CHANGES IN EROSION PROCESSES AND MORPHOLOGY OF STEP-POOL CHANNELS IN THE SKI RESORT WITH ARTIFICIAL SNOWMAKING, AN EXAMPLE FROM GUBAŁOWSKIE FOOTHILLS

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Abstract: The construction of ski runs with artificial snowmaking in mountainous areas changes natural water circulation and leads to the activation of erosion and deposition processes. To recognise this relationship, we selected a small catchment in the Gubałowskie Foothills, the Inner Carpathians, where 17% of the area is covered by the ski runs. In our study, we hypostatised that: (i) channels draining ski runs exhibit different morphological and morphometric characteristics compared to those that do not drain ski runs; (ii) the statistical relationships between channel morphometric parameters differ between impacted and non-impacted channels; and (iii) erosion and deposition processes lead to measurable changes in channel morphology that can be quantitatively assessed in the research area. To identify these changes, we conducted geomorphological mapping of step-pool channels, statistical analyses, digital elevation model (DEM), and DEM of difference (DoD) analyses (based on point clouds from 2016 to 2023). To identify the effect of ski run construction on channel morphology, we divided channels into two groups: (1) stream channels unaffected by ski infrastructure and (2) stream channels affected by ski infrastructure. Results showed that the routing of drainage from the ski runs to the channels leads to a significant erosion in the channels with the maximum deepening, up to 2.6 m. It also changes the dominant geomorphological processes in the channels. Fluvial processes are beginning to dominate slope processes. The described changes occurred already 8 years after the opening of the ski station and revealed environmental degradation connected to artificial snowmaking in ski resorts.

Keywords: human impact, erosion, step-pool channels, DEM of difference, artificial snowmaking, ski run

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Introduction

In the last decades, a construction boom has been observed in ski resorts in many mountain regions (Elsasser, Messerli 2001, Krzesiwo 2014, 2021, Vanat 2022). The main area where ski resorts are established in Poland is the Carpathians, where snow shortages are common in winter (Krzesiwo 2014, Piątek et al. 2022, Krzesiwo, Mika 2024). In such regions, ski resorts invest in advanced systems of draining, snow grooming, and artificial snowmaking. These activities lead to severe damage to the natural environment and land degradation (Mosimann 1985, Tsuyuzaki

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1994, Ries 1996, Keller et al. 2004, Wipf et al. 2005, Barni et al. 2007).

The most developed ski resorts adjust hillslopes to a proper gradient for skiers by levelling and building escarpments. It degrades the natural shape of hillslopes and disturbs typical hillslope processes in the area (Krzemień 1997, Ruth-Balaganskaya, Myllynen-Malinen 2000, Ristić et al. 2012, Fidelus-Orzechowska et al. 2018, Furdada et al. 2020, Piątek, Bernatek-Jakiel 2024). The use of snow groomers and the production of artificial snow led to an increase in the duration of snow cover. Snow grooming delays snow snow-melting season by up to 4 weeks in the Alps (Keller et al. 2004). Artificial snowmaking extends the duration of snow cover by 30–200% of natural snow cover duration (data from the Alps) (Bacchiocchi et al. 2019). It increases the amount of water on the hillslope several times (data for Gubałowskie Foothills, Wrońska-Wałach et al. 2019).

The construction of drainage systems reduces the intensity of erosion on the surface of ski runs but leads to activation erosion and deposition processes in the surroundings of ski runs (Fidelus-Orzechowska et al. 2018, Wrońska-Wałach et al. 2019, Furdada et al. 2020, Piątek, Bernatek-Jakiel 2024), including erosion in channel network (Krzemień 1997, David et al. 2009). David et al. (2009) recognised that ski run construction and artificial snowmaking may lead to lateral erosion, increased landslide activity on slopes, and a share of fine material at the channel bed. The scale of change in channels and on hillslopes is largely related to local lithology and plant cover (David et al. 2009).

Typically, ski runs are located in small, headwater catchments. In this type of area, channels have a high gradient and characteristic morphology types: cascade and step-pool (Montgomery, Buffington 1997, Chin, Wohl 2005). Channels in headwater areas are strongly coupled with hillslope processes, which provide additional sediment to the channel. It resulted in a differentiation of the longitudinal profile of channels (Brunsden 1993, Rice, Church 1996, Montgomery, Buffington 1997, Wohl et al. 1997, Knighton 1999, Gomi et al. 2003). The presence of steps forces a staircase profile of the channel and leads to the deposition of transported material (Wohl et al. 1997, Gomi et al. 2003, Chin, Wohl 2005, Lancaster, Grant 2006). It also reduces the erosive power of the stream (Chin, Wohl 2005).

Many studies focussed on statistical relationships (mainly Pearson correlation) between multiple parameters, including step height, step spacing, channel width, and channel gradient, to show relationships between the occurrence of steps and longitudinal channel morphology and the impact of hillslope processes on channel morphology (Whiting, Bradley 1993, Montgomery, Buffington 1997, Wohl et al. 1997, Chin 1999, Chartrand, Whiting 2000, Nickolotsky, Pavlowsky 2007).

A proven method for analysing geomorphic changes and erosion activity due to the impact of ski infrastructure is using data from airborne laser scanning (ALS) to conduct DEM of difference (DoD) analysis (Wrońska-Wałach et al. 2019, Piątek, Bernatek-Jakiel 2024). Digital elevation model (DEM) of difference analysis using repeated ALS surveys has a considerable capacity for quantitative analysis of landforms (Wheaton et al. 2010, Blasone et al. 2014, Okyay et al. 2019).

Therefore, the aim of our study, conducted in a small headwater catchment within a ski area, is to recognise changes in erosion processes and channel morphology in a catchment with artificial snowmaking. The study area is located in a ski resort in the Gubałowskie Foothills, Western Carpathians, Southern Poland. The analysed catchment has been a research area for different works since 2015. So far, measurements have been taken of changes in slope geometry during the construction of ski runs (Fidelus-Orzechowska et al. 2018) and how the catchment has changed to form new channel heads with new slope positions (Wrońska-Wałach et al. 2019). The channels in the surroundings of the ski runs have not been analysed before. This study includes field mapping as well as detection of changes in the stream channel thanks to the availability of multi-temporal ALS data. To achieve the aim of the study, we hypostatised that: (i) channels draining ski runs exhibit different morphological and morphometric characteristics compared to those that do not drain ski runs; (ii) the statistical relationships between channel morphometric parameters differ between impacted and non-impacted channels; and (iii) erosion and deposition processes lead to measurable changes in channel morphology that can be quantitatively assessed in the research area.

