Magnitude of sediment transport due to extreme windthrow event in small catchments in the Tatra Mountains

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INTRODUCTION

Forested landscapes for a long time were expected to be geomorphologicaly stable, with low intensity of slope processes, and, thus low denudation rate. In the recent years, however, geomorphic role of trees, especially tree uprooting, is increasingly acknowledged. Both in a form of single uprooted trees or large windthrow events it entails many environmental consequences including the changes in the relief of slope, mixing of soil and sediment transport. Recently increasing number of studies concentrate on geomorphic role of uprooting, however, few of them have reported catchment-scale consequences of this process. Also, there is lack of comparison of tree uprooting with other geomorphic processes (e.g. shallow landsliding) which could be helpful in understanding the importance of trees in denudation and soil mixing.

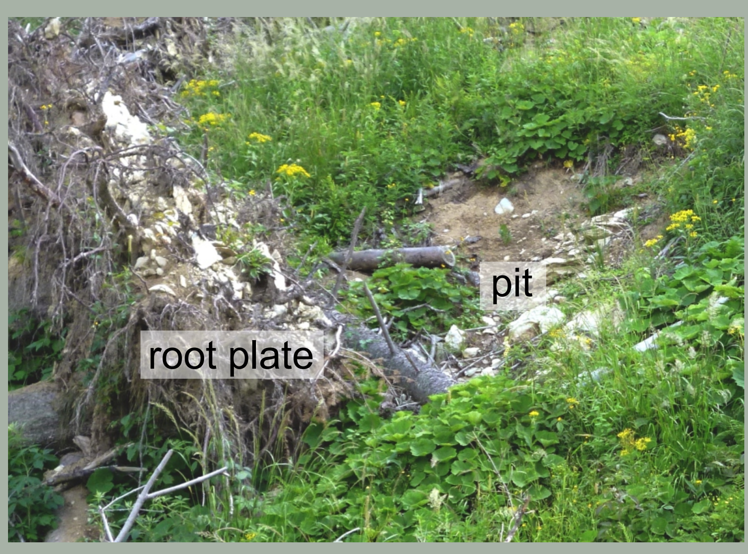

Fig 1. Root plate and pit resulting from tree uprooting.

Aim

In this study an attempt of quantifying the catchment-scale geomorphic consequences of an extreme windthrow event which had led to the destruction of significant proportion of forest stand, is conducted. The main goal was to quantify sediment flux due to uprooting for 3 catchment severely affected by uprooting and to compare the result with the sediment flux generated by a mass movement event which had occurred in the same catchments 6 years before windthrow.

STUDY AREA

Study was conducted in the Tatra Mountains, an alpine-type range in Southern Poland. 3 second- to third-order catchments located in the lower part of the Tatras were investigated.

Catchment's characteristics:

- bedrock composed of limestone and conglomerate (Bac-Moszaszwili et al., 1979)
- altitude 933-1334 m a.s.l., average slope inclination 28°
- thin, up to 1m deep soils, mostly Eutric Cambisols and Cambic-Rendzic Leptosolssoils (Skiba, 2002)
- annual rainfall at the rate of 1000-1400 mm, mean annual temperature 4-6°C (Hess, 1974)
- spruce-dominated forest

Investigated events:

- severe windthrow event on 25 December 2013 - extensive windthrow areas were created
- intense rainfall event in June 2007 - during one day 10% of mean annual rainfall occurred which triggered many shallow landslides

