ORIGINAL PAPER

Evaluating the potential for natural ecosystem recovery in cut-and-fill wetlands: case study of Pietersielieskloof palmiet wetland, South Africa

S. E. Grenfell ⬤ · **M. F. Mamphoka** · **M. C. Grenfell** · **N. Job**

Abstract Cut-and-fill processes, characteristic of many valley-bottom wetlands, present a major challenge to practitioners planning wetland restoration. It is not clear whether the current synchronicity and spatial scale of incision is 'natural', and whether these wetlands will naturally recover without intervention during the 'fill' phase. The aim of this study, focussed on a *Prionium serratum* dominated valley-bottom wetland in South Africa, was to evaluate the potential for natural ecosystem recovery in the context of current catchment constraints. Historical rainfall records, aerial photography and a DGPS survey were used to contextualise geomorphic processes. The sedimentology of alluvial fill was investigated by sampling sediment profiles. Samples were analysed for particle size and organic content, five were dated using radiocarbon. Sedimentology and radiocarbon dates were used to ascertain phases of incision and aggradation along wetland reaches. While several phases of incision are represented in the record, none were represented in more than one location, suggesting phases of erosion and subsequent deposition were spatially and temporally segregated. The current synchronous phase of incision across the wetland is therefore unprecedented. Analysis of sedimentation rates indicate that infilling of the gully decreases exponentially over time. Infilling of a 3m deep gully in the Pietersielieskloof wetland under natural catchment conditions is estimated to take ~ 5000 years. Analysis suggests that there has been a reduction in wetland resilience over the last century, and that a change in catchment hydrology and sediment supply has altered this system such that it has crossed a geomorphic threshold.

Keywords Cut-and-fill · Resilience · Natural recovery · Palmiet

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Introduction

Valley floors characterised by either no channel or a discontinuous channel pattern and associated

Quaternary alluvial fill (Patton and Schumm 1975) or cut-and-fill sequences (Brierley and Fryirs 1999) are common in dryland regions of the globe (Tooth 2000, 2013; Jaeger et al. 2017). While they are usually associated with desert ecosystems, they may also be sites of wetland formation (e.g. Grenfell et al. 2009; Pulley et al. 2018). Despite pervasive negative annual water balances across southern Africa, valley-bottom wetlands are fairly common in the region (Tooth and McCarthy 2007; Ellery et al. 2011). In South Africa, valley-bottom wetlands are usually smaller than 1000 ha in size, and occupy valley slopes of between 3 and 0.1% (Ellery et al. 2011). They are typically well-vegetated and fed by a combination of groundwater and surface water inputs resulting in sustained saturation or shallow inundation, and a diffuse pattern of low flows (Kotze et al. 2009; Grenfell et al. 2019). Their geomorphic characteristics vary from those that are completely unchannelled to those with discontinuous channels and floodouts (Grenfell et al. 2019). In dryland regions these wetlands are frequently 'hotspots' of biodiversity and ecosystem service provision (TWIDRN 2014), and are thus often a focus of conservation efforts. In South Africa, valley-bottom wetlands are the primary focus of wetland restoration efforts undertaken by the Working for Wetlands Programme (Department of Environmental Affairs: Natural Resource Management). This initiative aims to restore and protect wetlands while creating local employment, supporting small businesses, and developing transferable skills (Dini and Bahadur 2018). However, one of the difficulties in restoring valley-bottom wetlands has been a limited understanding of the natural range of geomorphic variability in system character and behaviour, which is needed to determine whether intervention is appropriate, and if so, what type of intervention is suitable.

Some of the most useful concepts regarding valley-fill systems were developed for arid regions. Patton and Schumm (1975) found that the formation of discontinuous gully systems could be attributed to variation in longitudinal valley slope, with gullies developing on locally oversteepened reaches of the valley floor. Furthermore, the valley slope on which a gully was likely to initiate could be predicted by catchment area, a proxy for mean annual run-off in ungauged catchments. This concept, termed the geomorphic threshold, was found to apply to valley-bottom wetlands in South Africa on a limited dataset

(Ellery et al. 2011). Catchment area was a poor predictor of mean annual run-off due to stark variations in annual rainfall across South Africa, and as a result, wetland size was used as a proxy. As per the threshold concept, larger wetlands typically have lower longitudinal slopes than smaller wetlands. Valleys that have aggraded beyond the slope 'threshold' are typically either incised or are considered vulnerable to incision.

