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**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– 1826 $m^2yr^{-1}$ and erosion rates are positively correlated with catchment area x slope. Analysis of gully erosion rates showed a linear increase in planemetric 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.

47

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.

64

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 km$^2$, 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

93 population of ~2 million people. The region itself has a population of ~2.73 million
94 (ABS, 2010). SEQ is a subtropical region with mean annual maximum
95 temperatures ranging between 21– 29 °C. The total annual rainfall ranges
96 between 900– 1800 mm, with the majority falling during the warm summer
97 season and stream flow in the region is seasonally variable (Pusey et al., 1993;
98 Abal et al., 2005). Approximately 60% of native vegetation in the region has been
99 cleared since the beginning of European settlement in 1823. The predominant
100 land uses include production from relatively natural environments (55%; of which
101 grazing is ~50%) and conservation and natural environments (21%). Intensive
102 uses, dryland agriculture and plantations, and irrigated agriculture and
103 plantations are also present in the region (14, 5, and 2%, respectively). Sheep
104 and cattle were farmed in south-east Queensland following early settlement of
105 the area but due to humid conditions and the effect of black spear grass on
106 sheep wool production, sheep grazing was predominantly phased out in the early
107 1900s. There are some small scale sheep producers (for meat) as well as horse
108 owners in the area, but they are minimal in comparison to cattle grazing
109 enterprises. The landuse term "grazing" is primarily used to describe the use of
110 the land for the production of beef cattle and dairy.
111
112 *2.2. Study areas*
113 The three areas selected for investigation were located in the Logan, Brisbane
114 and Bremer River catchments. The selected areas have channel and gully
115 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 $km^2$), 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 $mmyr^{-1}$. 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 $km^2$) 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 $mmyr^{-1}$. 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 Grandodiorite (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

161 of the region have grey and brown clays, sandy solodics and loamy solodics that
162 are highly dispersive (Noble, 1996).
163
164 The Bremer study area, located in the upper Bremer River Catchment, is
165 ~123 $km^2$ in area. The catchment has been partly cleared with 48% woody
166 vegetation remaining. Clearing has been most extensive in the lower catchment.
167 Landuse in the upper, steeper areas of the catchment is dominated by grazing.
168 The lower floodplain areas are used extensively for cropping (19.17 $km^2$ or 15.3
169 % of the catchment). Elevation along the main channel ranges from ~300 m at
170 the top of the catchment to ~73 m at the catchment outlet. The main channel
171 width varies from 2 m in the upper catchment to ~30 m in the lower. Mean annual
172 rainfall is estimated at 960 $mmyr^{-1}$. There are several large gullies in the
173 catchment. Many of these have now partially revegetated, suggesting that these
174 are now stabilizing, particularly in the lower catchment. The upper catchment is
175 underlain with Main Range Volcanics (Tertiary basalt-trachyte flows) with discrete
176 sections of Walloon Coal Measures and older Quaternary alluvium in higher river
177 terraces (Ipswich SG-S6-14, Australia 1:250,000 series Geology Map). Soils in
178 the catchment are described as sandy soloths and solodics and non-calcic brown
179 soils that have a hard setting surface soil that if disturbed will allow greater
180 infiltration of water into the dispersible sub soils (Johnston, 1979).
181

182 **3. Methods**

183 *3.1. Timing of gully initiation and historical erosion rates*

184 Historical erosion rates and the timing of gully initiation were determined using
185 historical aerial photographs. The methods for aerial photograph analysis are
186 similar to those described by Burkard and Kostaschuk, (1995). Briefly, electronic
187 scanned copies of aerial photographs from 1951– 2006 were supplied by the
188 Queensland Department of Environment and Resource Management (DERM).
189 The scale of the aerial photographs ranged from 1:23,900– 1:40,000. Each
190 photograph was geo-referenced to the GDA 1994 MGA Zone 56 spatial
191 coordinate system and rectified within ArcGIS (v9.3) software. The outline of
192 each gully was digitized by hand and the planemetric area of each gully was
193 measured. The evidence of erosion was interpreted in the aerial photographs
194 through changes in tone in the black and white photographs and differences in
195 colour in 2006 photographs. Radial distortion was minimised by using gullies in
196 the central area of the aerial photograph and control points set using an
197 underlying digital elevation model (DEM) derived from LiDAR scanning of each
198 catchment. The upper Brisbane River catchment did not have LiDAR derived
199 data and pan sharpened SPOT 5 imagery obtained in 2006 at a resolution of
200 2.5 m was used for the selection of control points. A 10 percent error was
201 included for each measured area to account for human error in mapping the
202 gullies and to account for differences between aerial photographs (Lawler, 1993).
203 The changes in gully area with time were then used to determine erosion rates
204 and the time of gully initiation by regression analysis.
205
206 *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