Study area

The study area consists of a small catchment of the Remiaszów stream (116 ha). It is located in the Gubałowskie Foothills in the Inner Carpathians (Fig. 1) and is part of one of the largest and most susceptible to erosion ski resorts in Poland: Kotelnica Białczańska (Krzesiwo 2014, Piątek et al. 2022). The area is formed of Podhale-type flysch consisting of sandstone shale layers and conglomerate horizons (Watycha 1976) and due to location in the area of neotectonic movements (Mastella et al. 1996), valleys in the studied area tend to aggradation and dominance of hillslope processes (Zuchiewicz 2010). Elevations range from 760 m to 950 m above sea level. The average hillslope gradient is 14°. Hillslopes have a straight and step-like profile due to the occurrence of agricultural terraces. The valley network of the Remiaszów stream catchment is 3.34 km long, and the channel density is 2.88 km · km^{-2}. The valley depth reaches 9 m. The valley network consists of Strahler third-order streams and their tributaries: 8 first- and second-order channels, whose morphology and erosional activity were our main points of interest. Three channels are located adjacent to ski runs 1 and 2 and drain water from ski runs (Fig. 1). The stream channels carry water only during snowmelt or after rainfalls.

The climate is temperate, with a mean annual temperature of 4–6°C (Obrębska-Starklowa et al. 1995). The number of days with a daily mean temperature below zero ranges from 100 to 130 (Obrębska-Starklowa et al. 1995). The number of days with snow cover ranges from 105 to 175. The mean annual precipitation in the study area in the period 1996–2016 was 869.4 mm Institute of Meteorology and Water Management (IMWM). In the study area, due to shortages in snow cover, artificial snowmaking is used to maintain ski runs on a wide scale, and the artificial snow season usually lasts from November 1 to March 30 under proper weather conditions (Wrońska-Wałach et al. 2019). The water sheet used to produce artificial snow on ski runs, ranges from 456 mm to 678 mm, which is 52–78% of the average annual rainfall (Wrońska-Wałach et al. 2019). In winter and during snowmelt, >2–3 times more water enters the catchment area due to artificial snowmaking than from precipitation (average

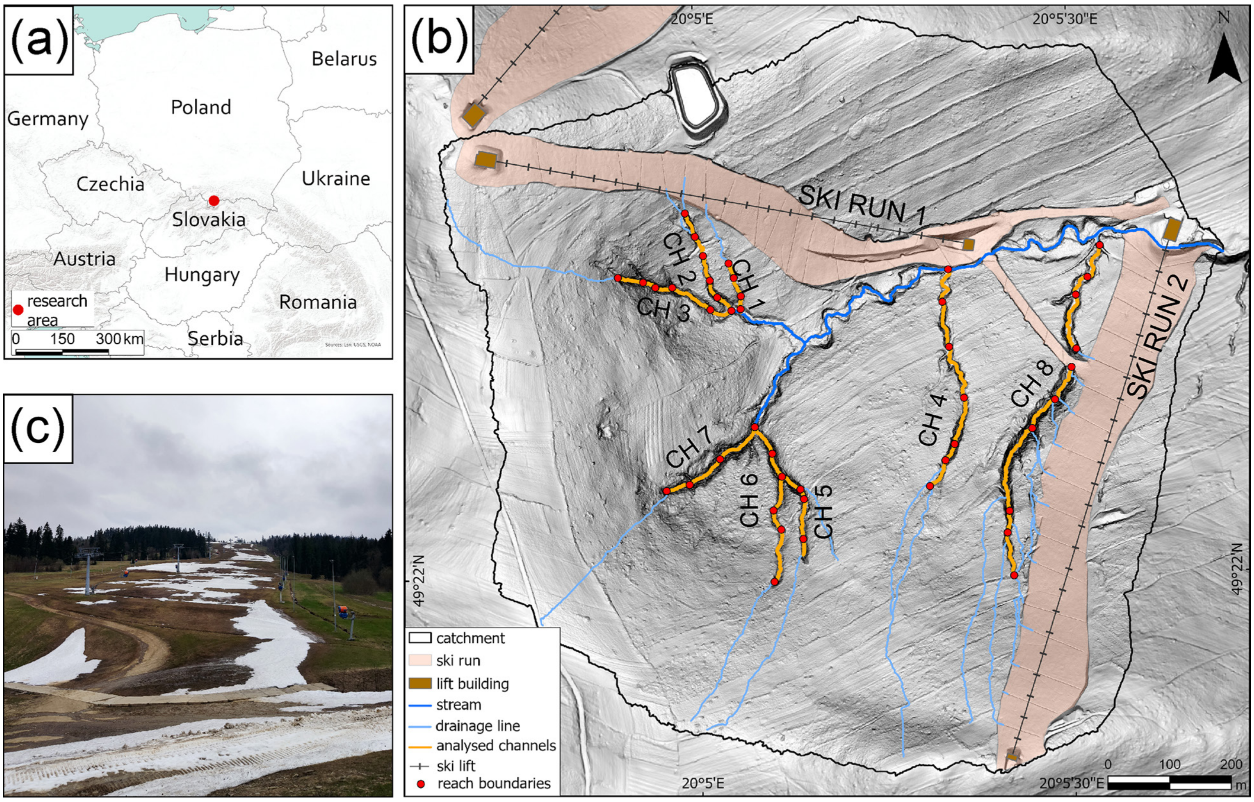

Fig. 1. Location of the study area: A – a regional overview, B – a hillshaded relief of the catchment with analysed channels. Channels are signed with CH and followed numbers. Important drainage lines and ski infrastructure are marked, and C – a photograph of the catchment with ski run 2 (photo: D. Piątek).

winter precipitation: 217.5 mm). The predominant directions of water runoff from ski runs indicate that most of this water enters the channel network around the ski runs. This was proved by the formation of new channel heads (Wrońska-Wałach et al. 2019).

The study area is 116 ha, and 17% of the area is covered by ski runs (19.7 ha) (Fig. 1). The ski run 1 was built in 2014 and is 8.76 ha; the ski run 2 was constructed in 2015 and is 10.74 ha. As a result of construction, 12% of the forest area in the catchment was removed. The construction of the ski runs was based on heavy earthworks, which significantly changed hillslopes. To level the hillslope surface by smoothing and lowering, about 43,000 m³ of soil on ski run 1 and about 32,000 m³ on ski run 2 were removed. In the different parts of the ski runs, the biggest changes occurred due to flattening of agricultural terraces, filling small gullies, and road construction, with height differences reaching up to 5 m (Fidelus-Orzechowska et al. 2018). The maximum elevation is 937 m for ski run 1 and 941 m for ski run 2. Denivelations differ from 165 m (the ski run 1) to 179 m (the ski run 2) (Fidelus-Orzechowska et al. 2018, Wrońska-Wałach et al. 2019). Before the construction of the ski resort, hillslopes had been used agriculturally since the 17th century. A remnant of this is the presence of agricultural terraces. Ski runs are covered with drainage ditches that direct water flow from the ski runs into the channel network (Fig. 1). The ditches have a dense network and are routed diagonally to the ski run, which results in low-intensity linear erosion on the ski run's surface.