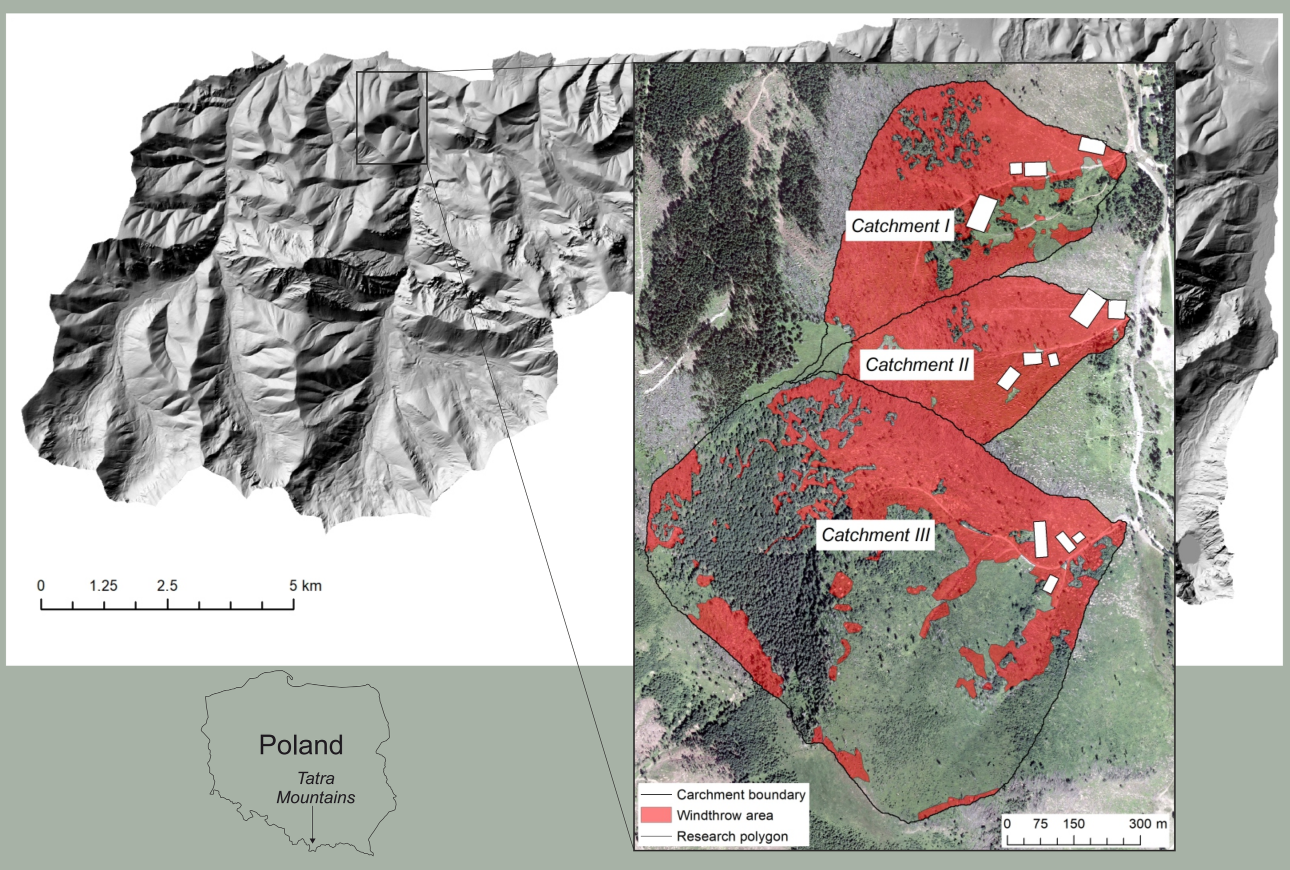

Fig 2. Location of three investigated catchments.

METHODS

1. GIS analysis

Mapping windthrow area

Windthrow areas created during the event in December 2013 were mapped based on an orthophoto taken in July 2015. An orthophoto taken in August 2012 was used to exclude each windthrow-affected existing in 2012.

Mapping all root plates

Within each investigated catchment all uprooted trees located within mapped windthrow areas were identified based on high-resolution orthophoto (4 cm) created using a UAV in 2019.

Directions of fallen trees

Directions of fall for the mapped uproots were determined. Because of local decreases in the quality of imageries the directions were mapped for 82, 84, and 72% of the mapped uproots in catchment I, II, and III, respectively.

Fig. 3. Orthophotos used to map windthrow area and individual root plates within the studied catchments.

2. Field work

Field survey was conducted in 2015 and 2019. Within each catchment 4-5 research polygons were selected (Fig. X), and the dimensions (width, height and depth) (Fig. X) of all root plates located within them were measured.

Fig. 4. Measured root plate dimensions.

