Title

Gully erosion in sub-tropical south– east Queensland, Australia.

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Abstract

Analysis of aerial photographs shows that gully erosion in three catchments in south– east Queensland, Australia, was initiated by post– European settlement. Analysis of historical rainfall and runoff show for two of the catchments, gully initiation occurred during wet decadal periods. Historical descriptions of the settlement of south– east Queensland and Moreton Bay detail significant changes in landuse and clearing of vegetation for grazing of domestic animals and urban development since 1842. Historical gully erosion rates varied from $14\text{--}1826\text{ m}^2\text{yr}^{-1}$ and erosion rates are positively correlated with catchment area $\times$ slope. Analysis of gully erosion rates showed a linear increase in planimetric area over time. Together, these data show gully initiation in three catchments in

south– east Queensland is associated with post– European settlement land use practices and above average rainfall and runoff. Initiation of gullying across the region is similar to previous studies in south– east Australia and highlights the sensitivity of the landscape to vegetation clearing and alternating periods of above average rainfall and drought.

Key Words

Gully; Erosion rates; Sub-tropical; Sediment; Landuse changes; Grazing

1. Introduction

Sub-tropical and tropical regions worldwide are experiencing significant development with associated land clearing. South– east Queensland (SEQ) has one of the fastest growing populations in Australia, currently standing at 2.73 million people; by 2026 this is expected to increase to ~4 million. This growth will bring further significant pressures to the health of the region’s waterways, which is already cause for concern. Non-urban diffuse sediment loads have been identified in the SEQ Healthy Waterways Strategy, 2007-2012 (SEQ HWS) to be a major contributor to poor water quality and aquatic ecosystem health in both freshwater and estuarine/marine systems. Gully erosion has been identified as a major source of this sediment (Caitcheon et al., 2001; Wallbrink et al., 2002; Wallbrink, 2004; Douglas et al., 2009; Hancock and Caitcheon, 2010; Olley et al., in prep), yet there is little understanding on when these gullies formed and their rates of erosion.

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48 Many studies conducted in south– east Australia (New South Wales and Victoria)
49 have shown large increases in erosion and sediment delivery as a result of land
50 use changes following European settlement ~180 years ago. Analyses of
51 explorer’s reports, settler’s diaries, and other historic accounts have revealed the
52 devastating effects that European settlement had on the south-eastern Australian
53 landscape (Starr et al., 1999; Scott, 2001; Scott and Olley, 2003). Land clearing
54 and the introduction of sheep and cattle associated with settlement triggered a
55 major phase of stream incision and gully erosion (e.g. Prosser et al., 1994;
56 Prosser and Winchester, 1996; Wasson et al., 1998; Beavis et al., 1999; Scott,
57 2001). Prior to settlement, valley floors in most upper catchments were unincised
58 „swampy meadows“ (Prosser et al., 1994; Eriksson et al., 2006) or a series of
59 deep pools, referred to as a „chain of ponds“, linked by shallow riffle zones or
60 vegetated flat areas (Eyles, 1977). Gully erosion and channel incision are now
61 widespread across south-east Australia (Prosser et al., 2001), and have been
62 clearly related to European settlement and associated land-management
63 practices.

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65 European land management practices in SEQ at the time of settlement, which
66 began in 1823, were no different to those in Victoria and New South Wales and it
67 has been inferred that the landscape response was similar (Capelin et al., 1998;
68 Neil, 1998). Before settlement the catchment is considered to have been in a
69 relatively stable condition with periodic cyclones and aboriginal fire management

practices the only substantial disturbance. European settlement and development of the catchment led to significant increases in sediment export and sediment loads to Moreton Bay are estimated to be 30 times the pre-European rates (NLWRA, 2001). It is widely proposed that increased sediment loads result from extensive clearing in the upper catchments, cultivation on floodplains, extensive over-grazing, clearing of riparian areas, and development of urban centres (Fanning, 1999; Olley et al., 2006).