Materials and methods

To present the changes in erosion processes and morphology of channels draining ski runs, we conducted fieldwork based on geomorphological mapping, DEM and DoD analyses, and statistical analyses.

Geomorphological mapping

Geomorphological mapping was conducted using a GNSS receiver Mobile Mapper 50 (Spectra Geospatial), laser-ranging Leica Disto Pro Touch D510, and measuring tape with an accuracy of 0.01 m. During geomorphological mapping, we analysed 2.2 km of first- and second-order stream channels and identified 37 stream reaches with relatively consistent morphology in eight stream channels. We visually recognised channels as cascade and step-pool channels based on the dominant bed forms (Montgomery, Buffington 1997). In every reach, we measured the following parameters: channel gradient, hillslope gradient, channel width (understood as an active zone), valley bottom width, number of steps, step height, step spacing, size of channel bed material, and size of the biggest clast building steps. For every reach, measured parameters were averaged (except number of steps). To present the data, parameters were averaged for each channel. Figure 2 shows how the selected parameters are measured. We measured the b-axis of clasts (second longest side). In general, we analysed 718 steps. Above the mapped eight stream channels, we recognised flow directions and flow connections/non-connections between channels and ski runs. To present the morphology and morphometry of channels, we averaged values of parameters from 37 stream reaches to respectively 8 channels (Fig. 1). In statistical analysis, we used values from 37 stream reaches.

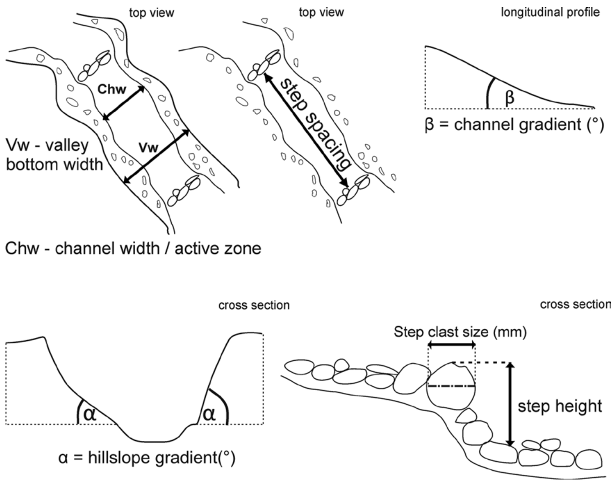

Fig. 2. Schematic diagram of selected measurements, black arrows and Greek letters show the way of measurement.

DEM and DoD analyses

DEM analyses and map layouts were performed in ArcGIS Pro 3.1 (ESRI). We conducted DEM analyses based on a point cloud from 2016, obtained via ALS from Kotelnica Białczańska

Company (Białka Tatrzańska, Poland), which commissioned the overflight with the ProGea4d company (Kraków, Poland, Warchoł 2017). The ALS was made by the RIEGL VQ-580 scanner with a density of 50 points per m² and a vertical resolution of about 0.03 m. We calculated the drainage area based on DEM from 2016 and generated drainage lines for every channel reach defined during geomorphological mapping. Drainage lines were determined based on flow accumulation and flow direction using an eight-direction (D8) approach (Jenson & Domingue, 1988). The recognition of drainage lines and observations during fieldwork led us to know the directions of water flow on hillslopes and ski runs. Due to this, mapped channels were divided into two groups: (1) stream channels that do not drain ski runs, called later: channels unaffected by ski infrastructure, and (2) stream channels that drain ski runs later called affected by ski infrastructure.

DoD was performed based on the point cloud from 2016 (described earlier) and the point cloud from 2023 obtained via ALS from the Head Office of Geodesy and Cartography in Poland. Point cloud from 2023 has 4–6 points per m² and vertical resolution from 0.07 m to 0.15 m. We calculated DoD using the raster calculator in ArcGIS Pro software, following the method proposed by Wheaton et al. (2010). The important part of DoD analysis is to specify a minimum level of detection (minLoD). The minLoD determines which values indicate a real change and which may be attributed to the elevation error of individual DEMs (Buckley, Mitchell 2004, Blasone et al. 2014, Fidelus-Orzechowska et al. 2018, Winowski et al. 2022). To determine minLoD, we calculated root mean square error (RMSE), mean error (ME), and standard deviation of error (SDE), according to Höhle, Höhle (2009). Error analyses were calculated for reference points. As reference points, we selected 32 stable objects whose position and height remained constant over time. We selected reference points based on an analysis of available maps, DEMs, and field observations conducted in the area since 2016. After comparing values of error calculations (ME = 0.147, SDE = 0.085, RMSE = 0.169), as a minLoD, we chose the most conservative value, RMSE (0.169) at 95% confidence interval to obtain the most precise results (MinLoD = 0.331). RMSE as a minLoD was used in many works, for example, by Fidelus-Orzechowska et al. (2018), Piątek, Bernatek-Jakiel (2024), and Winowski et al. (2022).

Statistical analyses

We performed statistical analyses using Statistica 13 software (StatSoft). Data were used to generate Pearson correlations. For the statistical analyses, we used the parameters measured for the reaches. The data were also standardised, and part of it, depending on skewness, was logarithmised. A $p = 0.05$ level of significance was assumed. We generated Pearson correlations in two stages: (1) for all analysed channels and (2) for the two groups defined earlier.

Results

Morphology and morphometry of channels

In the study catchment, the dominant type of channel morphology is step-pool. Channels unaffected by ski infrastructure in the upper parts are dominated by hillslope processes and have a cascade channel (Channel 3) or colluvial channel morphology (Channels 4, 5, and 7). In this group, small landslides are common, which transport material laterally, into the channels (Fig. 3E). Channels affected by ski infrastructure (1, 2, 8) (Table 1) are generally characterised by more traces of erosion, particularly related to deep and lateral erosion (Fig. 3A, C). Channel 8, located near ski run 2, in parts where it receives a lot of water, forms bedrock sections that are several dozen metres long (Fig. 3C).

In terms of morphometry, the channels located on the northern hillslopes in the catchment are characterised by a larger catchment area, greater channel length, and lower channel gradient. The catchment area of the eight analysed channels varies considerably (Table 1). The length of the channels also differs, ranging from short headwater sections to much longer reaches. The channel gradient varies from $0.17 \text{ m} \cdot \text{m}^{-1}$ to $0.24 \text{ m} \cdot \text{m}^{-1}$. The hillslope gradient remains relatively similar across the study area (Table 1). The valley bottom and channel active zone widths vary significantly, with some channels exhibiting narrow, confined valleys and others being much wider. The average bed material size is generally similar in most

Table 1. Morphometry of analysed channels. SD is the standard deviation.

