Next, using the '*Points to line*' tool, a line for each profile was created. By comparing the lines (the first and second measurements) for each profile, cross-sectional areas of erosion and accumulation were digitized as polygons, and their area (in cm^2) was calculated using the '*Calculate geometry*'. Those areas were divided by the given profile length, and, accounting for the elapsed time, they were transformed into the annual erosion and annual accumulation layer (in cm yr^{-1}).

4. Results

Road morphometry

The analyzed roads and linear erosion scars are located at the altitude between 932 and 1211 m a.s.l. In total, 116 road sections and 10 linear erosion scars were distinguished. The length of the roads is 6.2 km, and the length of the erosion scars is 1.1 km (Figure 1(c), Table 1). The mean inclination of the roads is 15°, with a maximum of 27°. The mean inclination of erosion scars is 27°, with a maximum of 36°. The mean width of erosion scars is 1 m, and their mean depth is 0.2 m. Over the 68% of their length, they are almost entirely vegetated. The remaining 32% are devoid of vegetation where erosion may occur. The mean width of the researched roads is 3.1 m, with their mean depth reaching 0.85 m. Within the cutslopes of the roads, a total of 275 signs of subsurface flow interception were observed, in 19 of which flowing water was observed during the field mapping (Table 1). Also, 76 micro-scale landslides were created, which delivered sediment to the road surface. The sizes of these landslides were not included in the measurements; however, most of them were 1.5 m in length, and 1 m in width. In one case, in the direct vicinity of a road, a larger landslide, 16.7 m wide and 9.5 m long, was created.

During the mapping of the roads, the most significant effects of geomorphic processes were observed in the Lejowa Valley, within the newly created road. Along the 490 m of the road's length, 150 signs of interception of subsurface flow were observed. Distinct erosion dissections, eversion kettles, and accumulation steps were created. The maximum depth of one of the eversion kettles reached 1.9 m (Figure 4). At the end of the road, in the valley floor, an accumulation fan was created, and signs of accumulated sediment were observed over an area of 1088 m^2. These changes, which were observed during the field work on 7.07.2016, were not observed during the earlier field observations in 2015 (29.10.2015) (Figure 4), which may point out that the most intense changes within the road located in the Lejowa Valley were created at the beginning of the summer season in 2016. They were probably triggered by the intense rainfall, which, over a period of 3 days (1.07.2016–3.07.2016), resulted in a precipitation sum of 112 mm.

Table 1. Morphometric parameters and number of landforms within strong and weak rocks.

Parameters	Units	Strong rocks	Weak rocks	All
Road length	(m)	1787	4408	6195
Mean WIDTH		3.5	3	3.1
Mean DISSECTION		0.1	0.2	0.2
Mean DEPTH		1	0.8	1
Mean INCLINATION	(°)	14	16	15
ISSF (no flowing water observed)	(*n*)	58	198	256
ISSF (flowing water observed)		6	13	19
Landforms				
Accumulation steps	(*n*)	108	226	334
Evorsion kettles		3	152	155

Figure 4. A forest road in the Lejowa Valley 1 year after construction (a), 2 years after construction: transformed by a rainfall event (b). Eversion kettles developed after the rainfall event in 2016 (c). The deepest (1.9 m) eversion kettle within the studied roads developed after the rainfall event in 2016 (d).

Factors influencing the magnitude of geomorphic changes

The PCA allowed us to distinguish three independent factors, which explain 66.30% of the total variance. The first factor (F1) explains 37.39% of the total variance and reveals a positive relation between almost all road parameters, except WIDTH and INCLINATION (Table 2, Figure 5). This shows that the magnitude of the subsurface flow interception within a given road section (ISSF_RATIO) is the most important feature influencing the geomorphic changes within a road such as the amount of steps and kettles, the amount of micro-scale landslides within the cutslope, and dissections depths. The second factor (F2) shows a negative relation between WIDTH and INCLINATION; thus, the higher the WIDTH, the lower the INCLINATION. The third factor (F3) shows a positive relation between WIDTH and CUMUL_LENGTH.