Using formula proposed by Norman et al. (1995), volume of each root plate was calculated as follows:

$$V = \pi whd/6$$

where w is width, h is height, and d is depth of a root plate. Also area of each root plate was calculated based on:

$$A = \pi wh/4$$

3. Calculations

Volume of sediment uplifted by uprooting

Total volume of sediment uplifted during windthrow event was estimated by multiplying the amount of mapped root plates and mean root plate volume. It was assumed that the proportion of sediment within each root plate is 50%.

Transport distance

Proportion between upslope and downslope uproots was established. Upslope (x_u) and downslope (x_d) transport distance was calculated using Gabet's et al. (2003) equations.

$$x_u = 2/\pi(w_m/2(\cos\theta - \sin\theta) - d_m/2(\cos\theta + \sin\theta)) \qquad x_d = 2/\pi(w_m/2(\cos\theta + \sin\theta) + d_m/2(\sin\theta - \cos\theta))$$

w_m - mean width of a root plate d_m - mean depth of a root plate θ - slope inclination

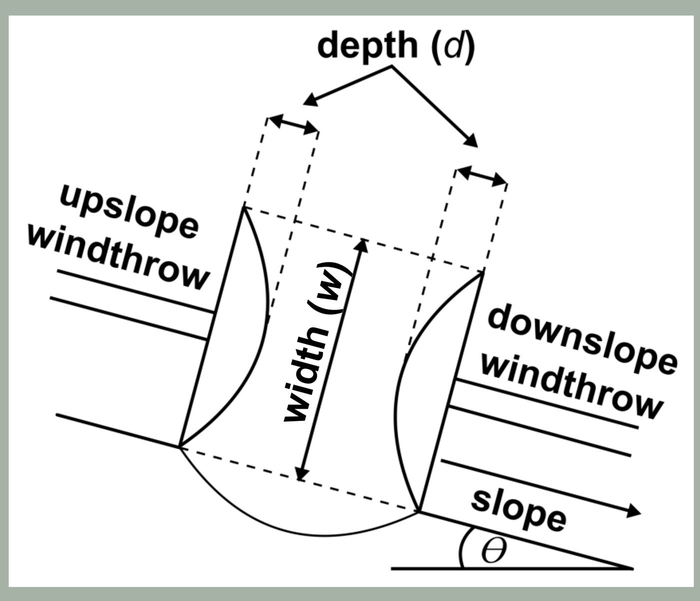

Fig. 5. Scheme presenting parameters used to calculate transport distance for upslope and downslope windthrows. Based on Gabet et al. (2003).

Sediment flux by uprooting

Net sediment flux by the windthrow event in 2013 was calculated for each catchment by subtracting upslope sediment flux from downslope sediment flux.

$$q_{sx2013} = (V_d/A\ x_d) - (V_u/A\ x_u)$$

V_d - the volume of sediment transported downslope V_u - the volume of sediment transported upslope A - the area of a catchment

4. Sediment flux by mass movement event in 2007

Extreme rainfall event occurred in the investigated catchments in 2007 (Gorczyca et al. 2014). Thanks to the data shared by E. Gorczyca and K. Krzemień it was possible to identify within the Digital Elevation Model (DEM; 1 m resolution) each landslide created during that event. The extent of all landslides that occurred in catchments I, II, and III was precisely determined and the surface area of landslides was calculated. Based on analysis of the Digital Elevation Model volume of displaced sediment and transport distance for each landslide were determined. Finally sediment flux by shallow landsliding event for each catchment was calculated.

$$q_{sx2007} = V_L/A\ x$$

V_L - total volume of sediment transported by landslides in a given catchment A - catchment area x - mean transport distance by landsliding

RESULTS

Tab. 1. Field survey results.

	Catchment I	Catchment II	Catchment III	Total
Area of research polygons (m^2)	0.76	0.74	0.41	1.91
Number of measured root plates (n)	81	82	48	211
Mean root plate area (m^2)	4.08	3.38	2.96	3.55
Mean root plate volume (m^3)	2.09	1.96	1.20	1.84

Tab. 2. Characteristics of the windthrow created in 2013.