While the threshold concept is useful, it is the mechanism by which discontinuous gully systems form and the resulting consequences for their management that has direct implications for those undertaking wetland restoration in these contexts. Termed cut-and-fill systems by geomorphologists, these processes are described by Schumm (1994) for semi-arid environments, and by Zierholz et al. (2001) and Grenfell et al. (2009) for wetland environments. In cut-and-fill systems, phases of aggradation lead to local valley slope steepening. Over time, the slope becomes excessively steep for the local run-off, resulting in erosion. Brierley and Fryirs (1999) found that the geomorphic threshold concept could not explain why some valley-bottom wetlands had eroded in the Wolumla catchment of New South Wales, Australia, while others were unaffected by vegetation clearing associated with European settlement. Their analysis found that the location of recently incised trunk (mainstem) channels relative to the tributary alluvial fill was critical, in that trunk connectivity represented a local fall in base level for tributary fill, leading to the headward extension of incision into a tributary. In the case of Pulley et al. (2018), tributary alluvial fans were considered to contribute to variations in trunk down-valley slope. It is clear that there is a range of possible trunk-tributary relations and associated effects on wetland origin and dynamics, as reviewed by Grenfell et al. (2010; 2019).

Studies of cut-and-fill wetlands all document several phases of rapid gully development. Zierholz et al. (2001) argue that these are punctuated by comparatively long periods of infilling. In the Wolumla catchment, Brierley and Fryirs (1999) found evidence for three erosional phases, and two aggradational phases in the last 6000 years, although periods of infilling lasted longer than periods of incision. In the Eastern Cape, South Africa, Pulley et al. (2018) document a similar sequence of four erosional gullies which were subsequently infilled, dating from

between 7060 years BP to 470 years BP. Crucially, both of these cases include accounts of wetland cut-and-fill processes operating prior to European impact, and indicate that some portions of the valley-fill were preserved over the 6000 year period. This suggests that scour did not completely evacuate all the valley-fill during one event, and that some portions of the wetland remained intact even during periods of gully-driven degradation.

For those tasked with restoring and conserving valley-bottom wetlands that are characterised by cut-and-fill processes, questions are typically focussed on whether the current synchronicity and spatial scale of incision can be considered 'natural', and whether these wetlands, if left to the processes of natural recovery illustrated by conceptual models of gully widening, self-stabilisation and filling over time (Schumm 1994), will in fact recover. Furthermore, if the wetland can recover, how long would it be before ecosystem processes and the associated ecosystem services delivery (Kotze et al. 2009) are restored? The above review highlights an understanding that valley-bottom wetlands are geomorphologically transient features, shaped by the dynamics of phases of aggradation, punctuated by phases of erosion. However, the temporal frequency and spatial scale of incision, as well as the exact sequence of geomorphic events leading to incision is a source of debate (see, for example, Joubert and Ellery 2013; Tooth et al. 2014; Pulley et al. 2018). Furthermore, the manner in which varying catchment sediment loads and flows impacts upon valley-bottom wetlands has not been numerically tested. This research focuses on the Pietersielieskloof wetland, a cut-and-fill valley-bottom system in the Western Cape, South Africa. The objectives of the study were to: a) contextualise geomorphic processes in the wetland in terms of their duration and frequency with reference to other published studies in similar environments, b) consider the potential impact of the catchment context on hydrological and sedimentological connectivity and thus geomorphic resilience (e.g. Tooth 2018), and c) evaluate the potential for natural ecosystem recovery given current catchment constraints.