If the coordinates of the variables for the first factor (F1), revealed by the PCA, are presented on a map, they show some pattern pointing out the influence of slope morphology. Within many of those sites where the influence of F1 is the highest, road sections run across the areas of flow convergence (Figure 6(a)). Figure 6(b–d) presents examples of such situations. In Figure 6(b,d), within the road sections which crossed convergence areas (e.g. a hollow or a gully), ISSF features occur. This is particularly expressed in Figure 6(b), where the road runs across several hollows, and where the most intense damage was observed (Figure 4). In Figure 6(c), however, roads also run across convergence

Table 2. Results of the PCA showing factor loadings and eigenvalues of each factor.

	F1	F2	F3
WIDTH*		0.70	0.55
DISSECTION*	−0.58		
DEPTH*	−0.52		
INCLINATION		−0.56	
SK_RATIO*	−0.79		
ISSF_RATIO*	−0.82		
L_RATIO*	−0.78		
CUMUL_LENGTH*	−0.54		0.52
Eigenvalue	2.99	1.26	1.05
Percentage of explained variance	37.39	15.80	13.11
Percentage of cumulative variance	37.39	53.19	66.30

Factor loadings below 0.5 are excluded.
* Values transformed using $\log_{10}$.

areas, and no ISSF features were noted there. Nevertheless, this may point out that constructing a road across a convergence area may promote subsurface flow interception, and in our study area, according to the PCA results, the latter is the most important in influencing the magnitude of geomorphic changes within roads.

The *t*-test for two independent samples showed that mean values of both DISSECTION and SK_RATIO are significantly higher within the weak rock group, comparing to the strong rock group (Figure 7), which points out that both the magnitude of erosion and geomorphic processes activity depend on the bedrock strength.

Changes within the road profiles

The analysis of changes within the profiles of the researched roads shows that in some cases significant activity of geomorphic processes occurred. When comparing the calculated annual erosion/ accumulation layers, there were four cases where erosion was higher than accumulation, two cases where accumulation was higher than erosion, and one case where both processes were almost equal (Figure 8). When both the erosion and accumulation layers are summed, the most intense

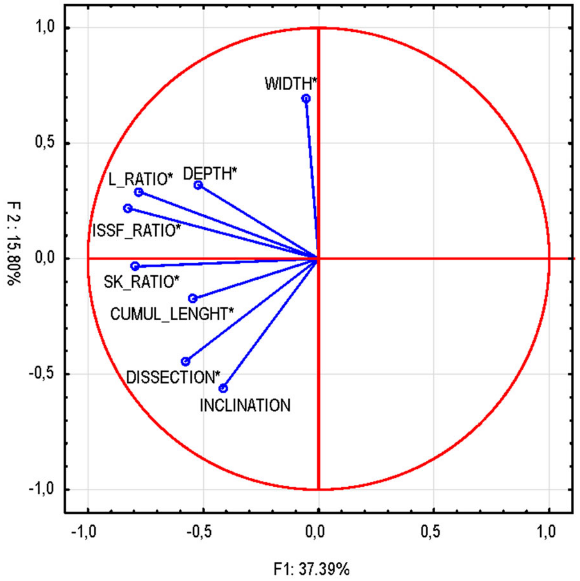

Figure 5. Projection of the variables on the plane of the two most important factors.

