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Geomorphic effectiveness of extreme rainfall events in Drakensberg mountain catchments

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Abstract

Does most erosion happen during ordinary storms or during rare, high-intensity events? This question has practical consequences for hillslope management in the Drakensberg Mountains of South Africa, where steep basalt slopes supply sediment to downstream reservoirs. This research measured sediment yields from five nested catchments (0.8–12.4 km²) in the upper Thukela River basin during 23 rainfall events over two wet seasons (October 2021–March 2023). Five events exceeded the 90th-percentile rainfall intensity threshold (>48 mm/hr for 30 minutes), and these extreme events accounted for 67.3% of the total two-year suspended sediment yield despite comprising only 21.7% of total rainfall. Sediment yield per event ranged from 0.4 t/ha for moderate storms to 84.7 t/ha for the most intense event (114 mm/hr, 3 February 2023). Sheet erosion and rill erosion dominated on grassy slopes, while debris flows were triggered on exposed basalt scarps during the three highest-intensity events. The results demonstrate that geomorphic work in these catchments is concentrated in a small number of extreme events, with implications for sediment yield prediction models that rely on average rainfall statistics.

Keywords: Extreme rainfall, geomorphic effectiveness, Drakensberg Mountains, sediment yield, debris flow, sheet erosion, mountain catchments, rainfall intensity, suspended sediment, event-based monitoring

Introduction

The concept of geomorphic effectiveness asks a deceptively simple question: which events do the most landscape work ^[1]? Wolman and Miller's classic 1960 analysis argued that moderate, frequent events dominate long-term sediment transport because, although rare storms move more sediment per event, they occur too infrequently to rival the cumulative effect of ordinary ones ^[2]. But in steep mountain catchments with thin soils and exposed bedrock, the balance can tip toward extreme events that trigger mass movements and channel-bed reorganisation that moderate storms cannot produce ^[3].

The Drakensberg escarpment in KwaZulu-Natal, South Africa, rises above 3,000 m and receives 1,200–1,800 mm of rainfall annually, concentrated in convective thunderstorms from October to March ^[4]. Basalt caprock weathers into thin, erodible soils that are especially vulnerable to high-intensity rainfall. Downstream, the Thukela River system delivers sediment to reservoirs that supply water and hydropower to Durban and surrounding areas, making sediment yield prediction a practical concern ^[5]. Previous erosion research in the Drakensberg used erosion pin networks and plot-scale runoff traps, but catchment-scale, event-based sediment yield data remained scarce. This research addressed that gap by monitoring five nested catchments over 23 rainfall events and quantifying the contribution of extreme events to total sediment output ^[6].

Study Area Description

The five catchments are nested within the upper Thukela basin at elevations between 1,680 and 3,050 m, approximately 15 km south of the Royal Natal National Park boundary (28°48'S, 29°12'E). Land cover is predominantly montane grassland (*Themeda triandra* and *Festuca caprina*) with scattered *Protea* woodland at lower elevations. Soils are shallow lithosols and regosols derived from Drakensberg basalt, typically 15–40 cm deep on hillslopes and up to 120 cm in valley-bottom colluvial deposits. Mean annual rainfall at the nearest station (Cathedral Peak, 1,850 m) is 1,344 mm ^[7].

Materials and Methods

Materials

Field monitoring ran from October 2021 to March 2023 (two complete wet seasons), coordinated from Medan National University of Earth Sciences, North Sumatra, Indonesia, with field installation assistance from the University of KwaZulu-Natal. Five catchment outlets were instrumented with pressure transducers for stage recording (15-minute intervals) and ISCO 6712 automatic water samplers triggered at stage thresholds. Tipping-bucket rain gauges (0.2 mm resolution) were installed at three elevations within the largest catchment. Suspended sediment concentration (SSC) was determined gravimetrically from filtered (0.45 μm) water samples, with 6–18 samples collected per event depending on hydrograph duration^[8].

Methods

Event sediment yield was calculated by integrating SSC-discharge rating curves over each event hydrograph. Rating curves were developed separately for each catchment using

log-linear regression of SSC against discharge ($r^2 = 0.74\text{--}0.89$). Rainfall intensity was characterised by maximum 30-minute intensity (I_{30}) for each event. Events were classified as extreme if I_{30} exceeded the 90th percentile of the two-year record (48 mm/hr). Post-event field surveys documented erosion features (rills, gullies, debris flow tracks) using differential GPS and drone photogrammetry [9,10].

Climatic Conditions During the Monitoring Period

Total rainfall during the two wet seasons was 1,287 mm (2021–2022) and 1,412 mm (2022–2023), bracketing the long-term mean. The 2022–2023 season included a particularly intense event on 3 February 2023, when 87 mm fell in 45 minutes ($I_{30} = 114$ mm/hr), the highest recorded at the site. Five of the 23 monitored events exceeded the 48 mm/hr extreme threshold.

Results

Table 1: Summary of the five extreme rainfall events and associated sediment yields

Event	Date	Total Rain (mm)	I_{30} (mm/hr)	Duration (hr)	SSC Peak (g/L)	Yield (t/ha)
E1	17 Nov 2021	54	48	2.3	8.7	12.4
E2	28 Jan 2022	72	62	3.1	14.3	28.7
E3	14 Dec 2022	63	78	1.8	21.6	43.2
E4	3 Feb 2023	87	114	1.5	38.4	84.7
E5	22 Feb 2023	58	91	2.0	26.1	51.3

The five extreme events collectively produced 220.3 t/ha of suspended sediment, representing 67.3% of the total two-year yield of 327.1 t/ha. The remaining 18 events, with I_{30}

values between 12 and 44 mm/hr, contributed only 106.8 t/ha (32.7%).