Regional setting

Pietersielieskloof is a discontinuous valley-bottom wetland (sensu Grenfell et al. 2019) situated within a large complex of wetlands located in the foothill valleys of the Bredasdorp Mountains, on the inland margin of the Agulhas Coastal Plain of South Africa (Fig. 1). The Pietersielieskloof wetland consists of two arms, the Blomkloof and Kiersgat reach in the west, and the larger Boskloof in the east. Downstream of the confluence of these arms, the Pietersielieskloof wetland system flows into the lowland meandering Nuwejaars River, which traverses a number of lowland floodplains with abutting alluvial plains / panveld, and the large Soetendalsvlei limnetic depression before entering the sea through a Ramsar-listed estuarine wetland system at De Mond. While large portions of the Nuwejaars River and tributaries are afforded some protection by the Nuwejaars Wetlands Special Management Area, and the Agulhas National Park, most of the natural vegetation of the foothills catchment has been removed to make way for wheat cultivation, livestock farming, vineyards, orchards, and indigenous flower cultivation for the cut-flower export market.

Where natural vegetation cover remains, most of the catchment and drainage line comprises endangered Elim Ferricrete Fynbos, which occurs on Bokkeveld Group shales and Cape Granite, and is a major node of red data plant taxa (Rebelo et al. 2016). The Elim Ferricrete Fynbos is characterised by open to closed dwarf shrubland with scattered tall shrubs. Tall shrub species such as *Protea repens* are common, while a diverse range of low shrubs may occur (Rebelo et al. 2016). In the eastern regions of the catchment underlain by sandstone, Overberg Sandstone Fynbos occurs. This vegetation type is considered less threatened and less diverse than Elim Ferricrete Fynbos, and supports moderately tall, dense ericoid and proteoid shrublands. The wetland itself is dominated by *Prionium serratum*, a semi-aquatic, rhizomatous flowering plant that grows up to 2 m in height that is commonly known as 'palmiet'. Despite the dominance of palmiet, many other species, such as *Wachendorfia thyrsiflora,* also occur within the wetland. In recent years, portions of the catchment and wetland have been invaded by the non-native tree *Acacia saligna*, known locally as Port Jackson wattle.

During the winter months, mid-latitude cyclones travelling on westerly winds bring moisture and rainfall to the region. However, coastal and cut-off lows occasionally result in unseasonal rainfall events during summer and autumn. A full description of
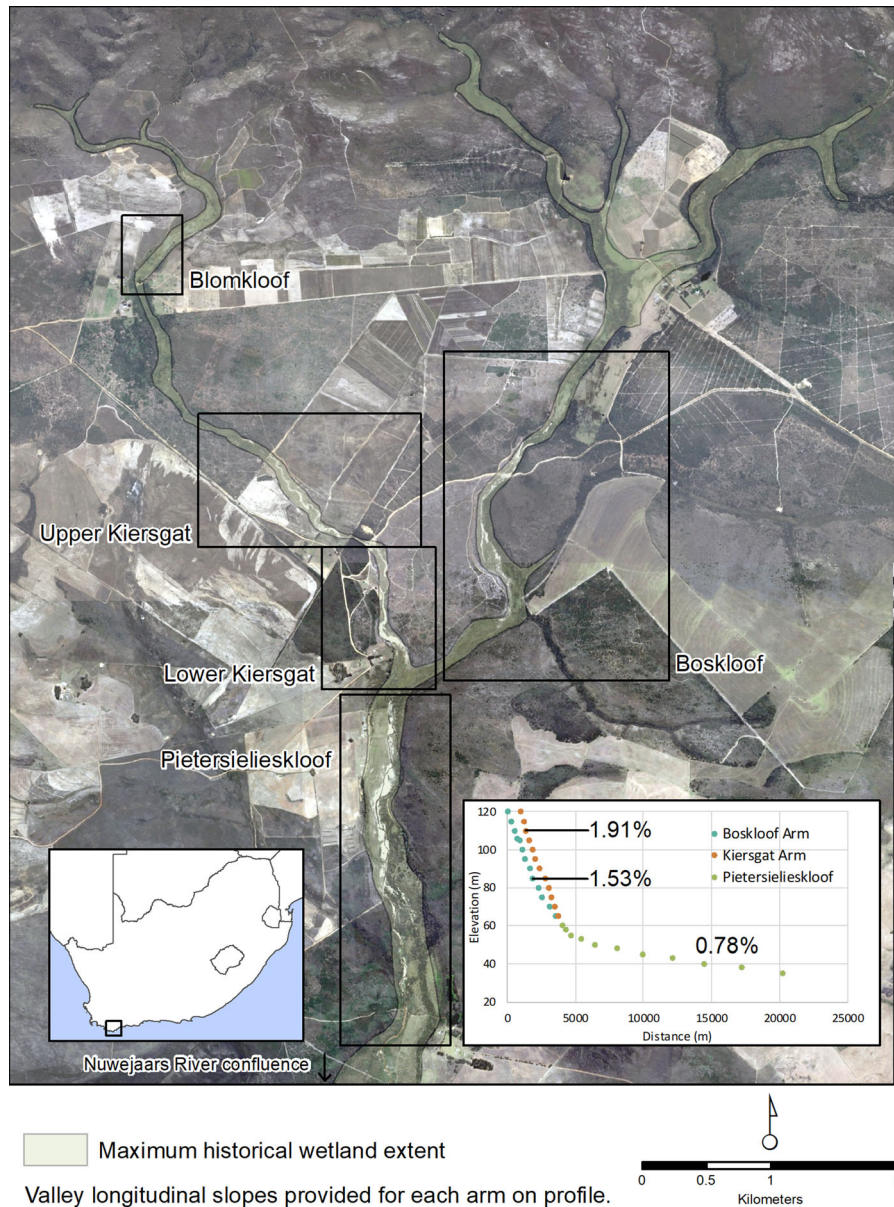
Fig. 1 The study area, located on the northern edge of the Agulhas coastal plain, may be sub-divided into 5 reaches. The longitudinal profile and associated valley surface slope are shown for each arm above the confluence at Pietersielieskloof