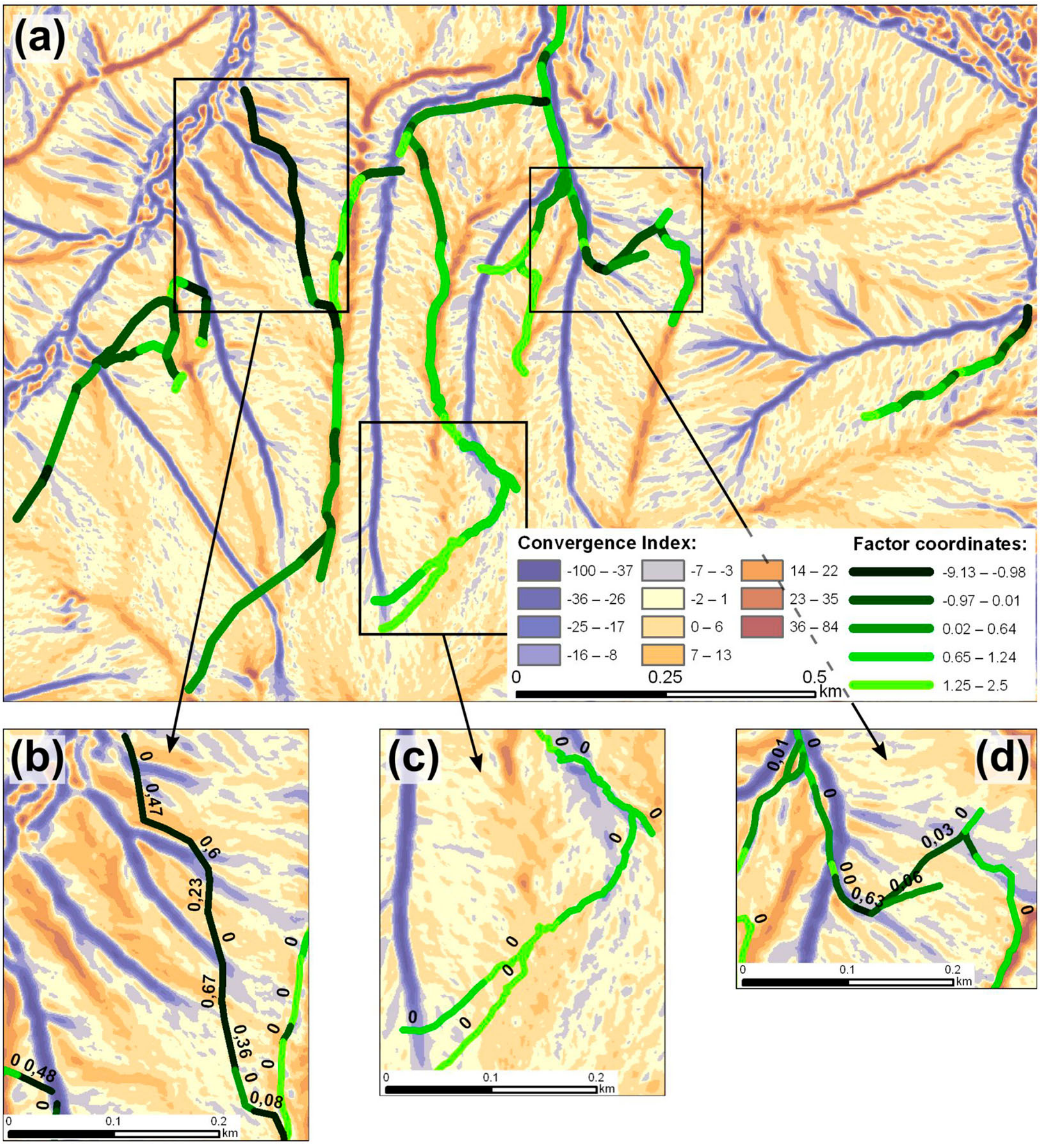

Figure 6. Spatial distribution of the PCA results on the map of convergence index (a); for each road section the factor coordinates for the first factor (F1) revealed by the PCA were assigned; the factor coordinates are divided into five classes using the quantile classification. Detailed examples of road sections which crossed a convergent slope (b, c, d); for each road section the ISSF_RATIO is labeled.

changes were observed within Profile 7 (Figure 9(b)). This profile was the only one in the vicinity of which ISSF features within the cutslope were observed.

The most intense net annual erosion was noted within Profile 6, and was at a rate of almost 10 cm yr^{-1} (Figure 10). In the cases where accumulation exceeded erosion, the net annual accumulation was 7.7 and 3.6 cm yr^{-1}.