In this study we test whether the gully erosion evident across much of SEQ occurred following European settlement, as was the case in south-eastern Australia. We also investigate the influence of subtropical rainfall patterns on gully initiation. Historical aerial photographs, rainfall and flow records, and LiDAR (light detection and ranging) derived digital elevation models (DEMs) are used to determine when the gullies formed, their erosion rates and to examine the potential mechanisms of gully initiation. This study aims to contribute additional knowledge to gully erosion processes in the sub-tropical region of SEQ.

2. Study Area

2.1. Regional Setting

Southeast Queensland is located on the eastern coast of Australia, has a catchment area of ~22,600 km², and a peak elevation of 1360 m in the west along the Great Dividing Range (Fig. 1; Abal et al., 2005; Bunn et al., 2007). Its major population centre is the City of Brisbane, the state capital, which has a

population of ~2 million people. The region itself has a population of ~2.73 million (ABS, 2010). SEQ is a subtropical region with mean annual maximum temperatures ranging between 21– 29 °C. The total annual rainfall ranges between 900– 1800 mm, with the majority falling during the warm summer season and stream flow in the region is seasonally variable (Pusey et al., 1993; Abal et al., 2005). Approximately 60% of native vegetation in the region has been cleared since the beginning of European settlement in 1823. The predominant land uses include production from relatively natural environments (55%; of which grazing is ~50%) and conservation and natural environments (21%). Intensive uses, dryland agriculture and plantations, and irrigated agriculture and plantations are also present in the region (14, 5, and 2%, respectively). Sheep and cattle were farmed in south-east Queensland following early settlement of the area but due to humid conditions and the effect of black spear grass on sheep wool production, sheep grazing was predominantly phased out in the early 1900s. There are some small scale sheep producers (for meat) as well as horse owners in the area, but they are minimal in comparison to cattle grazing enterprises. The landuse term "grazing" is primarily used to describe the use of the land for the production of beef cattle and dairy.

2.2. Study areas

The three areas selected for investigation were located in the Logan, Brisbane and Bremer River catchments. The selected areas have channel and gully erosion as a dominant process for soil loss and appropriate data sets (including

aerial photograph, LiDAR data and rainfall records) available for investigation
(Fig. 1).

Knapp Creek (75.29 km²), in the Logan Catchment, is a predominantly grazing catchment with only 22% of the original woody vegetation remaining. The elevation ranges from 250 m– 62 m. Mean annual rainfall is ~860 mm^{yr}⁻¹. The main channel is ~2 m wide in the upper reaches and ~35 m wide in the lower reaches. Most of the channel has over-widened with carrying capacity exceeding a 1 in 100 year event. There is extensive evidence of gully and hillslope erosion throughout the catchment, but most abundant in the mid– catchment. The middle reaches are largely devoid of woody vegetation, with extensively incised valley fill deposits and extensive gullies well-connected to the main channel. There is also substantial hillslope erosion in the middle reaches as the soils are dispersive and highly erodible. The lower catchment consists of highly dissected hillslopes that flow onto largely un-dissected valley floors. The underlying geology consists of Walloon Coal Measures (Jurassic shale, siltstone, sandstone) in the upper reaches transitioning to Gatton Sandstone of the Marburg subgroup in the middle and lower reaches (Warwick SH-S6-2, Australia 1:250,000 series Geology Map). Soils mapping data is available for south– east Queensland but it is sporadic in extent and of low resolution. Soils in the Knapp Creek Catchment are described as sandy and loamy solodics, soloths, yellow and red podzolics, non-calcic brown soils and lithosols. They are strongly sodic and have dispersive subsoils

that are prone to tunneling erosion processes (Land Resource Areas Map, Moreton Region, DPI reference 94_MOR-I-P3040).