rainfall seasonality and variability is provided in the results section. The region's mean annual temperature is 17 °C (Rebelo et al. 2016).

Methods

Data collection

Daily rainfall data was obtained from the South African Weather Bureau for Zoetendalsvallei for the period 1938 to 2019. The station is located ∼24 km south east of the study area, but was the only local rainfall station that covered the full period of historical

aerial photography without interruption. Furthermore, given the topography of the coastal plain, the data is likely representative of the study area.

In order to establish a historical range of landscape variability, aerial photographs from 1938 (1:25 000), 1961 (1: 36 000), 1989 (1: 50 000), 2003 (1: 50 000), 2005 (1: 10 000) and 2014 (1: 15 000) were georeferenced and analysed. Due to scale, detailed mapping was only possible on the 1938, 2005 and 2014 imagery. Other images were used to demarcate wetland extent, disturbed areas, moderate sized alluvial deposits and some channels. Within the wetland, a change in vegetation texture as *P. serratum* was replaced with invasive wattle species was discernible from 1989 onwards. Valley longitudinal slopes could be calculated using the 2005 orthophotographs which have 5 m contours and occasional spot heights. Geomorphic change in the last 20 years has been rapid and could be visually assessed using Google Earth, as such, high resolution satellite images from 2003, 2006, 2012, 2014, 2016 and 2020 were also included in the analysis.

A Differential GPS survey of the lower Kiersgat reach was conducted in April 2018 to capture detailed variation in thalweg longitudinal slope and valley morphology (sub-cm accuracy in x, y and z). In September 2018, the sedimentology of the Kiersgat reach was established by detailed sediment profile descriptions and sampling of the gully walls at 7 locations (Fig. 2; samples sites UK 1 to 5, and LK 1 to 3). The locations were selected by walking the length of the gully and choosing representative sites. Noticeable changes in particle size, colour or organic content were noted, and each layer sampled. When there were no obvious changes, samples were taken every 0.5 m. To compare to currently intact systems, two additional sites were selected. One at a headwater setting at Blomkloof, where a 1.75 m core was taken using a gouge corer (Fig. 2; sample site Blomkloof 1). The core was logged and sampled in the same way as the gully walls. A 5.7 m high sediment profile was sampled toward the northern end of the Boskloof reach (Fig. 2; Boskloof 1). While the wetland was completely dessicated at this position, the sedimentology was intact and a vertical incisional face allowed direct sampling.