Channel ID	Number of Reaches	Drainage area	Length	Channel gradient	Hillslope gradient	Valley bottom width	Channel/active zone width	Bed material size	Number of steps	Step height	Step height SD	Step spacing (m)	Step spacing SD	Step clast size (mm)	Step per channel length	Channels with skiing impact
		[km^2]	[m]	[m · m^{-1}]	[°]	[m]		[mm]	[–]	[m]	[–]	[m]	[–]	[mm]	[–]	[–]
1	3	0.01	77	0.27	26.75	1.97	0.63	68	28	0.38	17.38	1.41	0.89	220	0.36	YES
2	5	0.02	192	0.24	35.48	2.74	0.98	74	69	0.39	15.69	2.83	1.91	380	0.34	YES
3	5	0.14	223	0.24	35.39	1.80	1.80	84	50	0.4	12.43	4.05	2.52	450	0.22	NO
4	6	0.07	438	0.17	31.13	3.47	0.72	68	55	0.38	21.51	4.59	1.72	230	0.13	NO
5	2	0.05	161	0.25	33.55	2.05	0.45	66	50	0.41	18.24	2.18	1.36	540	0.31	NO
6	5	0.08	295	0.23	30.41	2.94	0.78	61	137	0.31	12.94	1.98	1.70	350	0.46	NO
7	3	0.14	199	0.24	32.42	1.83	0.50	68	43	0.44	15.04	5.71	4.47	350	0.22	NO
8	8	0.18	645	0.18	33.36	3.59	1.80	84	286	0.39	22.91	2.10	1.22	730	0.44	YES

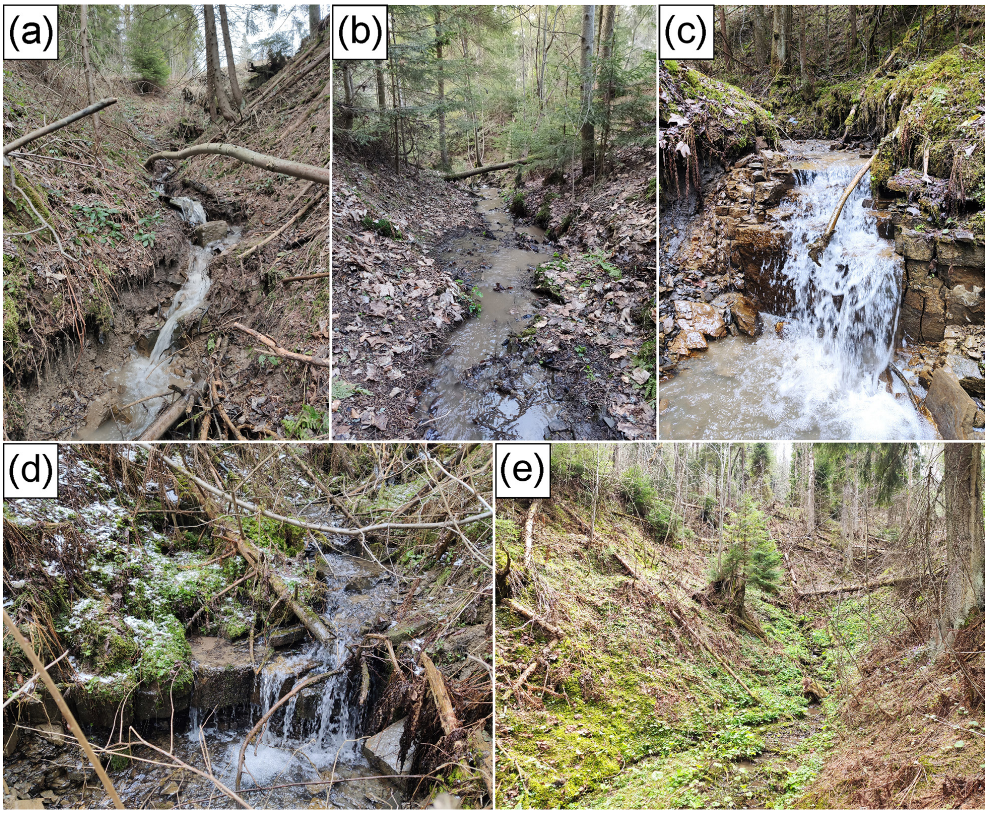

Fig. 3. Photographs of characteristic parts of analysed channels: A – a part of Channel 2 with traces of lateral and deep erosion, B – a part of Channel 4 with a relatively high gradient, C – a part of Channel 8 with a 0.6-m-high step below the rockfloor, D – a step with typical height for catchment, Channel 3, E – part of Channel 7, fulfilled with material from a small landslide visible in the left corner (photos: A. Gołąb and D. Piątek).

channels, except Channel 8, where intense headward and deep erosion, probably due to water inflow from ski run 2, has resulted in significantly larger material sizes. A total of 718 steps were measured in all channels. The average step height remains relatively uniform and ranges from 0.31 m to 0.44 m (Fig. 3D). The greatest differences in step height occur in Channel 8, which receives water from the largest area of the ski run, while the smallest variations are found in Channels 3 and 6, which are unaffected by ski infrastructure. Step spacing also varies, with the widest spacing occurring in Channel 7 and the smallest step spacing is in Channel 1, directly adjacent to ski run 1. The number of steps per unit of channel length differs slightly between the analysed channels. The highest values are found in Channels 6 and 8, while the lowest occurs in Channel 4. The largest clasts form steps in Channel 8, with an average size of 730 mm. It is the effect of fragmenting the rock floors, formed as a result of intensive erosion, into large debris, which, transported along the channel, forms new steps (Fig. 3C).

Statistical relationships between channel morphometrics

For all analysed channels, 27% of relationships (18 relationships) are statistically significant (Table 2). Most relationships are related to the hillslope gradient (5 relationships), the strongest correlation with bed material size (Fig. 4A). Hillslope gradient is also positively correlated with step clast size, channel width, and negatively correlated with valley bottom width. Channel gradient relationships are significant with drainage area (Fig. 4B) and with valley bottom width. The strongest correlation in this group is the relationship between bed material size and step clast size (Table 2).

In correlation with parameters from channels unaffected by ski runs, a total of 21% of relationships (14 relationships) are statistically significant (Table 3). The most correlations are with step clast size (four relationships, the strongest relation with hillslope gradient) (Fig. 5A). Significant correlations are between hillslope gradient and valley width and between the number of steps and the step spacing (Fig. 5B).

