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Badass gullies: Fluvio-mass-movement gully complexes in New Zealand's East Coast region, and potential for remediation

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ABSTRACT

This paper reviews gully erosion in the East Coast region of New Zealand's North Island and conceptualises fluvio-mass-movement gully complexes as badass gully systems. Tectonic setting and lithological control, with steep slopes and a climate influenced by tropical cyclones, predispose hill country in the East Coast region to gully erosion. The clearance of indigenous forest since the late 1800s has dramatically increased catchment erosion and paved the way for development of large-scale fluvio-mass-movement gully complexes. These features are a composite of fluvial and mass movement processes. They are conceptualised as 'badass' by not conforming to any existing gully model and by generating disproportionate results in East Coast catchment sediment cascades. Their remediation is discussed, but their nature means that prevention is better than a cure.

1. Introduction

1.1. Concept and context

Phillips (2015) defined the archetypal badass as 'individualistic, non-conformist and able to produce disproportionate results'. He argued for the application of the term in geomorphology to describe the individualistic behaviour of landforms that fail to conform to conventional wisdom and, because of amplifier effects, to generate disproportionate results. We will argue that the large gully systems in the East Coast region of New Zealand, which we here define as fluvio-mass-movement gully complexes, fit this categorisation of badass geomorphology (Phillips, 2015). As such, we agree with Bergonse and Reis' (2011) reflection on the inadequacy of the current theoretical concept of gullies as essentially fluvial forms. New Zealand East Coast gullies do not fit the traditional fluvial conception of gullies in which mass movements are only of secondary importance (Bergonse and Reis, 2011). Bergonse and Reis (2011) go on to observe the atypical (individualistic) behaviour of fluvio-mass-movement gully complexes that unlike typical fluvially conceived gullies, occur as complexes of coalesced channels developing via multiple head cuts. Strikingly, and that in support of their observation, they refer exclusively to gully complexes studied in New Zealand's East Coast region (De Rose et al., 1998; Betts et al., 2003; Parkner et al., 2006). More recently, however, similar complexes have been referred to in Taiwan and Portugal (Kuo and Brierley, 2014; Bergonse and Reis, 2016), although Kuo and Brierley's focus in Taiwan was on catchment-scale connectivity rather than gully dynamics, and the reference is oblique. Bergonse and Reis (2016) defined large gullies in tributaries of the Tagus River as varying from 200 m^2 to >3 ha, which, as we will demonstrate, is somewhat smaller than the majority of New Zealand East Coast gully mass movement complexes; but they do recognise the combined role of fluvial incision, head cut bifurcation, and mass movements (albeit on a smaller scale). Comparisons between erosion in New Zealand East Coast and French pre-Alp catchments have been made (Liébault et al., 2005), but sediment generation processes in the French catchments reflect typical badland processes (Mathys et al., 2003) rather than badass gullies. Here we review gully erosion in the East Coast region of New Zealand's North Island and conceptualise fluvio-mass-movement gully complexes as badass gully systems (sensu Phillips, 2015), which this regionwide gully erosion has spawned. At the outset, we define East Coast badass gullies as those gully complexes exceeding 10 ha, by which stage they have shown minimal response to either active remediation by reforestation within one rotation of forest (~27 years) (Marden et al., 2012), the primary means used to remediate catchment-scale erosion in NZ (Phillips and Marden, 2005), or to passive indigenous reversion and thus remain an ongoing and significant source of sediment generation.

1.2. Study area

New Zealand's North Island East Coast region consists of three major catchments; the Waipaoa (2208 km^2), Uawa (560 km^2), and the Waiapu (1758 km^2) (Fig. 1). About 90% of the region is classed as steep hill country, much of which is considered to be highly erodible

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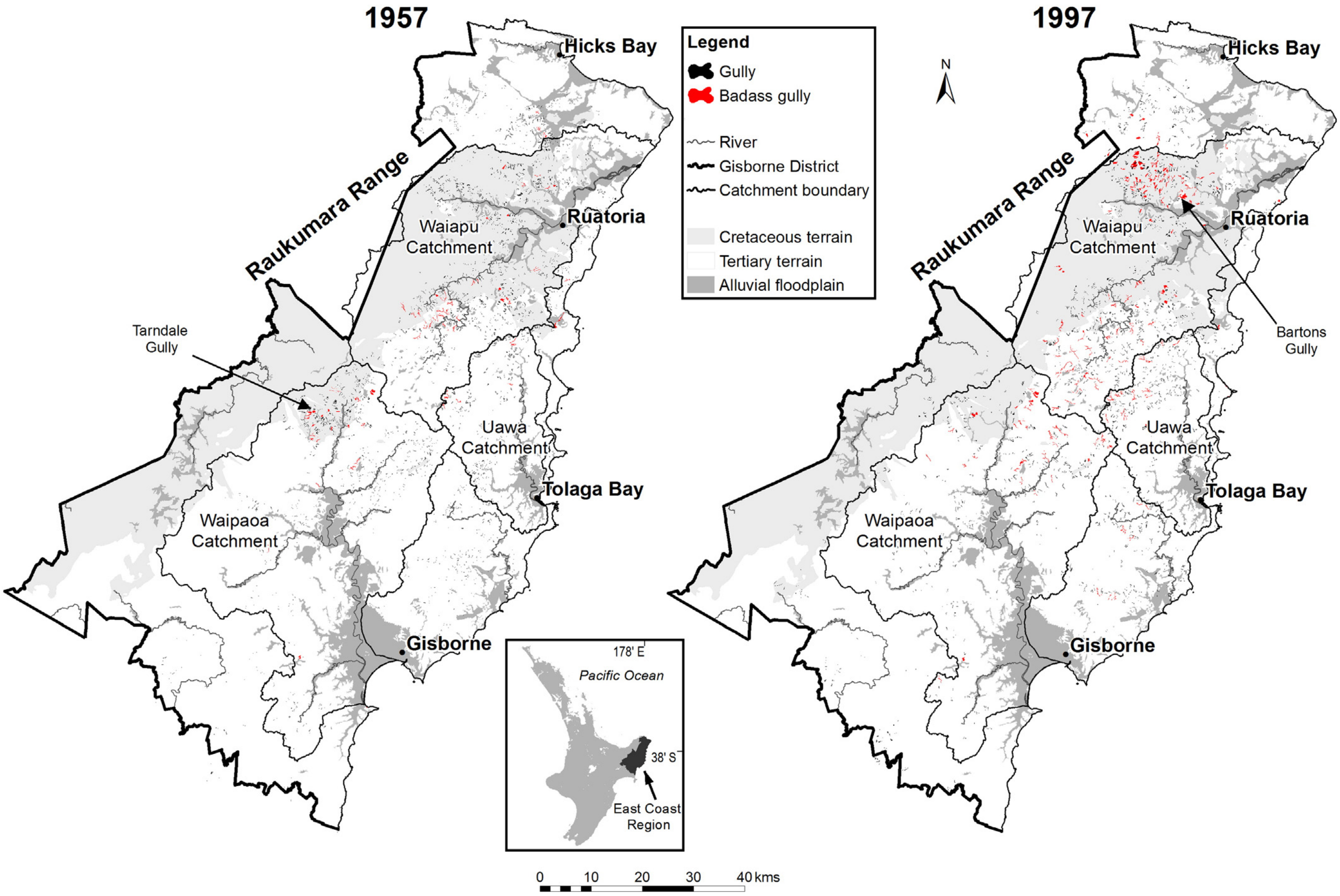