Data analysis

Daily rainfall data was used to calculate a long-term annual and monthly mean. An analysis of recurrence interval of ranked annual maximum daily rainfall was conducted for the period from 1938 to 2018, where recurrence interval (years) = $(n + 1)/m$, and n = number of years in the record and m = rank of event. For the 6 largest daily events on record, rainfall on surrounding days was considered and the cumulative total considered as a proportion of that year's total annual rainfall as well as relative to the annual mean.

Sediment samples were air dried and then processed for organic content and particle size. To determine organic content, a dried pre-weighed sample was burnt in a furnace for 12 h at 550 °C and the mass lost calculated. As the sediment samples were predominantly sand to silt sized, particle size was determined by sieving in a sieve shaker for 10 min.

Five samples were selected for radiocarbon dating at DirectAMS. These represent the only sedimentary layers within the system that had an organic content greater than 30%. To contextualise geomorphic processes along the different wetland reaches, an organic rich layer at a depth of 4.10 to 4.15 m from Boskloof was dated (Fig. 2; Boskloof 1), as was the basal organic layer at Blomkloof at a depth of 1.40 to 1.50 m (Fig. 2; Blomkloof 1). Only 3 organic layers were located within gully walls in the Kiersgat reach, but were considered indicators of the onset of an aggradational cycle (Fig. 2; UK 1, UK 5 and LK 3, described in section 4.4). These three samples were therefore also dated.

Sedimentation rates were calculated by comparing the radiocarbon date with the depth of overlying sediment. It was assumed that the overlying sediment was likely not a complete stratigraphic record, and likely represented a net sediment flux over the period concerned. The relationship between sedimentation rate and radiocarbon dates was evaluated using a power function to determine how sedimentation rates might adjust over time. The power function was used to estimate the time required for gully infill or recovery.
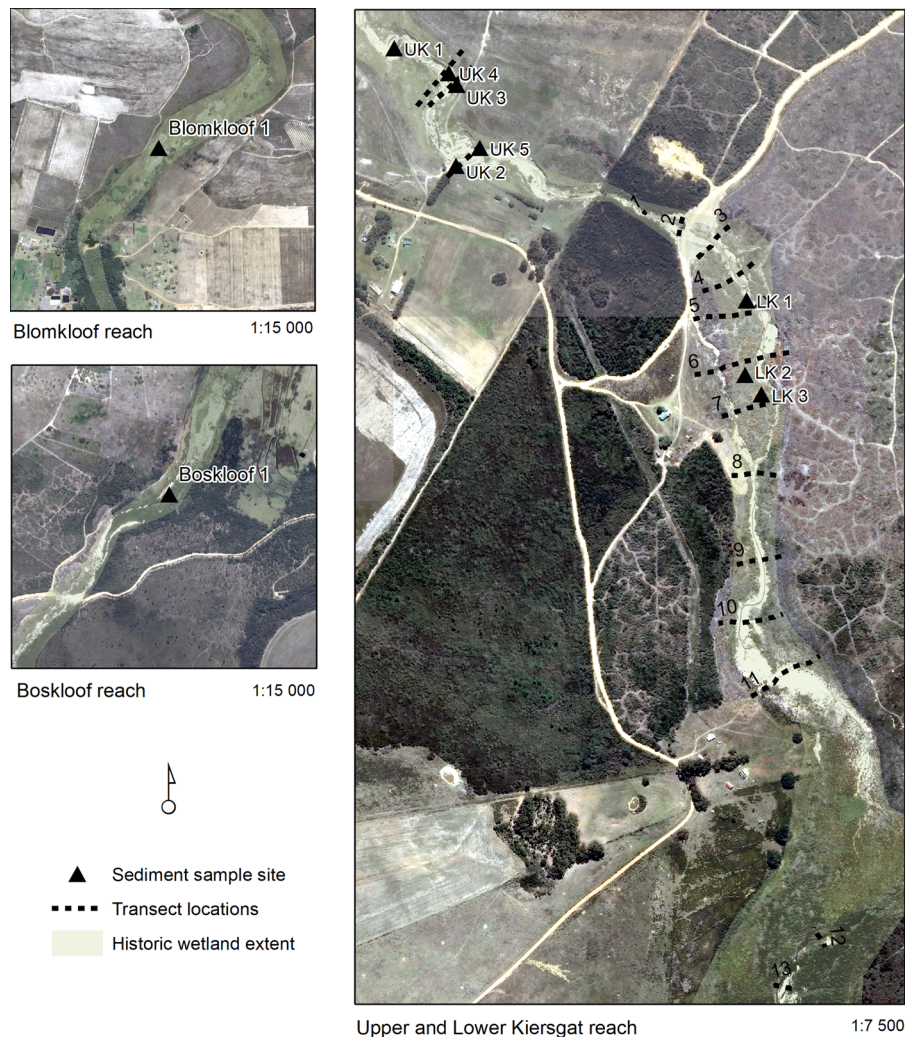
Fig. 2 Location of sediment sample sites and cross-sections selected for display in Fig. 8