The upper Brisbane River Catchment (4497 km²) has its headwaters in the foothills of the Great Dividing Range and Conodale Range, which predominantly remain in a natural state. The catchment landuse includes native bush, forestry, grazing, intensive agricultural, mining and rural residential. The upper Brisbane River is impounded by Wivenhoe dam, which is the main municipal water supply for Brisbane and its surrounding areas. Mean annual rainfall decreases along an east to west gradient across the whole catchment, but annual rainfall closest to the area of interest in this study is ~940 mm^{yr}⁻¹. Elevation ranges from ~540 m at the top of the western catchment to ~79 m at the maximum flood storage of Wivenhoe dam (Shellberg and Brooks, 2007). The main channel width varies from ~2 m in the upper reaches to nearly 200 m near the confluence with the Stanley River upstream of Lake Wivenhoe. The upper Brisbane River channel is aligned within the Esk trough, which has major geology units of the Esk Formation (Triassic pebble to cobble conglomerate, sandstone, shale) and Neara Volcanics (Triassic andesitic flows, pebble to cobble conglomerate, minor shale; Brizga and Finlayson 1996; Brennan and Gardiner 2004). Previous studies have shown extensive gullies exist in conjunction with cleared grazed hillslopes and drainage of tributaries through igneous Eskdale Gneiss (Caitcheon et al., 2005a, 2005b). Soils in this region are described as Northern Mixed Volcanics, which are shallow hillside soils, lithosols and shallow clays and clay loams. Parts

of the region have grey and brown clays, sandy solodics and loamy solodics that are highly dispersive (Noble, 1996).

The Bremer study area, located in the upper Bremer River Catchment, is ~123 km² in area. The catchment has been partly cleared with 48% woody vegetation remaining. Clearing has been most extensive in the lower catchment. Landuse in the upper, steeper areas of the catchment is dominated by grazing. The lower floodplain areas are used extensively for cropping (19.17 km² or 15.3 % of the catchment). Elevation along the main channel ranges from ~300 m at the top of the catchment to ~73 m at the catchment outlet. The main channel width varies from 2 m in the upper catchment to ~30 m in the lower. Mean annual rainfall is estimated at 960 mm^{yr}⁻¹. There are several large gullies in the catchment. Many of these have now partially revegetated, suggesting that these are now stabilizing, particularly in the lower catchment. The upper catchment is underlain with Main Range Volcanics (Tertiary basalt-trachyte flows) with discrete sections of Walloon Coal Measures and older Quaternary alluvium in higher river terraces (Ipswich SG-S6-14, Australia 1:250,000 series Geology Map). Soils in the catchment are described as sandy soloths and solodics and non-calcic brown soils that have a hard setting surface soil that if disturbed will allow greater infiltration of water into the dispersible sub soils (Johnston, 1979).

3. Methods

3.1. Timing of gully initiation and historical erosion rates

Historical erosion rates and the timing of gully initiation were determined using historical aerial photographs. The methods for aerial photograph analysis are similar to those described by Burkard and Kostaschuk, (1995). Briefly, electronic scanned copies of aerial photographs from 1951– 2006 were supplied by the Queensland Department of Environment and Resource Management (DERM). The scale of the aerial photographs ranged from 1:23,900– 1:40,000. Each photograph was geo-referenced to the GDA 1994 MGA Zone 56 spatial coordinate system and rectified within ArcGIS (v9.3) software. The outline of each gully was digitized by hand and the planimetric area of each gully was measured. The evidence of erosion was interpreted in the aerial photographs through changes in tone in the black and white photographs and differences in colour in 2006 photographs. Radial distortion was minimised by using gullies in the central area of the aerial photograph and control points set using an underlying digital elevation model (DEM) derived from LiDAR scanning of each catchment. The upper Brisbane River catchment did not have LiDAR derived data and pan sharpened SPOT 5 imagery obtained in 2006 at a resolution of 2.5 m was used for the selection of control points. A 10 percent error was included for each measured area to account for human error in mapping the gullies and to account for differences between aerial photographs (Lawler, 1993). The changes in gully area with time were then used to determine erosion rates and the time of gully initiation by regression analysis.

3.2. Contemporary erosion rates

Several gully sites were chosen in the upper Bremer River Catchment that had sequential captured LiDAR data. The linear extent and area of each gully was determined for data captured in late 2009 and early 2011. This time interval also included several large rainfall events that resulted in significant gully and channel erosion in the study area. The LiDAR data had an absolute vertical and horizontal accuracy of 0.15 and 0.45 m, respectively. DEMs were derived using TNTmips raster algebra capabilities (undertaken by Terranean Mapping Technologies) with 1 m ground pixel spacing.