In the correlation of parameters from channels affected by ski runs, a total of 20% of relationships (13 relationships) are statistically significant (Table 4). The most correlations are with the drainage area (five relationships), the strongest relation with the number of steps, and the distinctive negative correlation with the channel gradient (Fig. 6A). There are some significant correlations between the number of steps and the

Table 2. Correlation matrix of parameters from all analysed channels. Red marked statistically significant values.

Variable	Bed material size	Step clast size	Hillslope gradient	Channel gradient	Step height avg.	Step height SD	Step spacing Avg.	Step spacing SD	Number of steps	Channel/active zone width	Valley bottom width
Bed material size											
Step clast size	0.712										
Hillslope gradient	0.482	0.390									
Channel gradient	0.213	-0.063	0.263								
Step height avg.	0.147	0.044	0.388	0.253							
Step height SD	0.080	0.044	0.220	0.049	0.713						
Step spacing avg.	–0.063	–0.256	0.075	–0.032	0.393	0.058					
Step spacing SD	–0.208	–0.289	–0.090	–0.192	0.002	–0.273	0.629				
Number of steps	–0.076	0.278	–0.071	–0.259	–0.380	–0.047	–0.652	–0.135			
Channel/active zone width	0.321	0.368	0.383	–0.153	0.071	0.036	0.021	0.076	0.128		
Valley bottom width	–0.159	–0.060	–0.365	–0.356	–0.184	–0.044	–0.143	0.115	0.355	0.091	
Drainage area	0.246	0.533	0.042	–0.592	–0.144	–0.131	0.050	0.206	0.397	0.374	0.231

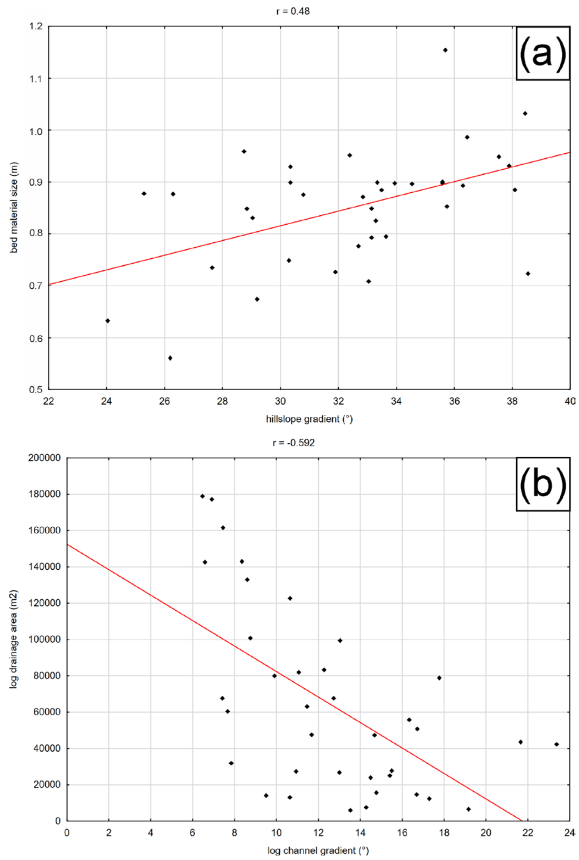

Fig. 4. Distinctive correlations in the group of all analysed channels (reach averaged data), A – hillslope gradient versus bed material size; B – channel gradient versus drainage area.

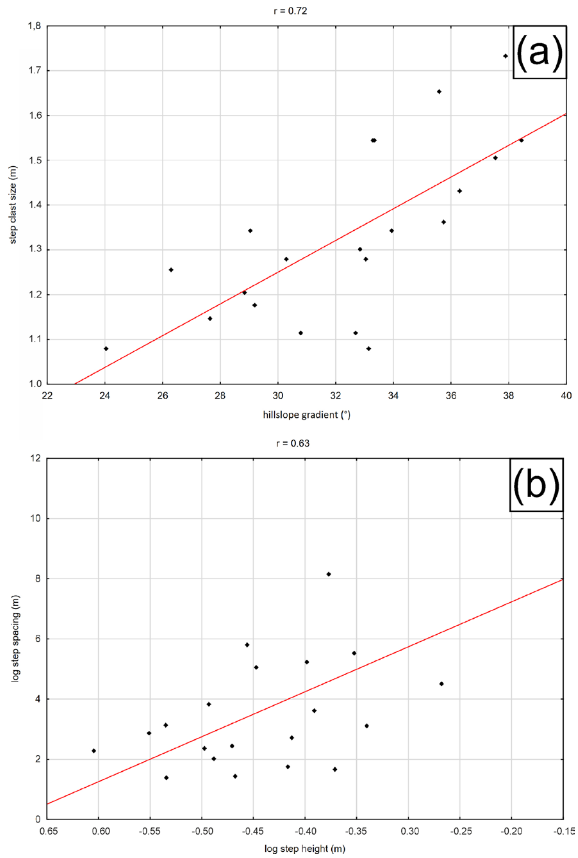

Fig. 5. Distinctive correlations in the group of channels without impact of ski runs (reach averaged data), A – hillslope gradient versus step clast size; B – step height versus step spacing.

Table 3. Correlation matrix of parameters from channels without impact of skiing. Red marked statistically significant values.

Variable	Bed material size	Step clast size	Hillslope gradient	Channel gradient	Step height avg.	Step height SD	Step spacing Avg.	Step spacing SD	Number of steps	Channel/active zone width	Valley bottom width
Bed material size											
Step clast size	0.678										
Hillslope gradient	0.705	0.716									
Channel gradient	0.108	0.030	0.399								
Step height avg.	0.184	0.005	0.406	0.175							
Step height SD	–0.037	–0.119	0.198	–0.053	0.626						
Step spacing avg.	–0.044	–0.299	–0.012	0.013	0.625	0.280					
Step spacing SD	–0.179	–0.282	–0.340	–0.096	0.172	–0.212	0.567				
Number of steps	–0.281	0.137	–0.267	–0.073	–0.578	–0.294	–0.799	–0.121			
Channel/active zone width	0.611	0.455	0.392	–0.028	0.079	–0.078	0.181	0.142	–0.190		
Valley bottom width	–0.304	–0.449	–0.773	–0.323	–0.326	–0.179	–0.085	0.222	0.165	–0.169	
Drainage area	0.285	0.430	0.053	–0.489	0.005	–0.326	0.121	0.440	0.051	0.333	0.003