5. Discussion

The most intense changes in the slope relief and functioning caused by forest roads occur in the period immediately after the construction of a new road, and during the period of its use. Megahan

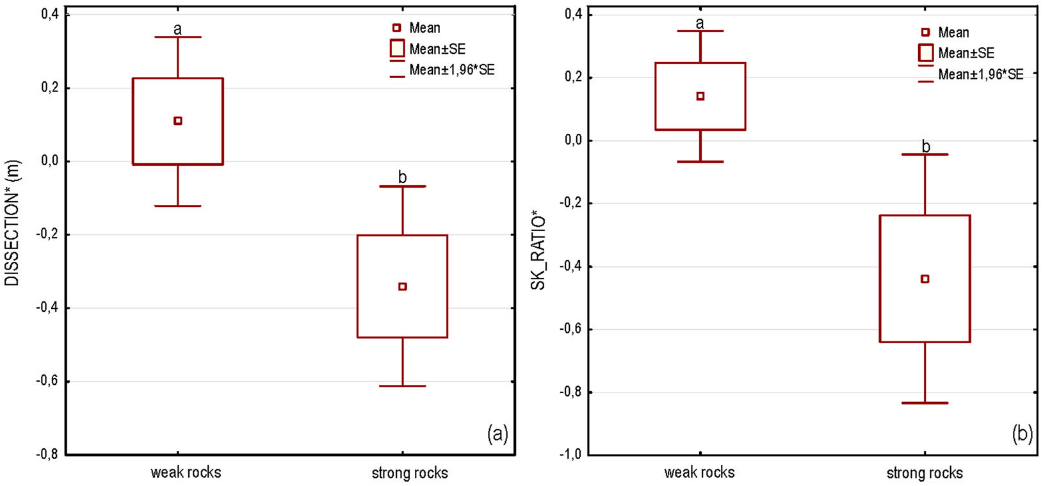

Figure 7. Results of the *t*-test showing the differences of mean values of DISSECTION (a) and SK_RATIO (b) between weak and strong rocks. The means with a different letter are significantly different ($p = 0.05$).

et al. (2001) showed that in the first season of using a road, erosion was 4 times higher than in the other, following seasons. The research of Kasprzak (2005) showed that substantial relief changes may occur during one season of logging works. Similar results are also provided by our research. In the study area, high-magnitude geomorphic changes within the new roads constructed in 2014, occurred in 2016 after intense rainfall, and forced the abandonment of some of the road sections.

The type of the applied logging technique influences the magnitude of erosion to a considerable degree (Modrý and Hubený 2003; Byblyuk et al. 2010). In our study area, most of the linear erosion scars created by cable crane logging were vegetated and did not present any signs of significant erosion. This is in contrast to the roads within which substantial erosion and deposition of sediment was observed. However, those erosion scars may still play some role in modifying slope runoff, while the hydraulic conductivity of such surfaces may not fully recover even after several decades (Ziegler et al. 2007).

Significant relief changes may occur within the road surface, cutslope, and fillslope (Sidle et al. 2004; Wałdykowski and Krzemień 2013). Sidle et al. (2004) estimated that 60% of the soil loss on roads they studied was generated by the erosion of a road surface, and the remaining 40% was generated by the erosion of the cutslope (22%) and fillslope (18%). Within our research area, road

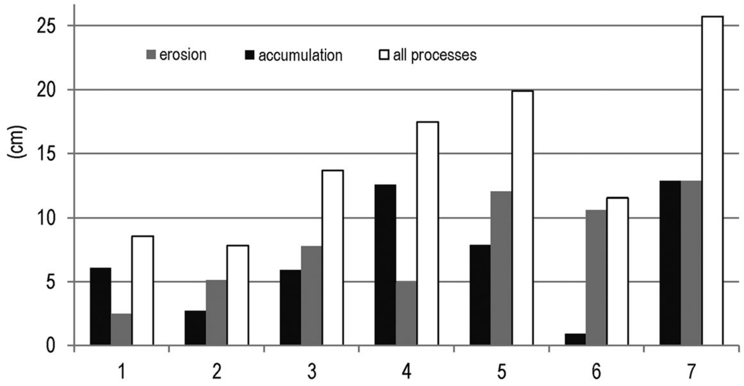

Figure 8. Calculated mean annual erosion and accumulation layers, and the sum of both processes for each measured road profile.