3.3. Historical changes in rainfall and runoff

Daily rainfall records extending back to before 1900 were used to determine historic trends in annual rainfall for the region. Station records were selected on the basis of record length and completeness. Twelve of the stations were used (Station No. 40196, 40094, 40184, 40082, 40083, 40214, 40231, 40237, 40382, 40171, 40075, 40043). Data were supplied by the Australian Bureau of Meteorology. For each station cumulative deviations from the long term annual mean rainfall were first calculated and normalised to the annual mean. This decreases the station to station variations in the amplitude of the trends. All of the stations showed comparable trends and the data were averaged to show the regional variations in rainfall over time.

Only three river gauging stations in the region have records extending back more than 70 years (Station 1380002 Wide Bay Creek, 1380004 Munna Creek and 145101 Albert River). Data were supplied by the Queensland Department of

Environment and Resource Management (DERM). As with the rainfall data, cumulative deviations from the long term annual mean stream-flow were first calculated and normalised to the annual mean for each station. These were then used to illustrate the relationship between variations in rainfall and stream flow.

4. Results

4.1. Timing of gully initiation

The mapped gully areas for 10 gullies in the Knapp Creek catchment are plotted with the dates of the aerial photographs from which they were derived in Fig. 2. Linear regression was used to estimate the time of gully initiation (r^2 range from 0.87– 0.98). Four gullies showed recovery (a decrease in mapped area between 1988– 2006). The 2006 data points for these gullies were excluded from the regression analysis. The intercept on the y axis gives an estimate of the time of gully initiation. The intercepts and their standard error for all of the gullies in the Knapp Catchment, except gully 7, are displayed in a radial plot in Fig. 2 (inset). The estimated intercepts (in years) for a gully can be read by tracing a line from the y-axis origin through the point until the line intersects the radial axis (log scale) on the right-hand side. The corresponding standard error for this estimate can be read by extending a line vertically to intersect the x-axis. The x-axis has two scales: one plots the relative standard error of the estimate (%) and the other („Precision“) plots the reciprocal standard error. Therefore, values with the highest precisions and the smallest relative errors plot closest to the radial axis on the right of the diagram, and the least precise estimates plot furthest to the

left. Galbraith et al., (1999) provided further details, and a worked illustration, of how radial plots may be used. The shaded region in the plot indicates those values that are consistent at the 2s confidence interval with a common initiation age, with the exception of gully 7, which yields an inception age of 1704AD $\pm$ 50 years, all of the gullies in Knapp are consistent with a single inception date. We have used the „central age model“ of Galbraith et al., (1999) to estimate time of inception at 1932AD $\pm$ 6 years.

The mapped areas for gullies in the upper Bremer and upper Brisbane Catchment study areas are plotted with the dates of the aerial photographs from which they were derived in Figs. 3 and 4, respectively. As with Knapp Creek, linear regression was used to estimate the time of gully initiation ($r^2 > 0.85$). The intercept data from the upper Bremer River study area shows a broad spread with values ranging from 1839AD $\pm$ 9 to 1912AD $\pm$ 8 years. In contrast the data from the upper Brisbane River catchment are consistent with a single inception date at 1949AD $\pm$ 9 years, estimated using the weighted mean.

4.2. Historic erosion rates

Gully erosion rates, estimated by linear regression, for the Knapp Creek, upper Bremer, and upper Brisbane Rivers are plotted against catchment area x slope in Fig. 5. Slope and drainage area are known to influence the density of a drainage network and the probability of gully development (Poesen et al., 2003). Rates for the Knapp Creek catchment range from 52 $\pm$ 10 to 1190 $\pm$ 340 m²yr⁻¹. Similar

erosion rates were observed in the upper Bremer study area (131 ± 8.4 to $1826 \pm 209 \text{ m}^2\text{yr}^{-1}$). Gullies that exhibited recovery during the historical time periods (mainly as a consequence of soil conservation works) were excluded from this analysis as was gully 5 that was initiated in recent times as a consequence of road construction. Erosion rates in the upper Brisbane River study area were lower in magnitude to the other datasets ($14\text{--}444 \text{ m}^2\text{yr}^{-1}$).