	Catchment I	Catchment II	Catchment III
Area of catchment affected by windthrow (%)	76	94	34
Number of uprooted trees in catchment (n)	1553	1269	1828
Total amount of uplifted sediment ($m^3\ ha^{-1}$)	61.8	77.7	13.6
Proportion of trees fallen downslope (%)	75	83	47
Proportion of disturbed catchment area (%)	4.8	5.4	1.3
Sediment flux ($m^3\ m^{-1}$)	3.5 × 10-3	4.9 × 10-3	5.0 × 10-4

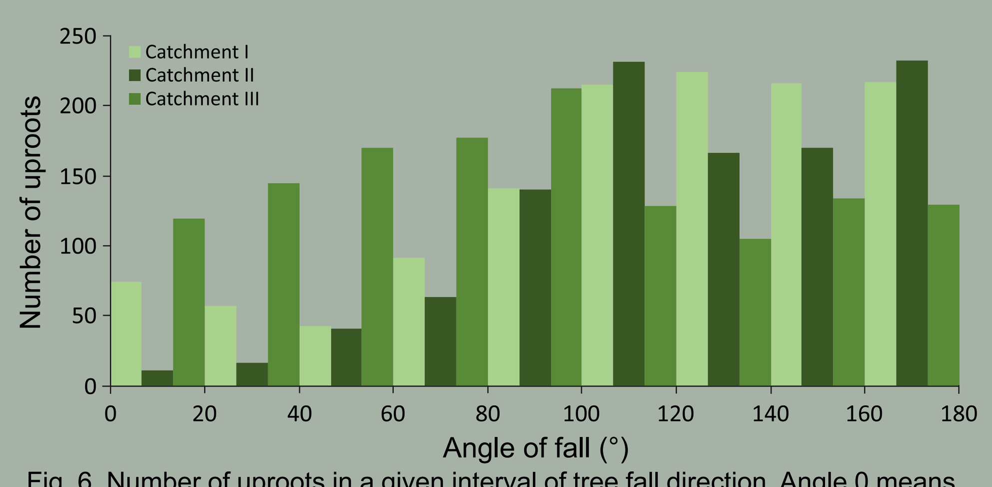

Fig. 6. Number of uproots in a given interval of tree fall direction. Angle 0 means directly upslope, angle 180 means directly downslope.

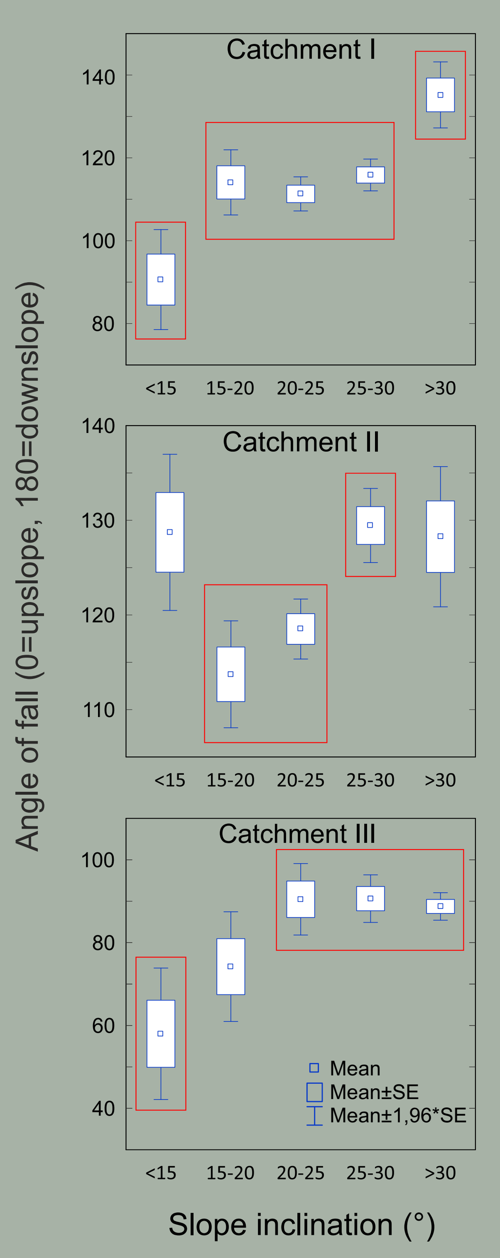

Fig. 7. Analysis of variance showing differences of the mean tree fall direction between different slope inclination intervals. Angle 0 means directly upslope, angle 180 means directly downslope. Scheffe Test, p = 0.05.