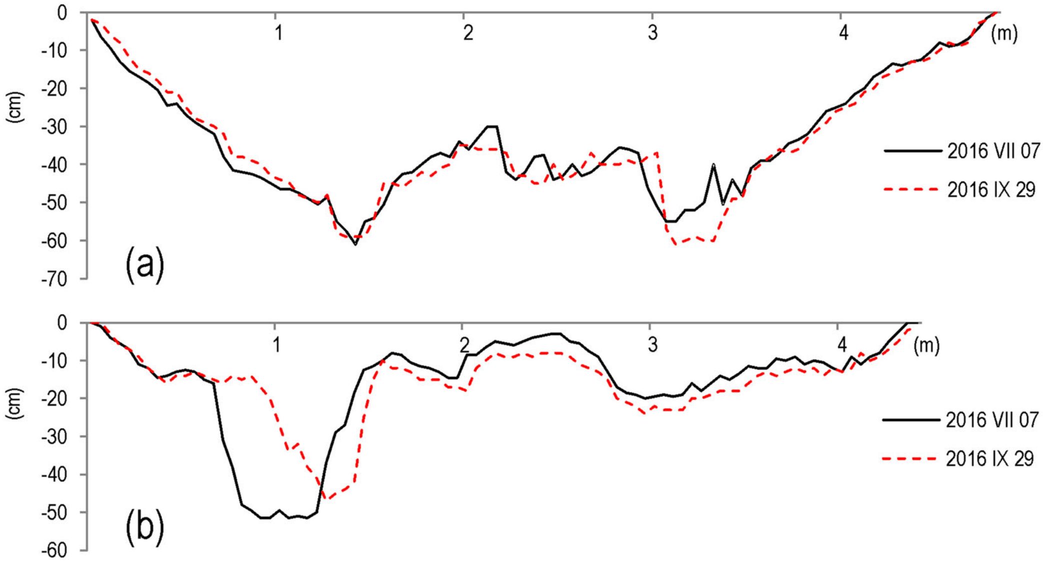

Figure 9. Changes within the researched profiles between 7 July 2016 and 29 September 2016 within profile 5 (a) and profile 7 (b).

surfaces are densely covered by accumulation and erosion features such as eversion kettles, erosion dissections, and accumulation steps, which indicate highly dynamic geomorphic processes. Similar landforms were identified within the roads in other mountain areas (Kasprzak 2005; Gorczyca and Krzemień 2010; Wałdykowski and Krzemień 2013; Łukasik et al. 2016). The cutslopes of the researched roads are also modified by landsliding, which delivers sediment to the road surface (Sidle et al. 2006; Negishi et al. 2008).

Numerous studies underlined the important role of road inclination in the magnitude of erosion within roads (Luce and Black 2001; Megahan et al. 2001; Byblyuk et al. 2010; Nasiri and Hosseini 2012; Yousefi et al. 2016). The research of Akbarimehr and Jalilvand (2013) showed that significant erosion occurred on highly inclined roads; therefore, transport of tree trunks should be limited to hill slope angles <20% (11°). The intensity of erosion within a road surface is undoubtedly influenced by the amount of flowing water, much of which may come from the intercepting of

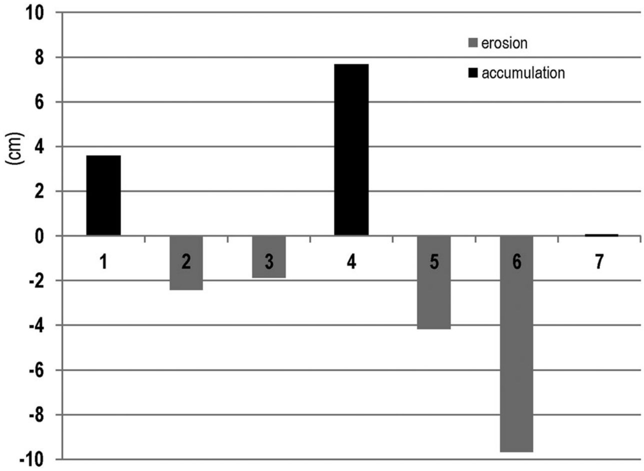

Figure 10. The net annual change in the depth of the measured road profiles.