Results

Historical rainfall variability

Rainfall is seasonal with 36% falling during winter and 28% during autumn (Fig. 3a). The summer months of December, January and February are usually extremely dry.

An analysis of long-term trends in annual rainfall indicates that prior to 1965, rainfall was generally higher than the long-term average (Fig. 3b). This was followed by a distinctly drier period between 1965 and 1984. In the period since 1984, rainfall has been highly variable, with lower than average rainfall between 1999 and 2001, 2009 and 2011, and again from 2016

until present. The wettest year on record occurred in 1964 (980.7 mm), while the driest year on record was 1973 (124.5 mm). The annual coefficient of variation is high by global standards at 31%, but is similar to other regions in southern Africa (Dettinger and Diaz 2000).

Annual rainfall variability is related to irregular, extremely large rainfall events (Fig. 3c), which frequently account for a large proportion of the annual rainfall in that year. Daily rainfall events greater than 100 mm are ranked in Table 1. The largest daily rainfall event occurred on 6 November 1964 (260 mm), rain fell over a period of 9 days reaching a cumulative total of 323.5 mm. This event accounted for 33% of the rainfall in that year, but is equivalent to
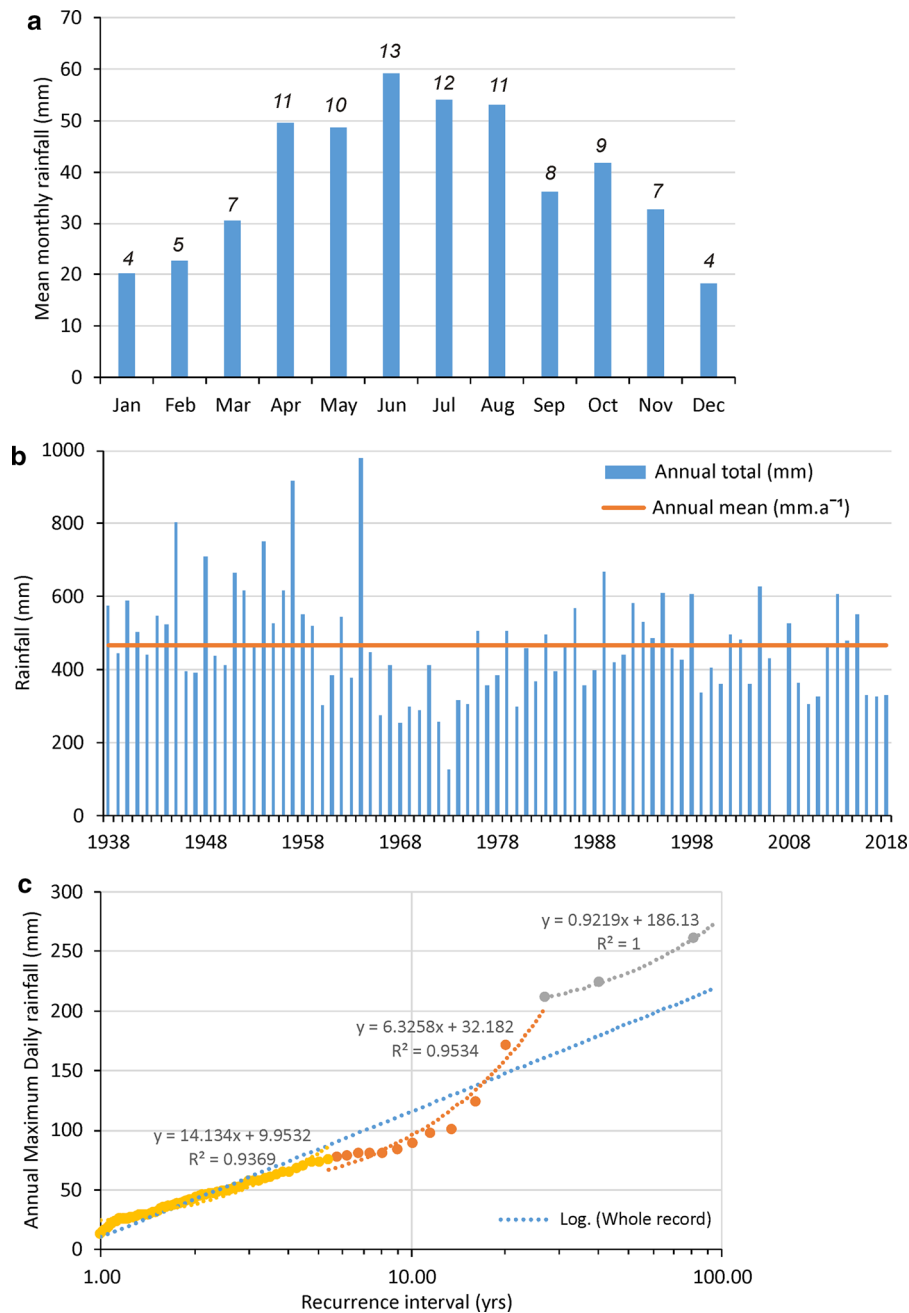
Fig. 3 Rainfall seasonality with contribution of each month as a percentage of annual mean given as a percentage in italics (**a**), historical rainfall relative to the long-term mean (**b**), and recurrence interval of annual maximum daily rainfall (**c**). The best-fit line to the entire data set is shown in blue, indicating the likelihood of under-estimating large magnitude events. Alternative best-fit lines for the different slopes are shown. Data shown is for Zoetendalsvallei obtained from the South African Weather Bureau