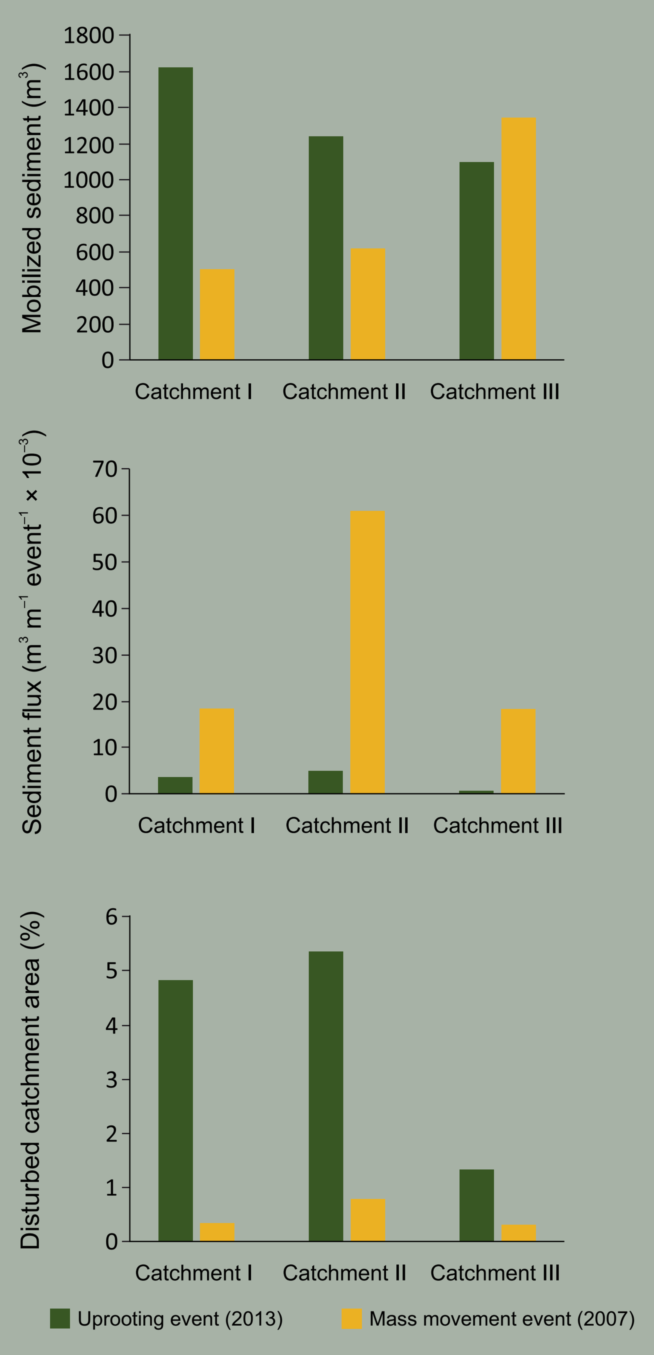

Fig. 8. Comparison of different geomorphic consequences of windthrow event in 2013 and mass-movement event in 2007 in three investigated catchments.

CONCLUSIONS

- In the investigated catchments 34-94% of their area was affected by windthrow event
- 13.6-77.7 m^3 of sediment per ha was uplifted
- Most of the trees were fallen downslope, slope inclination had positive effect on the proportion of downslope uproots
- Sediment flux by windthrow event ranged from $5.0 \times 10^{-4}\ m^3\ m^{-1}\ event^{-1}$ up to $4.9 \times 10^{-3}\ m^3\ m^{-1}\ event^{-1}$
- The amount of sediment mobilized by uprooting event in 2013 was slightly higher than the amount of sediment mobilized by shallow landsliding in 2007
- Sediment flux due to shallow landsliding in 2007 was at least one order of magnitude greater than sediment flux by uprooting in 2013
- Windthrow pits and root plates resulting from windthrow event in 2013 affected substantially higher proportion of each catchment than shallow landslides created during extreme rainfall in 2007
- While landslides appear to be far more effective in sediment transport than tree uprooting the latter is probably one of the most important factors causing soil mixing

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