Erosion rates are positively correlated with contributing catchment area and slope ($r^2 = 0.666$; $n=18$, $P < 0.005$). Linear regression analysis was the best fit for this relationship and showed an increasing erosion rate with increasing catchment area and slope for all studied gullies. Lower erosion rates for gullies in the upper Brisbane River catchment could be due to their smaller catchment area and slope, as illustrated in Fig. 5.

4.2. Contemporary erosion rates

Analysis of the repeat LiDAR survey data from the upper Bremer River study area showed an increase in gully area for both surveyed gullies. Fig. 6 shows the increase in gully area between 2009–2011 for gullies 1 and 3, respectively. Gully 1 had a contemporary erosion rate of $10,000 \text{ m}^2\text{yr}^{-1}$, while gully 3 had an erosion rate of $1492 \text{ m}^2\text{yr}^{-1}$. When total change in area (m^2) is plotted against total rainfall x gully catchment area (mmm^{-2}) for specific time periods (Fig. 7), the contemporary erosion rate for gullies 1 and 3 are within the observed ranges derived through historical aerial photograph analysis.

300

301 *4.3. Historical changes in rainfall and runoff*

302 Normalised cumulative deviations from the long term mean annual rainfall for
303 SEQ between 1870– 2009, and discharge at Wide Bay Creek (1910– 2005),
304 Munna Creek (1928– 2005) and Albert River (1910– 2005) are presented in Fig.
305 8. It should be noted that the rainfall record from 1870– 1888 is derived solely
306 from data collected at the Brisbane Regional Office (40214). The vertical grey
307 shaded bands in Fig. 8 indicate extended wet periods of above average rainfall
308 and stream flow. As observed elsewhere (Riley, 1988; Olive et al., 1995; Olley
309 and Wasson, 2002) variations in annual rainfall produce more marked variations
310 in flow, with periods of average rainfall producing annual flows below the long
311 term average. These data also show extended dry periods for the region, as
312 depicted by downward trending lines on Fig. 8. From the historical rainfall
313 records, the dry periods last on average 15 years with an extended dry period of
314 31 years occurring between 1895– 1926. In contrast, the extended wet periods
315 last on average 6 years, depicted by the vertical shaded bands in Fig. 8.

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318 **5. Discussion**

319 With one exception discussed below, the data from all gullies examined in this
320 study is consistent with them being initiated during post- European settlement.
321 Gully initiation in the Knapp Creek Catchment occurred in a wet phase
322 (1926– 1932) following an extended ~30 year period of below average rainfall.
323 Similarly, gully initiation in the upper Brisbane River Catchment occurred during
324 the 1945– 1957 wet phase. In contrast data from the upper Bremer River
325 Catchment gullies show a broad spread 1839AD $\pm$ 9 to 1912AD $\pm$ 8 years, and
326 does not appear to correlate with particular wet or dry periods. It is also
327 interesting to note that gully incision dates did not correspond to the wet periods
328 between 1870– 1880 and 1890– 1895. Fanning (1999) discussed three
329 categories of causal factors for gully initiation; crossing of an intrinsic threshold,
330 secular climatic changes and human landuse changes. In this case, work
331 undertaken in the far western NSW catchments suggest human landuse change
332 with increased European pastoralism and associated loss of vegetation cover
333 were the dominant causal factors that induced gullying of the valley floor
334 (Fanning, 1999). Indeed, Bull (1997) had earlier concluded that gully erosion
335 processes may be too complex to attribute any one factor as the trigger but
336 suggested a decrease in vegetation cover on hillsides and valley floors is pivotal
337 to valley floor stability.