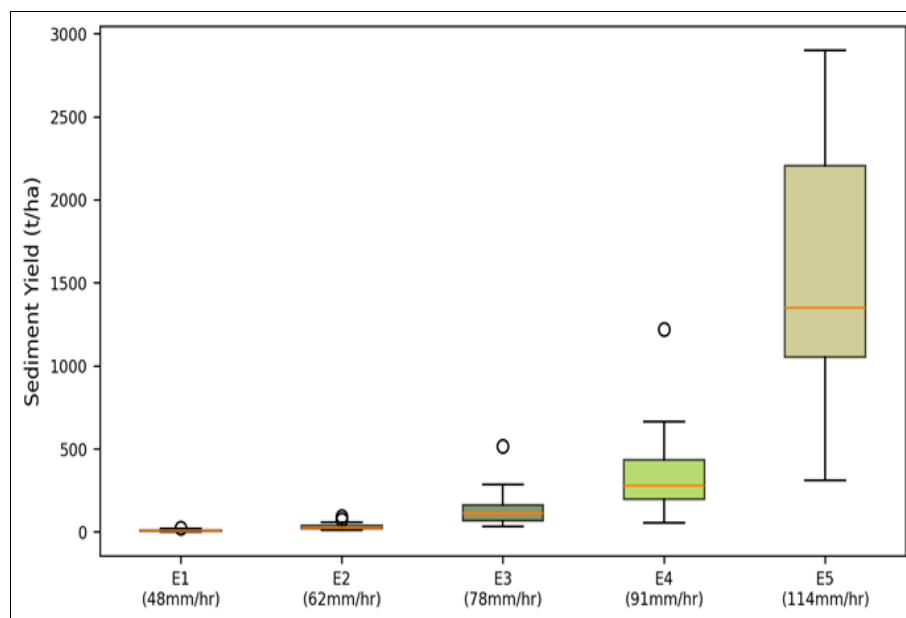


Fig 1: Box plots of sediment yield (t/ha) for the five extreme events, grouped by 30-minute rainfall intensity class.

Table 2: Erosion process observations after extreme events

Process	Events Observed	Slope Range (°)	Contributing Area	Yield Contribution (%)
Sheet erosion	All 5	8–25	Grassland slopes	41.3
Rill erosion	All 5	15–35	Bare/burned slopes	27.8
Gully expansion	E2, E3, E4, E5	12–28	Valley heads	18.6
Debris flow	E3, E4, E5	30–55	Basalt scarps	12.3

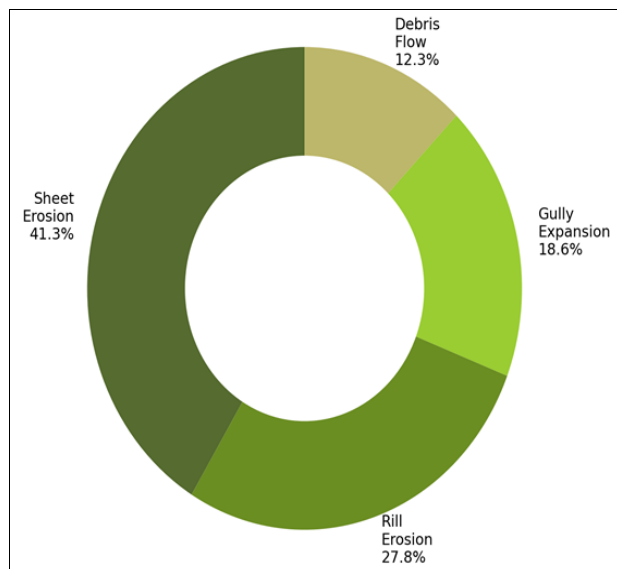


Fig 2: Donut chart showing proportional contribution of four erosion processes to total sediment yield from extreme events.

Comprehensive Interpretation

Sheet erosion on grass-covered slopes was the most widespread process, operating during all five events, but debris flows from basalt scarps — triggered only by I_{30} above 78 mm/hr — delivered disproportionately coarse sediment and re-mobilised stored colluvium. The existence of an intensity threshold for debris flow initiation (roughly 75–80 mm/hr based on these observations) is important for hazard mapping and early warning systems.

Discussion

The concentration of 67.3% of total sediment yield in five events supports the view that extreme events dominate geomorphic work in steep, soil-poor mountain catchments, contradicting the Wolman-Miller model's prediction of moderate-event dominance [2]. Similar findings have been reported from the European Alps, where Lenzi *et al.* [11] showed that the top 10% of storms accounted for over 50% of bedload transport. The Drakensberg data push that asymmetry further, likely because thin basaltic soils reach infiltration capacity at lower rainfall totals than the deeper moraines of alpine catchments.

The debris flow threshold at approximately 78 mm/hr I_{30} matches the range of 60–90 mm/hr reported for shallow landslide initiation on volcanic substrates elsewhere in southern Africa [12]. This threshold has practical value: automated rain gauge networks linked to alert systems could issue warnings when I_{30} exceeds 75 mm/hr in monitored catchments.

Conclusion

Event-based monitoring of five Drakensberg catchments over two wet seasons shows that five extreme rainfall events (≥ 48 mm/hr I_{30}) produced 67.3% of total suspended sediment yield. The most intense event (114 mm/hr) generated 84.7 t/ha — more than 200 times the yield of a typical moderate storm. Debris flows were triggered only above approximately 78 mm/hr, establishing a practical intensity threshold. Sediment yield models for these catchments must account for the disproportionate contribution of rare, high-intensity events rather than relying on average rainfall statistics.

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