231 Environment and Resource Management (DERM). As with the rainfall data,
232 cumulative deviations from the long term annual mean stream-flow were first
233 calculated and normalised to the annual mean for each station. These were then
234 used to illustrate the relationship between variations in rainfall and stream flow.
235
236 **4. Results**
237 *4.1. Timing of gully initiation*
238 The mapped gully areas for 10 gullies in the Knapp Creek catchment are plotted
239 with the dates of the aerial photographs from which they were derived in Fig. 2.
240 Linear regression was used to estimate the time of gully initiation ($r^2$ range from
241 0.87– 0.98). Four gullies showed recovery (a decrease in mapped area between
242 1988– 2006). The 2006 data points for these gullies were excluded from the
243 regression analysis. The intercept on the *y* axis gives an estimate of the time of
244 gully initiation. The intercepts and their standard error for all of the gullies in the
245 Knapp Catchment, except gully 7, are displayed in a radial plot in Fig. 2 (inset).
246 The estimated intercepts (in years) for a gully can be read by tracing a line from
247 the *y*-axis origin through the point until the line intersects the radial axis (log
248 scale) on the right-hand side. The corresponding standard error for this estimate
249 can be read by extending a line vertically to intersect the *x*-axis. The *x*-axis has
250 two scales: one plots the relative standard error of the estimate (%) and the other
251 („Precision“) plots the reciprocal standard error. Therefore, values with the
252 highest precisions and the smallest relative errors plot closest to the radial axis
253 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 ± 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 ± 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 ± 9 to 1912AD ± 8 years. In contrast the data from the upper Brisbane River catchment are consistent with a single inception date at 1949AD ± 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 ± 10 to 1190 ± 340 $m^2yr^{-1}$. Similar

277 erosion rates were observed in the upper Bremer study area (131±8.4 to 1826±
278 209 $m^2yr^{-1}$). Gullies that exhibited recovery during the historical time periods
279 (mainly as a consequence of soil conservation works) were excluded from this
280 analysis as was gully 5 that was initiated in recent times as a consequence of
281 road construction. Erosion rates in the upper Brisbane River study area were
282 lower in magnitude to the other datasets (14– 444 $m^2yr^{-1}$).
283
284 Erosion rates are positively correlated with contributing catchment area and
285 slope ($r^2$ = 0.666; n=18, P< 0.005). Linear regression analysis was the best fit for
286 this relationship and showed an increasing erosion rate with increasing
287 catchment area and slope for all studied gullies. Lower erosion rates for gullies in
288 the upper Brisbane River catchment could be due to their smaller catchment area
289 and slope, as illustrated in Fig. 5.
290
291 *4.2. Contemporary erosion rates*
292 Analysis of the repeat LiDAR survey data from the upper Bremer River study
293 area showed an increase in gully area for both surveyed gullies. Fig. 6 shows the
294 increase in gully area between 2009– 2011 for gullies 1 and 3, respectively. Gully
295 1 had a contemporary erosion rate of 10,000 $m^2yr^{-1}$, while gully 3 had an erosion
296 rate of 1492 $m^2yr^{-1}$. When total change in area ($m^2$) is plotted against total
297 rainfall x gully catchment area ($mmm^{-2}$) for specific time periods (Fig. 7), the
298 contemporary erosion rate for gullies 1 and 3 are within the observed ranges
299 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.