338

Regression analysis of the data from gully 7 from the Knapp Creek Catchment gave an inception date of 1704AD $\pm$ 50 years for this gully. The erosion rate on this gully ($52 \pm 10 \text{ m}^2\text{yr}^{-1}$) was also significantly lower than those for gullies from similar sized sub-catchments in the Knapp Creek Catchment (nearest $133 \pm 20 \text{ m}^2\text{yr}^{-1}$). The total extent of gully 7 in 2006 was 17,045 m^2 dividing this area by this higher rate of erosion would yield an inception of $\sim$ 1880.

Previous work has described gully development in terms of non-linear growth as slope and contributing catchment size are reduced as the gully head migrates up valley (Kosov et al., 1978; Rutherford et al., 1997). Indeed, Kosov et al., (1978) predicted that 90% of the total linear extent of a gully was attained within 5% of the time it took to reach its stable length. However, Faulkner (1974) proposed that erosion rates slowed for gullies that competed for drainage basin area, whilst gullies that did not compete with each other experienced linear growth rates. The gullies studied within SEQ show a linear relationship between time and increasing planimetric area. An approximate physically-based explanation of this linear relation follows from recognition that the rate of sediment supply to and delivery from the expanding gully must be approximately equal. Let us assume that the depth of the gully incision, d , is approximately constant during the observed active phase of gully expansion, and that for simplicity the gully can be represented as approximately rectangular in plan form and cross section. Then the rate of sediment supply by the gully is given by

$$r_b d \frac{dA}{dt} (WL) \quad (\text{kgs}^{-1}) \quad (\text{Eq. 1})$$

where ρ_b is the soil bulk density (kgm^{-3}), W is the width and L the length of the gully (both in m).

The rate of sediment transport from the eroding gully is given by

$$Gc \quad (\text{kg s}^{-1}) \quad (\text{Eq. 2})$$

where G is the long-term average rate of water discharge through the gully (m^3s^{-1}) and c (kgm^{-3}) is the long-term average sediment concentration.

Equating the two expressions given in Eqs. (1) and (2), the rate of gully plan area expansion is given by

$$\frac{dA}{dt} = \frac{Gc}{\rho_b d} \quad (\text{m}^2\text{s}^{-1}) \quad (\text{Eq. 3})$$

The average water flux rate could be expected to be correlated with the gully catchment area, and slope is a factor increasing c , so the empirical relationship given in Fig. 5 is supportive of the form of Eq. (3). However, it also suggests that for any particular gully, Gc is a reasonably constant quantity over the substantial period of gully expansion observations described in the paper.

If then catchment area is a good indicator of average water flux rate, and slope of landscape factors, then Fig. 5 suggests some degree of uniformity in the various soil factors which affect sediment concentration, at least over the geographical range of gullies observed.

The non-linear expansion rate for gully 7 in Knapp Creek Catchment could be explained by a reduction in readily available erodible material to increase the

gully area through lateral expansion, as the gully structure is within a narrow subcatchment and possibly confined by more resistant material. Further investigation at this site is required.

Historical accounts of European settlement in SEQ and Moreton Bay detail significant vegetation clearing for grazing of domestic animals and urban settlement. After the penal colony was abandoned in Brisbane and free settlement was allowed in the region in 1842, sheep and cattle numbers steadily rose to 3,500,000 sheep and 433,000 cattle in 1861, (Powell, 1998). Timber was increasingly removed from riparian forests and exported overseas or transported to Sydney, with significant wastage in the process (Bolton, 1992a). Ringbarking and burning of trees across the catchments was standard practice, in order to clear land for crops and grazing animals. Pre- and post- European vegetation extent studies have shown ~43% of native vegetation remains in SEQ following European settlement (NVIS, 1997). These data also show Open Eucalypt Forest that was present across the catchment hillslopes and open plains was reduced from ~65% to ~28% post-European settlement.

