Reworking of a Rock Flow by Gullying, East Coast Region, New Zealand

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Abstract

Gullying is a common process in the mountainous areas of the East Coast Region, New Zealand, causing serious environmental damage. We analyze gully development into a rock flow between 1939 and 1997 and relate gully activity to topographic thresholds and to major rainfall events ($>150\text{mm/day}$). Aerial photographs of the years 1939, 1957, 1971, 1981, 1984, 1988, and 1997 were orthorectified to measure active gully extent for each time slice. A digital elevation model was constructed to measure catchment slope and areas for topographic threshold values.

The 1.3km$^2$ rock flow is located in the East Coast Region, New Zealand and is comprised of Late Cretaceous to Paleocene highly crushed and sheared mudstones. Average annual rainfall is 2400mm dominated by frequent but irregular storm events. By 1920, European settlers had deforested the study area and established pastures.

Ten gullies were identified in the study area covering 16.7ha or 13\% of the study area at their maximum extent. Gullies were classified in two groups according to their peak activity. Gullies of the first group exhibit their peak activity by 1988, after Cyclone Bola, the highest event on record. Catchments of this group were larger than 10ha. Cyclone Bola in 1988 generated enough overland flow to increase gully extent within this first group, as the veneer soil layer is saturated by the short-term major rainfall events in such steep mountainous topography. The second group showed their peak activity either on the 1957 or 1971 aerial photographs. Cyclone Bola could reactive the larger catchments of this group (4.4ha–9.6ha), whereas smaller ones were not active located at the foot slope of the rock flow. Next to rainfall induced overland runoff, the gullies of the second group might be also affected by sapping from the rock flow during prolonged, lower-intensity rainfall periods such as during the 1950s.

The topographic threshold approach has been successfully used to predict gully development for undisturbed hill slopes, but might not equally apply to disturbed catchments characterized by additional runoff supply, as shown in this study for (the foot slope of the investigated) rock flows. This implies that the geomorphic history of a site needs to be considered when predicting the locations of gully initiation and gully development.

Keywords: gully erosion, rock flow, topographic threshold, major rainfall event

Introduction

Gullying is a common process in the mountainous areas of the East Coast Region, North Island, New Zealand causing serious environmental damage such as soil loss (Allsop, 1973, Harmsworth et al., 2002) and damage to infrastructure (Rau, 1993). Gully erosion is favored by the combination of bedrock susceptible to gully erosion, mountainous topography, extreme rainfall events, and land use changes. Most gullies in this geomorphologically highly active region were initiated between the end of the 19\textsuperscript{th} and early 20\textsuperscript{th} century triggered by clear-cutting of indigenous forest by European settlers for pastoral farming (Harmsworth et al., 2002, Gomez et al., 2003) followed by a period of greatly accelerated erosion.

Medium-term gully system activity in the East Coast Region between 1939 and 1992 was estimated using sequential aerial photographs (DeRose et al., 1998, Betts and DeRose, 1999, Gomez et al., 2003). These studies indicated increased gully activity between 1939 and 1958 followed by decreased activity attributed to large scale afforestation programs.

Various gully system types were identified in the East Coast Region. Gullies with linear shape occupy topographically convergent areas in unchanneled zero-order basins. Small-scale mass failures at gully heads (Bull and Kirkby, 1997) also contribute here to gully expansion. For gullies developing in undisturbed substrate, Parkner et al. (in press) showed that gullies, which developed in bedding orientation, exhibit higher topographic threshold values (larger catchment areas and steeper slopes) compared to gullies developed in joint orientation,
because gullies in bedding direction need to cut through a lower number of erosion resistant sandstone layers during incision.