316

## 5. Discussion

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

339 Regression analysis of the data from gully 7 from the Knapp Creek Catchment
340 gave an inception date of 1704AD ± 50 years for this gully. The erosion rate on
341 this gully (52 ± 10 $m^2yr^{-1}$) was also significantly lower than those for gullies from
342 similar sized sub-catchments in the Knapp Creek Catchment (nearest 133 ±
343 20 $m^2yr^{-1}$). The total extent of gully 7 in 2006 was 17,045 $m^2$ dividing this area by
344 this higher rate of erosion would yield an inception of ~1880.
345
346 Previous work has described gully development in terms of non-linear growth as
347 slope and contributing catchment size are reduced as the gully head migrates up
348 valley (Kosov et al., 1978; Rutherfurd et al., 1997). Indeed, Kosov et al., (1978)
349 predicted that 90% of the total linear extent of a gully was attained within 5% of
350 the time it took to reach its stable length. However, Faulkner (1974) proposed
351 that erosion rates slowed for gullies that competed for drainage basin area, whilst
352 gullies that did not compete with each other experienced linear growth rates. The
353 gullies studied within SEQ show a linear relationship between time and
354 increasing planemetric area. An approximate physically-based explanation of this
355 linear relation follows from recognition that the rate of sediment supply to and
356 delivery from the expanding gully must be approximately equal. Let us assume
357 that the depth of the gully incision, *d*, is approximately constant during the
358 observed active phase of gully expansion, and that for simplicity the gully can be
359 represented as approximately rectangular in plan form and cross section. Then
360 the rate of sediment supply by the gully is given by

361 $$r_b d \frac{\partial (WL)}{\partial t} \qquad (kgs^{-1}) \qquad \text{(Eq. 1)}$$

362 where $\rho_b$ is the soil bulk density (kgm$^{-3}$), *W* is the width and *L* the length of the
363 gully (both in m).
364 The rate of sediment transport from the eroding gully is given by
365 $Gc$ (kgs$^{-1}$) (Eq. 2)
366 where *G* is the long– term average rate of water discharge through the gully
367 (m$^3$s$^{-1}$) and *c* (kgm$^{-3}$) is the long– term average sediment concentration.
368
369 Equating the two expressions given in Eqs. (1) and (2), the rate of gully plan area
370 expansion is given by
371 $$\frac{\partial (WL)}{\partial t} = \frac{Gc}{\rho_b d} \quad (m^2 s^{-1}) \quad \text{(Eq. 3)}$$
372 The average water flux rate could be expected to be correlated with the gully
373 catchment area, and slope is a factor increasing *c,* so the empirical relationship
374 given in Fig. 5 is supportive of the form of Eq. (3). However, it also suggests that
375 for any particular gully, *Gc* is a reasonably constant quantity over the substantial
376 period of gully expansion observations described in the paper.
377 If then catchment area is a good indicator of average water flux rate, and slope of
378 landscape factors, then Fig. 5 suggests some degree of uniformity in the various
379 soil factors which affect sediment concentration, at least over the geographical
380 range of gullies observed.
381
382 The non-linear expansion rate for gully 7 in Knapp Creek Catchment could be
383 explained by a reduction in readily available erodible material to increase the

384 gully area through lateral expansion, as the gully structure is within a narrow
385 subcatchment and possibly confined by more resistant material. Further
386 investigation at this site is required.
387
388 Historical accounts of European settlement in SEQ and Moreton Bay detail
389 significant vegetation clearing for grazing of domestic animals and urban
390 settlement. After the penal colony was abandoned in Brisbane and free
391 settlement was allowed in the region in 1842, sheep and cattle numbers steadily
392 rose to 3,500,000 sheep and 433,000 cattle in 1861, (Powell, 1998). Timber was
393 increasingly removed from riparian forests and exported overseas or transported
394 to Sydney, with significant wastage in the process (Bolton, 1992a). Ringbarking
395 and burning of trees across the catchments was standard practice, in order to
396 clear land for crops and grazing animals. Pre– and post– European vegetation
397 extent studies have shown ~43% of native vegetation remains in SEQ following
398 European settlement (NVIS, 1997). These data also show Open Eucalypt Forest
399 that was present across the catchment hillslopes and open plains was reduced
400 from ~65% to ~28% post-European settlement.
401
402 The initiation dates for Knapp Creek and the upper Brisbane River catchments
403 were 1932AD ± 6 and 1949AD ± 9, respectively. However, detailed data on
404 vegetation cover in SEQ and grazing numbers on a subcatchment scale is very
405 limited for these time periods. Historical accounts of settlement in SEQ and
406 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 20$^{th}$ 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 decadel 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 decadel 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 planemetric 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 (tri2angles) 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.