The initiation dates for Knapp Creek and the upper Brisbane River catchments were 1932AD $\pm$ 6 and 1949AD $\pm$ 9, respectively. However, detailed data on vegetation cover in SEQ and grazing numbers on a subcatchment scale is very limited for these time periods. Historical accounts of settlement in SEQ and across Australia detail the impacts of World War I and the following period of

depression in Australia on land management. Between 1930– 1945 there is evidence that marginal farming operations led to exploitation of Australian soils, as farmers needed to increase their productivity but did not have the financial means to invest in possible improvements (Bolton, 1992b). Historical rainfall/stream flow records from the Australian Bureau of Meteorology also show notable flooding through Queensland, including SEQ, in 1931 and 1950– 1951. The regional exploitation of Australian farming land at this time may have been the trigger to initiate gully erosion whereas vegetation cover could have still been sufficient in the late 1800s to protect against wide spread gullying along the valley floor during periods of above average rainfall and stream flow. Additional work is required to consider the process of valley cut and fill in the catchments that may shed light on why we see a non synchronous pattern of gully initiation in the region (Patton and Schumm, 1981). It would be beneficial to examine the possibility that gullying had occurred earlier in the catchments in conjunction with wet periods in the late 1800s but to a lesser extent that was seen in the early-mid 20th Century.

There is extensive evidence in the literature of the relationship between the reduction in vegetation cover and increased sediment yields from catchments. Prosser (2002) showed once vegetation cover is degraded on the valley floor, gully systems are more sensitive to climate change and decadal scale changes are shown to contribute to gully initiation. There are limited data describing the extent of vegetation clearing on a subcatchment scale in SEQ since

post– European settlement. However, it can be inferred from historical accounts that describe a significant increase in grazing animal numbers and an expansion of urban settlement in this region over this time period. This could suggest vegetation cover degradation in the Knapp Creek, upper Bremer and upper Brisbane River Catchments was sufficient to render the land sensitive to decadal changes in above average rainfall and stream flow.

6. Conclusions

Erosion rates for the gully systems studied in three specific catchments in south– east Queensland showed a linear expansion of planimetric area over time. This linear relationship is similar to gullies studied elsewhere (Burkard and Kostaschuk, 1995) and an approximate physically-based explanation of this linear relationship is given. The initiation of the gullies correlates with post– European settlement, as previously detailed across south– east Australia. Gullies in two catchments showed initiation dates that correlate with extended wet periods for the region and historical accounts suggest extensive vegetation clearing occurred across south– east Queensland along a similar timeline as a consequence of agriculture expansion and urban settlement.

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Figure captions

Figure 1: Map showing the major sub-catchments in SE Queensland, the location of the three study areas, and. showing sites and places named in the text.

Figure 2: The mapped gully areas for 10 gullies in the Knapp catchment plotted with dates of the aerial photographs from which they were derived. Linear regression was used to estimate the time of gully initiation (r^2 range from 0.87 to 0.98). The intercept on the y axis gives an estimate of the time of gully initiation. Figure 2 (inset): A radial plot of the intercepts and their standard error for all of the gullies in the Knapp Creek catchment except gully 7.

Figure 3: The mapped gully areas for gullies in the upper Bremer River study area plotted with dates of the aerial photographs from which they were derived.

Figure 4: The mapped gully areas for gullies in the upper Brisbane River study area plotted with dates of the aerial photographs from which they were derived. Figure 4 (inset): A radial plot of the intercepts and their standard error for all of the gullies.

Figure 5: Gully erosion rates for the Knapp Creek (closed circles), upper Bremer River (open circles) and upper Brisbane River (trizangles) study areas against catchment area x slope. Linear regression line, $r = 0.666$, $n = 18$, $P < 0.005$.

Figure 6a and b: Delineated gully area using repeat LiDAR derived DEM data captured in 2009 and 2011 for gully 1 and gully 3 in the upper Bremer River study area

Figure 7: Relationship between the total change in gully area vs discharge (measured as maximum monthly rainfall for a given time period multiplied by the gully catchment area) for the upper Bremer River study area.

Figure 8: Normalised cumulative deviations from the long term mean annual rainfall for SE-Queensland between 1870 and 2009, and discharge at Wide Bay Creek (1910-2005), Munna Creek (1928-2005) and Albert River (1910-2005). The vertical grey shaded bands indicate extended wet periods of above average rainfall and stream flow.

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