For gully complexes, the second gully system type, deep-seated mass movements are dominant over fluvial incision: In a first stage of gully complex evolution, incipient, linear gullies gradually develop oversteepened sidewalls, which in turn initiate mass movements (Betts et al., 2003). Such features can absorb their entire catchment (DeRose et al., 1998, Parkner et al., 2006, Parkner et al., in press) and might develop in bedding direction of the underlying lithological layers favoring mass movements (Parkner et al., in press). Surface erosion and incision respond rapidly to rainfall events, diminishing rapidly once rainfall deceased. In contrast, mass movement erosion shows a less clear response to individual rainfall events and is likely to reflect rainfall received over a longer period (Betts et al., 2003). A third gully system type was termed as “slide complex”. For this type gullying occurs in areas which has previously been disturbed by sliding (Parkner et al., in press).

Aim of this study is to analyze growth and recovery of gullies developing into a rock flow in the East Coast Region for the time span of 1939 to 1997. Conditions leading to the development and recovery of these gullies under pasture are analyzed by using topographic thresholds (slope-area relationships) of catchments and major rainfall events (>150mm/day).

Study area

The study area covers 1.3km$^2$ (Fig. 1) and is located in the lower part of the Mangaoporo River catchment, East Coast Region, North Island, New Zealand. We analyze a 1.9km long ridge containing a rock flow (using the terminology by Varnes, 1978. Rock flows, or “Sackung” are described as “creeping flow-type, deep-seated gravitational deformations... producing graben like depressions (trenches), double ridges” (Dikau et al., 1996)). The rock flow contains a graben like depression in the upper part of the rock flow parallel to the ridge and shows two major scars in the southeastern section. The rock flow has a maximal relief of 340m and an average slope of 20degree between the alluvial plain and ridge tops.

Lithology is made up by the Whangai Formation, Late Cretaceous to Paleocene highly crushed and sheared mudstones. The formation forms part of the tectonically active East Coast Allochthon, a series of thrust sheets, which has been emplaced in the Early Miocene time as a result of southwest to SSW-directed subduction of the Pacific Plate beneath the Australian Plate. (Mazengarb and Speden, 2000).

The climate is warm temperate maritime with warm moist summers and cool wet winters. Annual precipitation is ∼2400mm, and irregular, high intensity rainstorms are characteristic of the climate. Considerable land uses changes have occurred in the study area. By 1920 European settlers had deforested the area and...
established pastoral farming (Page et al., 2001). In contrast to surroundings, pastures were well maintained, whereas gullies were left for revegetation by scrub dominated by kanuka (Kunzea ericoides) manuka (Leptospermum scoparium) or tutu (Coriaria arborea). Other countermeasures to reduce erosion were not undertaken in the study area.

Methods and materials

Aerial photographs and interpretation

Gully development and recovery were documented by stereoscopic analysis of aerial photographs taken in 1939 (survey 127, 1:11,400), 1957 (survey 371 1:24,000), 1971 (survey 3298, 1 : 18,500), 1981 (survey 5929, 1:19,500), 1984 (survey 11065, 1:19,500), 1988 (11485.J survey 1:27,000), and 1997 (no survey number, 1:25,000). Except of the 1939 aerial photographs, all photographs were orthorectified. In a first step, 10m contours supplied by the forest company Rayonier (unpublished data) were converted to points in order to construct a Digital Elevation Model (DEM) with 5m resolution by applying non-linear rubber sheeting using ERDAS IMAGINE 8.7. Forty georeferenced points were collected from a digital map (Land Information New Zealand, 2000) from features including river confluences, ridges or mountaintops. The aerial photograph of 1957 was then orthorectified accepting a maximum total root-mean square error of 15m. As the last step, the 1957 aerial photographs were resampled by cubic convolution. The constructed map of 1957 was then used as a reference map for orthorectification of the other aerial photographs to increase the number of points suitable for georeferencing. The three aerial photographs of 1939 could not be orthorectified as camera details were unknown. Instead, they were georeferenced using more than 60 georeferencing points and third order polynomial transformation accepting a maximum total root-mean square error of 10m. Resulting images were imported to ArcGIS 9.0 and active areas of gullies were delineated on screen and calculated.