Figure 1

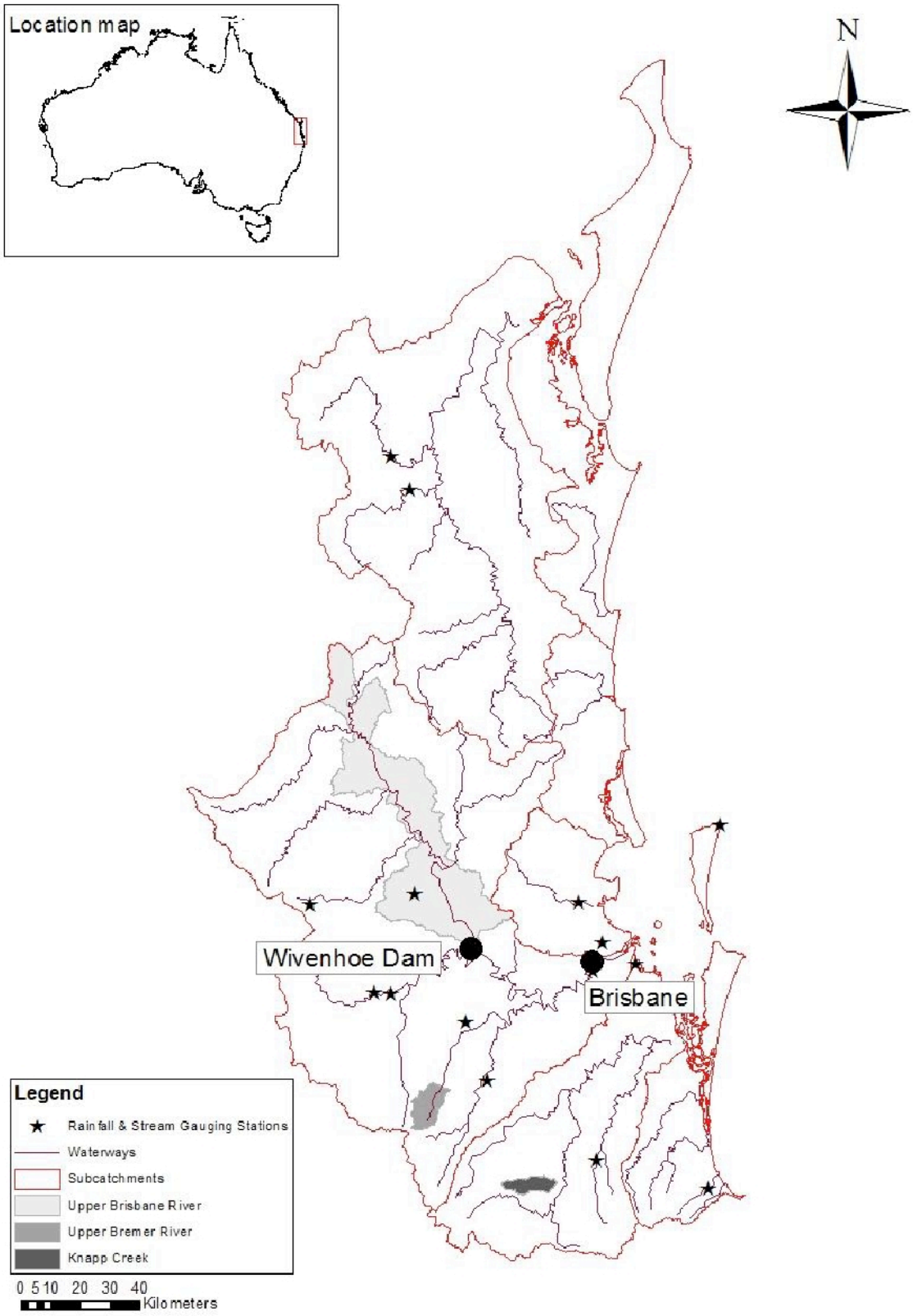