Fig. 1. Location map showing the distribution of gullies <10 ha (black) and badass gullies >10 ha (red) within the Cretaceous- and Tertiary-aged terrains and catchment boundaries, East Coast region, North Island, New Zealand. Arrows show the location of two of the largest gullies, Tarndale and Barton's gullies.
(After Marden et al., 2008a)

(National Water and Soil Conservation Organisation, 1975). These steep land rivers are among the highest sediment-laden rivers in New Zealand and together contribute ~55 Mt of suspended sediment annually (Hicks and Shankar, 2003). This amounts to ~0.3% of the total global suspended sediment input to the ocean (from ~0.0003% of Earth's total land area) and ~33% of New Zealand's sediment yield to the ocean (Hicks et al., 2011).

The East Coast is positioned on the circum-Pacific mobile belt at the boundary of the converging Pacific and Indian–Australian lithospheric plates, which results in high rates of tectonic uplift (1–4 mm y^{-1}) and frequent large magnitude earthquakes (Smith and Berryman, 1986). Based on lithology, age, and style of deformation, the region can be subdivided into two geologic terrains (sensu Von Zittel, 1901) (Fig. 1). An inland, 'Cretaceous terrain' (29% of the region) comprises variably indurated, extensively sheared, alternating siliceous mudstone and sandstone of late Cretaceous to Palaeocene age comprising part of the East Coast Allochthon (Mazengarb and Speden, 2000). Eastward of this allochthon lies the autochthonous 'Tertiary terrain' (61% of region), comprising tectonically less-deformed, bedded to massive sandstones and mudstones of early to middle Miocene age. In places, the two terrains are separated by areas of mélange consisting essentially of Cretaceous-aged lithologies. This mélange formed during the emplacement of the allochthon in early Miocene times and on the basis of its age and structural style has been included as part of the Cretaceous terrain.

The regional climate is warm temperate maritime, with warm moist summers and cool wet winters. Rainfall gradients increase from south to north and from the coast to inland areas. Mean annual rainfall for coastal areas in the south (Gisborne City) is 1200 mm, while that in the north (Ruatoria Township) is 1600 mm. Inland areas in the south of the region receive ~2500 mm, while areas in the north and near the main divide of the Raukumara Range get 4000 mm (Hessell, 1980). The region's climate is strongly influenced by the El Niño/Southern Oscillation (ENSO), with an increase in major rainfall events during La Niña conditions and severe and prolonged droughts during El Niño years. Since the turn of the twentieth century, 37 extreme rainfall events have occurred (Gisborne District Council hydrologists, pers. comms). Based on their experience, an extreme event is defined as one that results in a flood discharge rate from the Waipaoa River into poverty bay that exceeds the average by 2 orders of magnitude (>1500 $m^3 s^{-1}$). Widespread hillslope failure has occurred during many such events (Kelliher et al., 1995). In the north of this region (Waiapu catchment), erosion-generating storms have a recurrence interval of between 2.6 years in the headwaters and 3.6 years near the coast (Hicks, 1995). This volatile climate contributes to high erosion rates (Water and Soil Directorate, 1987).

The history of the clearance of extensive areas of indigenous forest (~1880s to 1920s) for conversion to pasture was similar in all three catchments. Within a decade or two a period of geomorphic slope adjustment followed (Hill, 1895; Henderson and Ongley, 1920; Allsop, 1973; Gage and Black, 1979; Cerovski-Darriau and Roering, 2016), the most noticeable being the initiation of gully erosion in areas of steep hill country. Cerovski-Darriau and Roering (2016) suggested that in one subcatchment of the Waipaoa erosion rates in the last ~50 years in response to deforestation exceeded background post-Last Glacial Maximum (LGM) erosion rates by an order of magnitude.