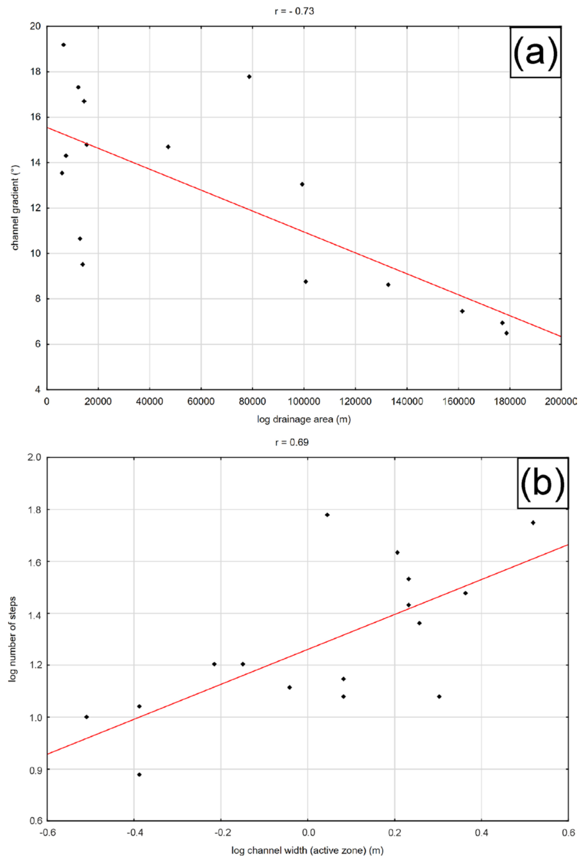

Fig. 6. Distinctive correlations in the group of channels affected by ski runs (reach averaged data), A – drainage area versus channel gradient; B – channel width versus number of steps.

channel gradient, the valley width (Table 4), and the channel width (Fig. 6B).

Estimation of changes in channels in the period 2016–2023

Analysing the changes in the ground level in all the studied channels, the results suggest a rise in all slopes of the valleys with a western aspect. This change has no confirmation in geomorphological processes or human impact and must be due to ALS errors and different angles during the ALS surveys. However, when analysing the bottoms of the channels, the changes are most clearly visible in Channel 8 (Fig. 7). Channels 1 and 2, classified as channels unaffected by ski infrastructure, during the study period have some sections marked by erosion of up to 0.7 ± 0.331 m along a maximum length of 6 m. (Fig. 8A) This is backward erosion and erosion associated with the formation of new small colluvial channels as tributaries to Channels 1 and 2 (Fig. 8A). Due to outflow from ski run 2, in Channel 8, we can observe significant lowering in the channel bed (Fig. 8B). The maximum value of lowering is observed in the upper part of the channel and exceeds 2.6 m. It is a part of the channel where three drainage ditches route water. This also indicates

Table 4. Correlation matrix of parameters from channels with impact of skiing. Red marked statistically significant values.

Variable	Bed material size	Step clast size	Hillslope gradient	Channel gradient	Step height avg.	Step height SD	Step spacing Avg.	Step spacing SD	Number of steps	Channel/active zone width	Valley bottom width
Bed material size											
Step clast size	0.718										
Hillslope gradient	0.269	0.098									
Channel gradient	0.342	–0.153	0.071								
Step height avg.	0.085	0.049	0.355	0.395							
Step height SD	0.116	0.082	0.235	0.188	0.862						
Step spacing avg.	0.158	0.000	0.616	–0.292	–0.081	–0.105					
Step spacing SD	–0.178	–0.219	0.429	–0.438	–0.308	–0.266	0.815				
Number of steps	0.027	0.333	0.188	–0.590	–0.142	0.111	0.058	0.100			
Channel/active zone width	–0.184	0.202	0.404	–0.474	–0.027	0.077	–0.013	0.247	0.695		
Valley bottom width	–0.092	0.295	0.331	–0.447	0.056	0.031	0.085	0.104	0.632	0.679	
Drainage area	0.224	0.599	0.033	–0.729	–0.307	–0.033	0.045	0.056	0.763	0.572	0.510

an intense head cut of the valley. Erosion exceeding an average of 1 ± 0.331 m and reaching a maximum of 2.6 ± 0.331 m occurs over a length of 41 m (Fig. 8B). After a short section of the channel with no change, there is a 240 m long section with an average lowering of the ground surface of 0.5 ± 0.331 m and a maximum of 1.7 ± 0.331 m (Fig. 8B). Below the new gullies with intensive erosion, Channel 8 is characterised by alternating deposition (average 0.6 ± 0.331 m and maximum 1.2 ± 0.331 m) and erosion (average 0.4 ± 0.331 m and maximum 1.5 ± 0.331 m) (Fig. 8B). The section below the ski run link is characterised by a dominance of deposition between 0.5 ± 0.331 m and 1 ± 0.331 m. Channel 8 enters the main stream channel with an intensively overbuilt alluvial fan with an area of 218 m². An average overbuild is 0.6 ± 0.331 m, and a maximum is 1.3 ± 0.331 m (Fig. 8B). In the channels described as channels unaffected by ski infrastructure, there is a limited change. Erosion is most common on the hillslopes and is associated with the formation of small landslides (up to 1 m of lowering) (Fig. 8C), which we often observed during fieldwork.