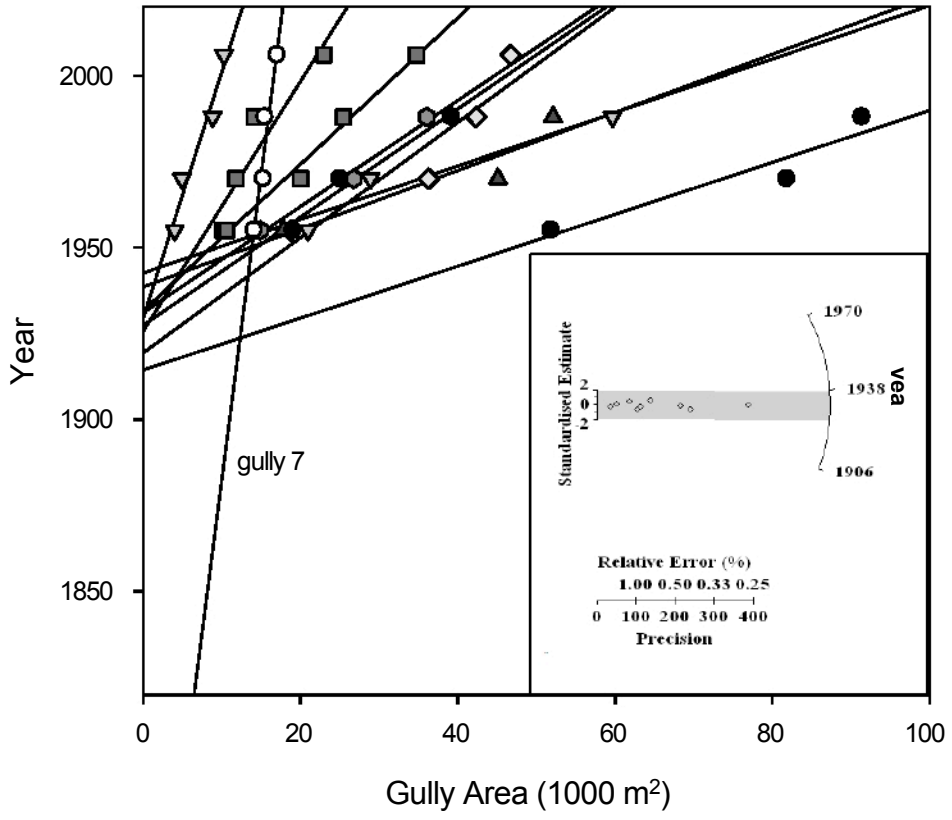
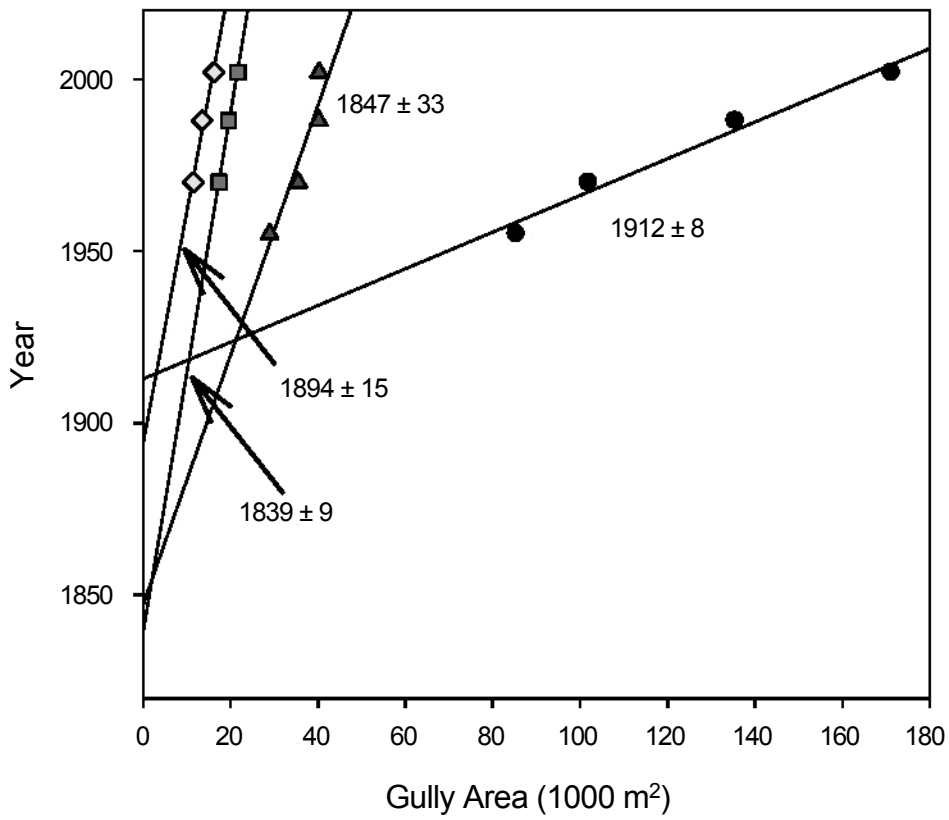