Major rainfall events

In order to relate gully activity and recovery to storm events, we use the history of major storms records provided by Parkner et al. (2006, in press) shown in figure 2. For this time series, rainfall data with daily resolution were collected from five rainfall stations, which are all closer than 15km to the study area. The earliest data were acquired from the Whakaangiangi station, located 2km northeast of the study area, for the period of August 1930 to September 1945. No data were available for the period of October 1945 to July 1946. Between August 1946 and October 2003, data of three stations near the town Ruatoria were evaluated, all about 15km southeast of the study area. As no data were measured between November 1958 and June 1960 at these three stations, daily rainfall data of the Poroporo station were evaluated, but events did not
exceed 150mm/day. Only major rainfall events, defined as rainfall days of >150mm/day, are included, because major events are expected to produce erosion severe enough to be identifiable on aerial photographs with such temporal resolution. 22 major rainfall events occurred between August 1930 and April 1997. Prior to the 1939 as well as to the 1957 aerial photography, major storm series occurred. Until the next aerial photography of 1971 only 1 major rainfall event occurred within 14 years. The major storms of December 1974, December 1980, and June 1984 were followed by Cyclone Bola in March 1988 during which 535mm fell in two consecutive days, the highest daily rainfall event of 535mm occurred during this two-day event. This was followed by another 5 storms prior to the 1997 aerial photographs.

**Topographic threshold**

The topographic threshold approach (Patton and Schumm, 1975) is widely used to predict conditions leading to gully incision, which occurs only when a threshold in terms of rainfall, topography, and land use is exceeded (Horton, 1945). Threshold lines for gully development by hydraulic erosion can be described by \( S = aA^b \), with \( S \) as slope gradient, \( A \) as upslope drainage area, and \( a \) and \( b \) coefficients depending on the environmental characteristics (Begin and Schumm, 1979). Critical slope gradients are obtained by measuring maximum slope gradient where gully head formation started determined by field measurements, extraction from topographic maps, or are derived from digital elevation models (Vandaele et al., 1996). As in the studies by Parker et al. (2006, in press), we use catchment slope and catchment area of whole catchments in which gullies develop as threshold values, because phases of headward expansion, inactivation, and reactivation starting at various positions of the previously inactive gullies occur. Values were determined from the DEM described above. Catchment areas of individual gullies were derived from the DEM using ArcGIS9.0 and catchment slopes were measured in m/m.

**Results and Discussion**

Ten gullies were identified in the study area covering 16.7ha or 13% of the study area at their maximum gully extent (Table 1), which was attained in the years 1957, 1971, or 1988. Maximum extents reached from 0.07ha (gully 2) to 4.95ha (gully 3). Data on active gully areas for all time slices is given in Table 1 and their spatial extent shown in Figure 3. Except of gully (g) 6, all gullies were already developed by 1939. The development of gullies complexes was classified into two groups according to the timing of their maximum spatial extent (Table 2). The first group (g3, g5, g6, g8) reached their activity peak by 1988, whereas the second group (g1, g2, g4, g7, g9, g10) reached their maximum extent in 1957 or 1971. Gully catchments of the first group were larger (>10ha) and showed higher slope/catchment relationships (Figure 4, Table 2) compared to the catchments of the second group. The gullies of the three smallest catchments of the second group (g2, g7, g10) were already closed or remained shut in 1988, whereas the catchments with a secondary activity peak exhibited larger catchment areas compared to the former ones.

The relation of activity peak and major rainfall events suggests that peak activity of the first group is related to the largest rainfall event on record, Cyclone Bolas in 1988; assuming that larger rainfall events produce higher runoff leading to higher gully erosion rates compared to smaller rainfall events for a given catchment. Cyclone Bola in 1988 generated enough overland flow to increase gully extent within this first group, as the veneer soil layer is saturated by the short-term major rainfall events in such steep mountainous