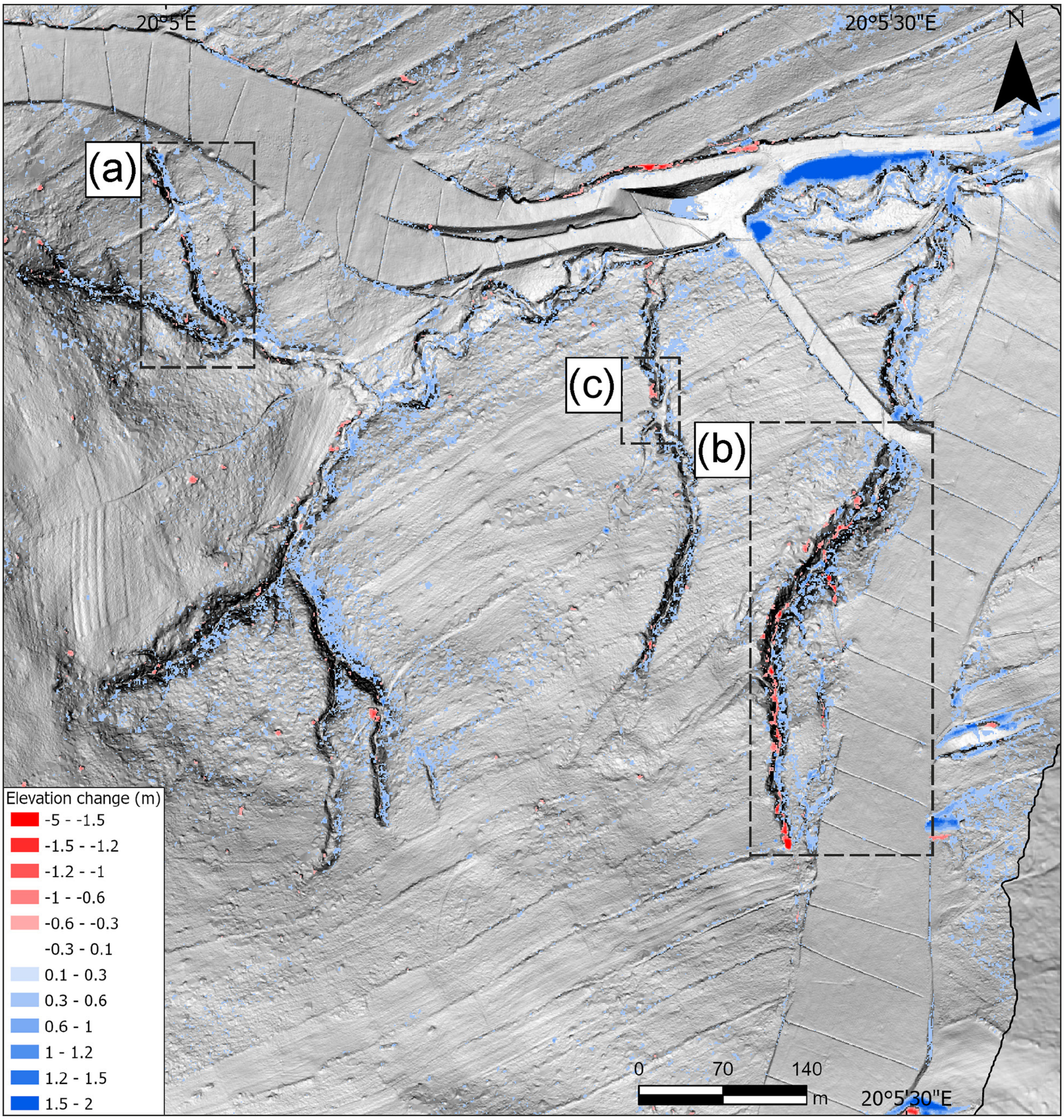

Fig. 7. Elevation changes in analysed channels in the period 2016–2023, in rectangle areas presented in Figure 8.

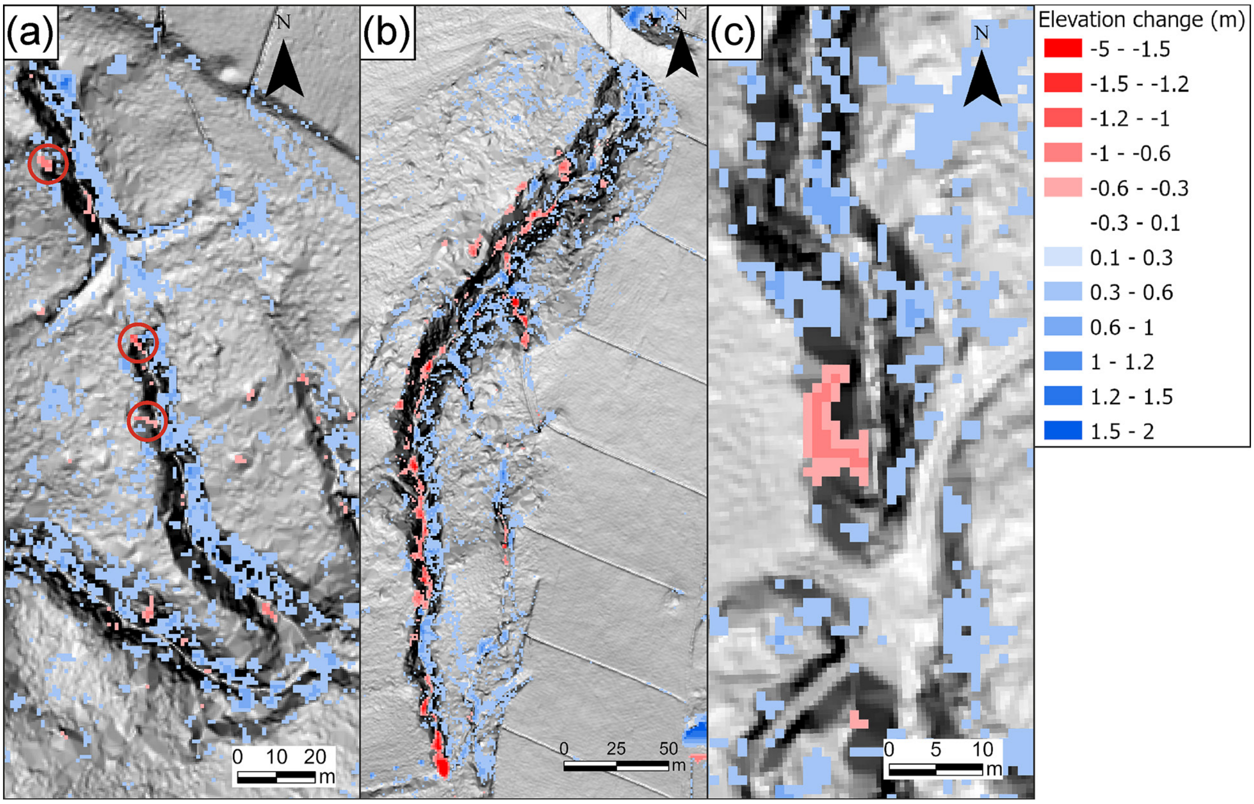

Fig. 8. Close up on areas with elevation changes marked with rectangles on Figure 7; A – close up on Channel 2, in red rings marked results of headward erosion; B – close up on Channel 8 with zones with erosion and deposition; and C – close up on a small landslide on hillslopes of Channel 4.