subsurface flow by the cutslope. Wemple and Jones (2003) assessed that intercepted subsurface flow constituted 95% of the total road runoff on the roads they studied. Similar results were obtained by Negishi et al. (2008), who assessed this value at a rate of 79%, and they also estimated that the runoff generated by intercepted subsurface flow accounted for 28% of the total sediment export from a road within their study site. In our research, the PCA showed that the most important relationship within studied road sections is the influence of the ISSF features on the number erosion/accumulation forms within road surfaces and the number of landslides within road cutslopes. The latter may cause road widening and deliver sediment to the road surface, from where it may be subject to further transport (Sidle et al. 2006; Negishi et al. 2008). The occurrence of ISSF is, in turn, frequently connected with the location of a road according to the terrain morphology, and in most cases these features occur in a place where a road is built across small valleys (e.g. hollows). There are some exceptions where a road crosses a hollow and no ISSF signs were noted (Figure 6(c)). In our study, however, the evidence of subsurface flow interception was inferred based on the visible signs in the relief of the cutslope left by water; thus, it may be the case that in some road sections, interception of subsurface flow had occurred, but it did not leave any visible signs in the cutslope relief. Nevertheless, our results show that the intercepting subsurface flow by forest roads may be particularly important in places where a road crosses convergence areas. Such a notion was pointed out in some other works (Luce 2002; Wemple and Jones 2003; Mirus et al. 2007; Negishi et al. 2008). In our study site, many of the road sections which crossed a convergent slope encountered the highest magnitude of geomorphic changes, and should be given the highest priority of restoration. Other important features, identified in the first factor of the PCA, influencing the magnitude of changes include the road length and the road depth. The latter may also facilitate subsurface flow interception by the cutslope, which was also pointed out by Wemple and Jones (2003), Ziegler et al. (2007), and Negishi et al. (2008). Factors F2 and F3 revealed by the PCA are less significant, and their interpretation does not lead to the distinction of factors influencing geomorphic activity within roads.

Bedrock strength is also an important factor influencing the magnitude and type of the geomorphic changes on the slopes affected by roads (Megahan et al. 2001; Bajrić et al. 2013). Our research showed higher erosion, and higher intensity of geomorphic processes on the roads located within bedrock characterized by lower strength. These results are similar to those obtained by Bajrić et al. (2013), who showed higher erosion on roads located within flysch rocks compared to limestone.

The CSA method showed that locally there are differences in the magnitude of changes within the road profiles. The highest intensity of geomorphic processes occurred in the profile located within road section within which subsurface flow interception was observed. The mean rate of net annual road deepening for all of the measured profiles is 4.5 cm yr^{-1}. These results are similar to those obtained in other mountain areas. The research conducted in the Gorce Mountains in 2004–2008 showed that that the mean annual rate of road deepening was 3.3 cm yr^{-1}, and the mean maximum annual rate was 4.1 cm yr^{-1} (Wałdykowski and Krzemień 2013).

For comparison, the measurements conducted within tourist trails showed maximum annual deepening of 3 cm yr^{-1} in the Gorce Mountains (Wałdykowski 2006) and 2.1 cm yr^{-1} in the Karkonosze Mountains (Kasprzak 2005). Erosion within a road on the granite soils in the Idaho Batholith ranged from 1 to 1.1 cm yr^{-1} (Megahan et al. 1983).

6. Conclusion

Forest roads may leave a significant imprint on the natural environment, especially when they are constructed improperly, without the stage of earlier planning. In our study area, the first seasons after road construction contributed to the significant geomorphic changes within roads, which precluded some of the road sections from use.

Our research shows that the most important factor determining the magnitude of geomorphic processes within roads is the number of subsurface flow interception features within cutslopes. In many cases, their presence is related to the road location relative to terrain morphology, especially where a road section crosses a convergence area. Other factors which influence relief transformations are the length of a road, which affects the energy of the flowing water, and the depth of a road, which may promote the interception of subsurface flow. Thus, our study shows that at the planning stage of forest road construction, particular attention should be paid to the road location in relation to slope morphology and the depth of the road excavation.

Also, the strength of bedrock plays a significant role in the magnitude of the geomorphic activity within road sections. There is a significant difference in the depth of dissections and in the amount of accumulation steps and evorsion kettles between the road sections located on strong, compared to weak rocks.

The magnitude of changes within roads based on profile measurements varies locally. While some of the profiles do not present large net annual change in their depth, the magnitude of both accumulation and erosion processes is relatively high. When the net annual change in the depth of all of the profiles is averaged, the researched road profiles show a tendency of deepening at a rate of 4.5 cm yr^{-1}.

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