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<tbody>
<tr>
<td>g2</td>
<td>0.46</td>
<td>0.87</td>
<td>0.25</td>
<td>0.05</td>
<td>0.05</td>
<td>0.68</td>
<td>0.51</td>
</tr>
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<td>g3</td>
<td>0.03</td>
<td>0.07</td>
<td>0.06</td>
<td>-</td>
<td>-</td>
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<td>-</td>
</tr>
<tr>
<td>g4</td>
<td>0.75</td>
<td>1.93</td>
<td>2.80</td>
<td>4.30</td>
<td>4.00</td>
<td>4.95</td>
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<tr>
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<td>0.70</td>
<td>1.11</td>
<td>0.86</td>
<td>0.37</td>
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<td>0.67</td>
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<tr>
<td>g6</td>
<td>1.71</td>
<td>2.48</td>
<td>2.53</td>
<td>2.56</td>
<td>2.56</td>
<td>2.70</td>
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<td>g7</td>
<td>0.08</td>
<td>0.10</td>
<td>0.45</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>3.88</td>
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<tr>
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<td>0.92</td>
<td>0.87</td>
<td>0.40</td>
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<td>0.14</td>
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<tr>
<td>g10</td>
<td>0.11</td>
<td>0.65</td>
<td>0.32</td>
<td>0.38</td>
<td>0.32</td>
<td>-</td>
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Fig. 3. Spatial extent of gullies at all time slices
Table 2. Catchment area (A) and slope (S) of the gullied catchments

<table>
<thead>
<tr>
<th>gully</th>
<th>A (ha)</th>
<th>S (m/m)</th>
<th>max. extent</th>
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<tr>
<td>g2</td>
<td>1.7</td>
<td>0.00</td>
<td>1957</td>
</tr>
<tr>
<td>g7</td>
<td>7.7</td>
<td>0.34</td>
<td>1971</td>
</tr>
<tr>
<td>g10</td>
<td>3.0</td>
<td>0.31</td>
<td>1957</td>
</tr>
<tr>
<td>g9</td>
<td>4.4</td>
<td>0.40</td>
<td>1957</td>
</tr>
<tr>
<td>g1</td>
<td>8.2</td>
<td>0.40</td>
<td>1957</td>
</tr>
<tr>
<td>g8</td>
<td>10.4</td>
<td>0.33</td>
<td>1957</td>
</tr>
<tr>
<td>g4</td>
<td>11/2</td>
<td>0.35</td>
<td>1988</td>
</tr>
<tr>
<td>g6</td>
<td>11.0</td>
<td>0.39</td>
<td>1988</td>
</tr>
<tr>
<td>g5</td>
<td>29.2</td>
<td>0.30</td>
<td>1988</td>
</tr>
</tbody>
</table>

Fig. 4. Relation between catchment slope (S) and area (A)

For the smallest catchments (g2, g7, g10) of the second group, topographic threshold might not apply, as these gullies remained inactive also during the extreme event of Cyclone Bola. Next to rainfall induced overland runoff the gullies of the second group might be also affected by sapping from the rock flow as during the 1950s. Prolonged, lower-intensity rainfall periods might lead to saturation and higher ground water tables which play a major role for the mass failure of gully slopes (Harvey 2001), but also might lead to water sapping at the smaller gullied catchments located at the foot slopes of the rock flow. The dominance of sapping for runoff production diminishes with increasing catchment area in contrast to surface runoff production, because the three larger catchments of the second group (g4, g1, g9) exhibit reactivation peaks after Cyclone Bola and the first group showed their peaks after the extreme rainfall event.

Conclusion

Predicting gully development using a topographic threshold approach is widely applied in many regions of the world. In the East Coast Region, New Zealand, this approach has been successfully applied for undisturbed mountainous catchments under pasture and indigenous forest (Parkner et al., 2006, in press), but might not be equally applied to any catchment, because runoff necessary for gully incision might also be supplied from other sources than rainfall induced. This case study showed that areas containing rock flows need to be excluded due to water sapping at the foot slopes of a rock flow. Other areas to be excluded might be along fault lines characterized by groundwater sapping (Parkner et al., in press), or areas where earth flow deposits are reworked (Parkner et al. 2006). This implies that the geomorphic history of a site needs to be considered when predicting the locations of gully initiation and gully development.
Acknowledgement

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References