Discussion

A comparison of the morphometric parameters of channels impacted and not impacted by ski infrastructure does not indicate significant differences between them. However, as shown in fieldwork and DoD analysis, the channels that drain ski runs have a significantly higher number of erosion forms, such as undercuts of lateral erosion or traces of deep erosion. Fresh traces of erosion as a result of water drainage from ski runs were observed in channels in the Rocky Mountains – lateral erosion (David et al. 2009) and in the Gubałowskie Foothills – deep erosion and headward erosion (Wrońska-Wałach et al. 2019, Piątek, Bernatek-Jakiel 2024). David et al. (2009) reported that the discharge of water from the ski runs into the channels increases the share of fine material in the channels. In our study, no such relationship was observed. Moreover, Channel 8, which has the biggest drainage area, is characterised by the largest bed material size and step clast size. This is the result of intensive deep and headward erosion in this channel, up to 2.6 m. Remarkably, there are more steps in the transformed channels (Channels 1, 2, and 8), and they occur more frequently per channel length. Only one channel unaffected by ski infrastructure (Channel 6) has a similar ratio. The higher number of steps is probably the result of greater fluvial process activity due to the greater amount of water from snow, draining into the channel from the ski runs. As indicated by works for this type of channel (e.g., Montgomery, Buffington 1997, Chin, Wohl 2005), the formation of steps is related to reductions in the erosive power of the stream. In the study area, a higher number of steps indicates an adaptation of the system to new environmental conditions (a much higher snow cover on the slopes from artificial snowmaking [Wrońska-Wałach et al. 2019]). The lack of significant differences in morphometric parameters between the analysed groups of channels suggests that not enough time has passed for changes in environmental conditions to significantly impact the channel forms. The presence of statistically significant relationships suggests that changes may be occurring but are not yet reflected in the measured parameters. The literature points out that a lack of typical correlations or changes in channel morphology, despite statistical relationships, could be due to imperfect morphological adjustments in step-pool bedforms (Chin 1999, Lenzi 2001), especially with external factors such as vegetation and bedrock outcrops (Furbish 1998). In our study, this external influence is the influence of ski infrastructure manifested by a significant increase in the snow cover and therefore the amount of water from snow melting and flowing in channels. It should be noted that the greatest number of correlations with the drainage area are observed in the group of channels affected by ski infrastructure (five correlations, mostly rather strong, only two weaker correlations in the group of channels unaffected by ski infrastructure). It suggests that processes connected with water flow determine the morphology of channels in this group. This can be confirmed by the fact that we observed a noticeable difference between the number of correlations with the bed material size and the step clast size in both analysed groups. In the group of channels without the impact of ski runs, there are six correlations with the size of the material, while in the second group, there are only two correlations. It shows that the bed material size, step material size, and moreover valley bottom width depend on hillslope gradient and generally hillslope processes only in non-affected channels. This reflects the influence of hillslope processes, indicating that the intensity of slope processes in this area typically exceeds that of fluvial processes. Correlations in a group of channels affected by ski infrastructure indicate that water from snowmaking drained into the channels has changed this relationship, and fluvial processes are dominant, leading to intense erosion and channel deepening. These relationships can be proved by the results of DoD analysis. As DoD analysis showed, only erosion changes in a group of channels unaffected by ski infrastructure are an effect of hillslope processes – landslides. On the contrary, DoD analysis in a group of channels impacted by ski infrastructure reflects very intensive headward and deep erosion, especially in Channel 8. In this channel, intensive erosion leads to the creation of high rock steps (up to 1.5 m). Comparing the typical statistical relationships of the morphometric parameters in the group of channels with affected by ski infrastructure and in the group unaffected by ski infrastructure in this study with the relationships reported in the literature (Heede 1972, 1981, Montgomery, Buffington 1997, Wohl et al. 1997, Billi et al. 1998, Chin 1999; Chartrand, Whiting 2000, Chin, Wohl 2005, Nickolotsky, Pavlowsky 2007), the channels unaffected by ski infrastructure show more of the typical step-pool statistical relationships. These are positive correlations between channel gradient and number of steps, channel width and drainage area, clast size and drainage area, and a negative correlation: channel gradient and drainage area. In a group of channels unaffected by ski infrastructure, only correlation occurs between step spacing and step height (positive) and negative correlation: channel gradient – drainage area. It is significant that, without dividing channels into groups, there are no strong correlations. The channels affected by ski infrastructure, apart from more correlations, also show more typical relationships for step-pool channels. This confirms that the drainage of water from the ski runs has made fluvial erosion more active in these channels and that the development of the channels tends towards a more typical step-pool morphology, which is less characteristic of unaffected channels in this part of the Gubałowskie Foothills. This study was conducted 6 years later (in 2023) than the study described by Wrońska-Wałach et al. (2019) (conducted in 2017 and 2018). It indicated that the change in the position of the channel heads 2 years after the launch of the ski station (launched in 2015) intensify erosion in the lower parts of the channels in the future and may lead to the disappearance of some processes (Wrońska-Wałach et al. 2019). Our study conducted 8 years after the launch of the ski station and 5 years after the study by Wrońska-Wałach et al. (2019) confirms the conclusions made there. It proves a significant intensification of erosion in channels that drain ski runs and indicates a significant decrease in the importance of slope processes in favour of domination of fluvial processes. Our study is a good example of how the drainage of ski runs using drainage ditches, which reduces erosion on the ski run surface and leads to erosion outside the ski runs. It was observed earlier in the Pyrenees (Furdada et al. 2020), Mont Dore (Krzemień 1997), the Polish

Carpathians (Fidelus-Orzechowska et al. 2018, Wrońska-Wałach et al. 2019, Piątek, Bernatek-Jakiel 2024), and in the Rocky Mountains (David et al. 2009). However, this is the first study to show how routeing drainage from ski runs with intensive artificial snowmaking into a network of channels leads to intensive erosion and changes the morphology and morphometry of mountain stream channels.

Conclusions

In our study, we analysed the changes in erosion that occurred in the channels of streams that drain the ski runs with artificial snowmaking compared to the channels without such influence in the same small catchment in the Polish Carpathians. The obtained results allow us to conclude that the routing of drainage from the ski runs to the channels in their surroundings leads to a significant intensification of deep and backward erosion in the channels. Maximum erosion reached up to 2.6 m in 7 years. It was -37 cm $\cdot$ year^{-1}. It also led to deposition up to 1.3 m in the analysed period (+19 cm $\cdot$ year^{-1}). The research also indicates a change in the dominant geomorphological processes in the channels. In the study catchment, the morphology of the channels that do not drain the ski runs is dominantly influenced by hillslope processes. The influence of ski infrastructure, manifested by water from artificial snow reaching the channels, leads to the dominance of fluvial processes. As far as we know, our study is the first work that shows how routing drainage from ski runs with intensive artificial snowmaking into a network of channels leads to intensive erosion and changes the morphology and morphometry of stream channels in headwater areas. When we compare our results with the intense growth of ski resorts and the increasingly frequent lack of snow, we observe that ski infrastructure significantly contributes to environmental degradation. It is resulting in both quantitative changes in stream channels and modifications in the processes and functioning of the headwater areas environment. Furthermore, it should be noted that in the study area, these changes have already taken place 8 years after the opening of the ski station and are still being monitored.

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Author's contribution

D.P.: conceptualization, validation, formal analysis, investigation, data curation, writing – Original Draft, writing – review & editing, visualization, supervision, project administration, funding acquisition; A.G.: investigation, data curation; D.W.-W.: conceptualization, writing – Original Draft, writing – Review & Editing, supervision.

Conflict of interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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