Location map
N
Wivenhoe Dam
Brisbane
Legend
Rainfall & Stream Gauging Stations
Waterways
Subcatchments
Upper Brisbane River
Upper Bremer River
Knapp Creek
0 5 10 20 30 40
Kilometers

Figure 2:


2000
1950
1900
1850
Year
gully 7
0
20
40
60
80
100
Gully Area (1000 m2)
1970
1938
1906
vea
Standardised Estimate
2
0
2
Relative Error (%)
1.00 0.50 0.33 0.25
0 100 200 300 400
Precision

10 Figure 3:

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14 Figure 4:
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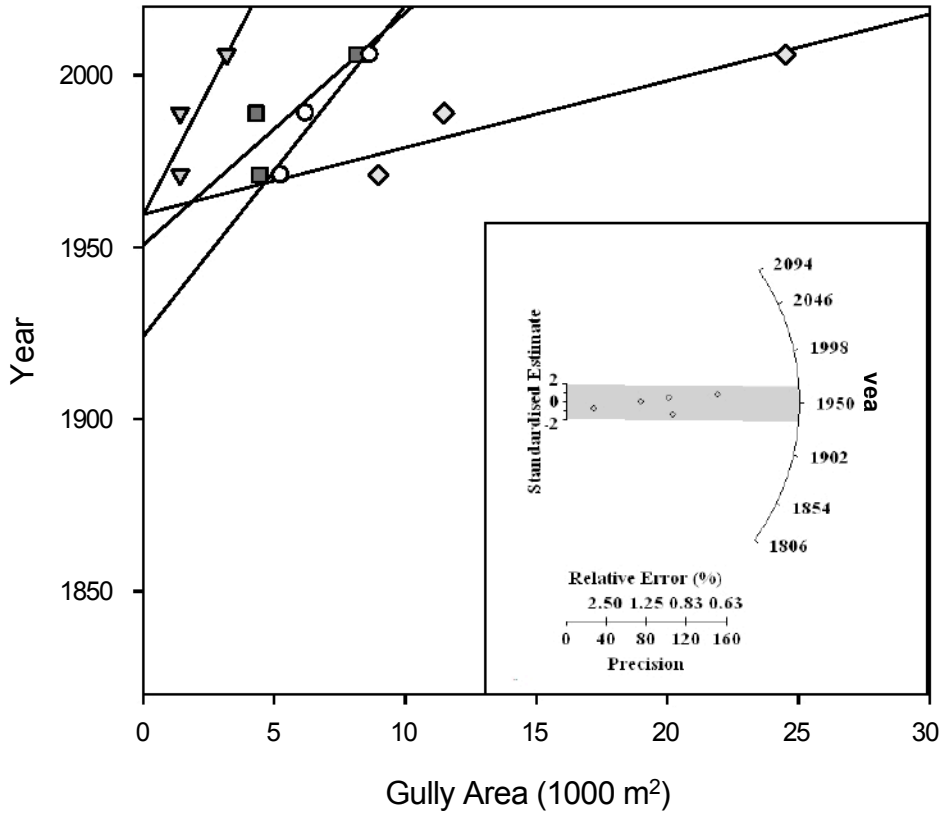


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19 Figure 5:

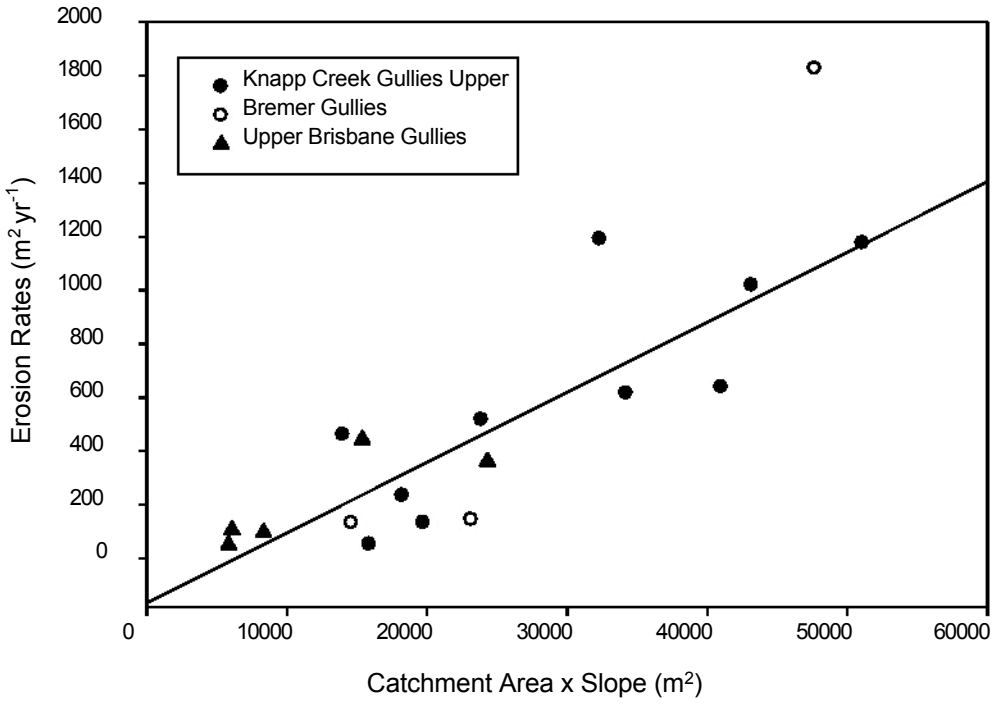


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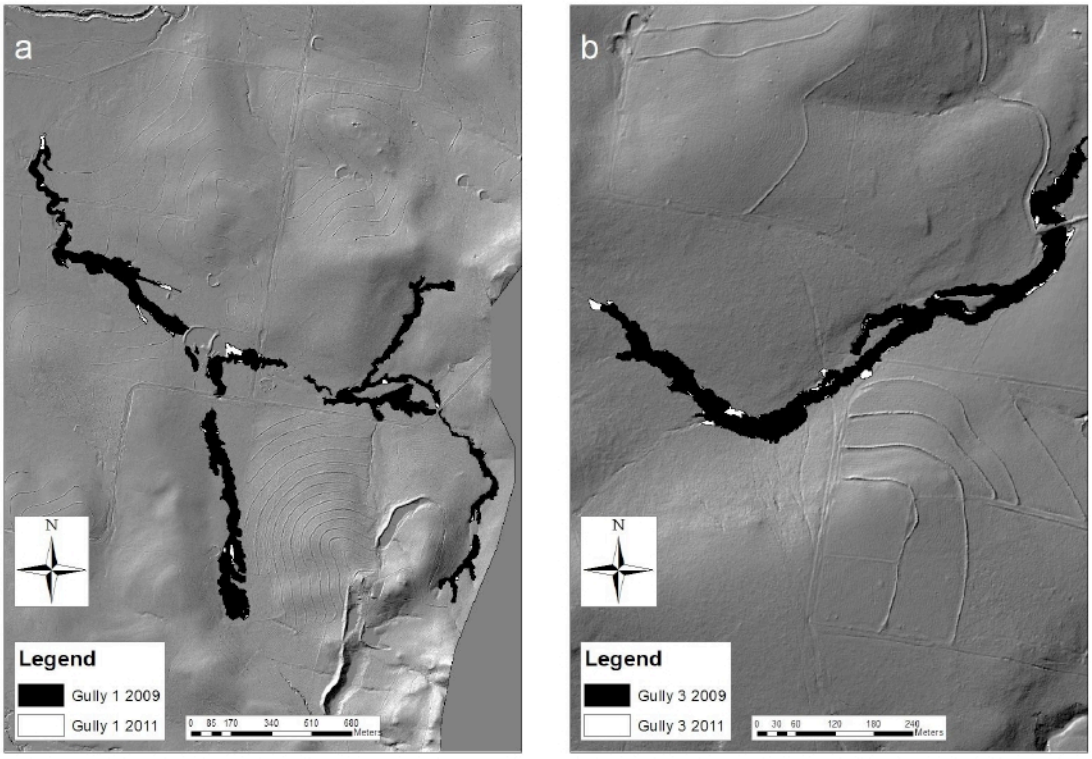
Figure 6a and b:



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27 Figure 7:

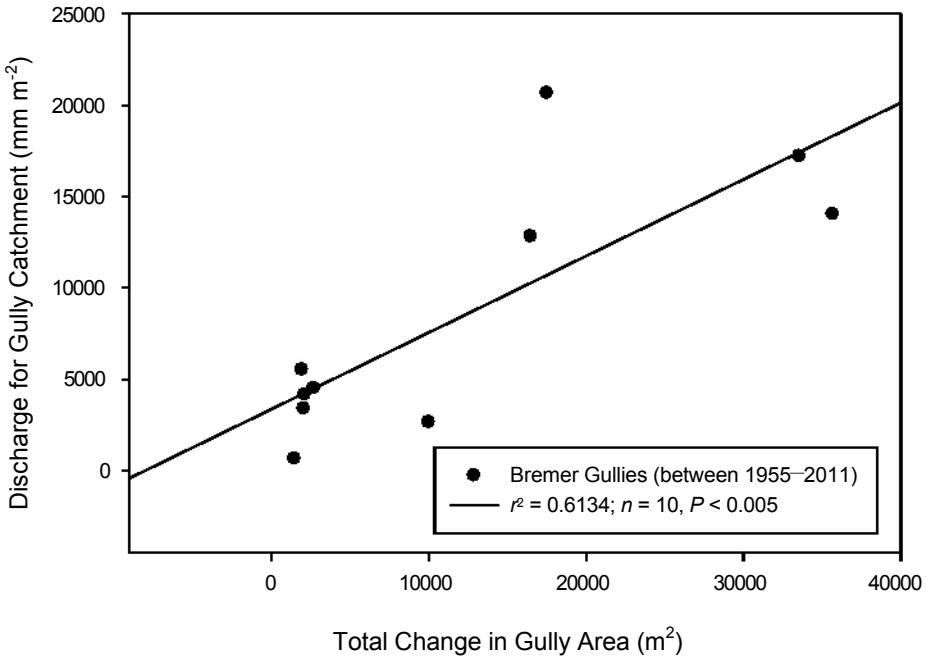


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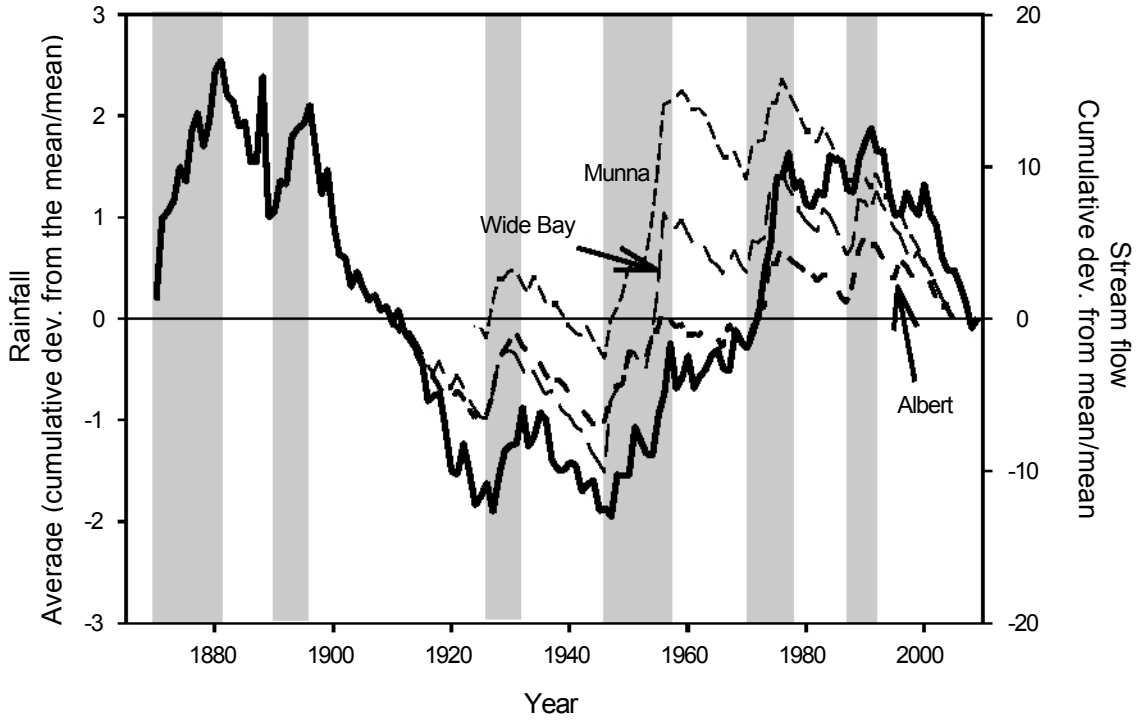
Figure 8:


Rainfall
Average (cumulative dev. from the mean/mean)
Stream flow
Cumulative dev. from mean/mean
Munna
Wide Bay
Albert
Year
3
2
1
0
-1
-2
-3
20
10
0
-10
-20
1880
1900
1920
1940
1960
1980
2000