70% of the long-term annual mean. Similarly large events occurred in October 1948 (223.5 mm) and April 2005 (211.0 mm), the latter event is recorded in local news articles as causing major floods in the area, while historical orthophotographs of the date document the

Table 1 Summary of daily rainfall events exceeding 100mm at Zoetendalsvallei between 1938 and 2018

Rank	Date of rainfall peak	Maximum daily rainfall recorded (mm)	Recurrence interval (years)	Annual probability (%)	Event duration (days)	Event total (mm)	% of annual rainfall for event	% of annual long-term mean for event
1	06-Nov-64	260.8	81.0	1.2	9	323.3	33	69
2	11-Oct-48	223.5	40.5	2.5	7	315.5	45	68
3	11-Apr-05	211.0	27.0	3.7	4	293.5	47	63
4	16-Feb-40	171.7	20.3	4.9	3	223.1	38	48
5	19-Mar-95	124.0	16.2	6.2	2	125.0	20	27
6	29-Apr-76	101.0	13.5	7.4	5	127.7	25	27

wide-scale occurrence of landslides in the catchment of Pietersielieskloof.

During each year, there is usually a single rainfall event that delivers 11 % of the annual total for that year. A detailed analysis of recurrence intervals indicates an unusual spread of large events that cannot be accurately described using a single best-fit line (Fig. 3c). A 1 in 100 year rainfall event is likely to be in the region of 278 mm, while a 1 in 25 and 1 in 10 year event are 190 mm and 95 mm respectively.

21% of each year's largest rainfall events occur in April, even though April accounts for only 11% of the mean annual rainfall. A further 11% of the largest events occur in March. This is geomorphically significant as catchment sediment availability is typically high in autumn following the summer dry season as vegetation cover typically only re-establishes mid-to-late winter.

Historical geomorphic change

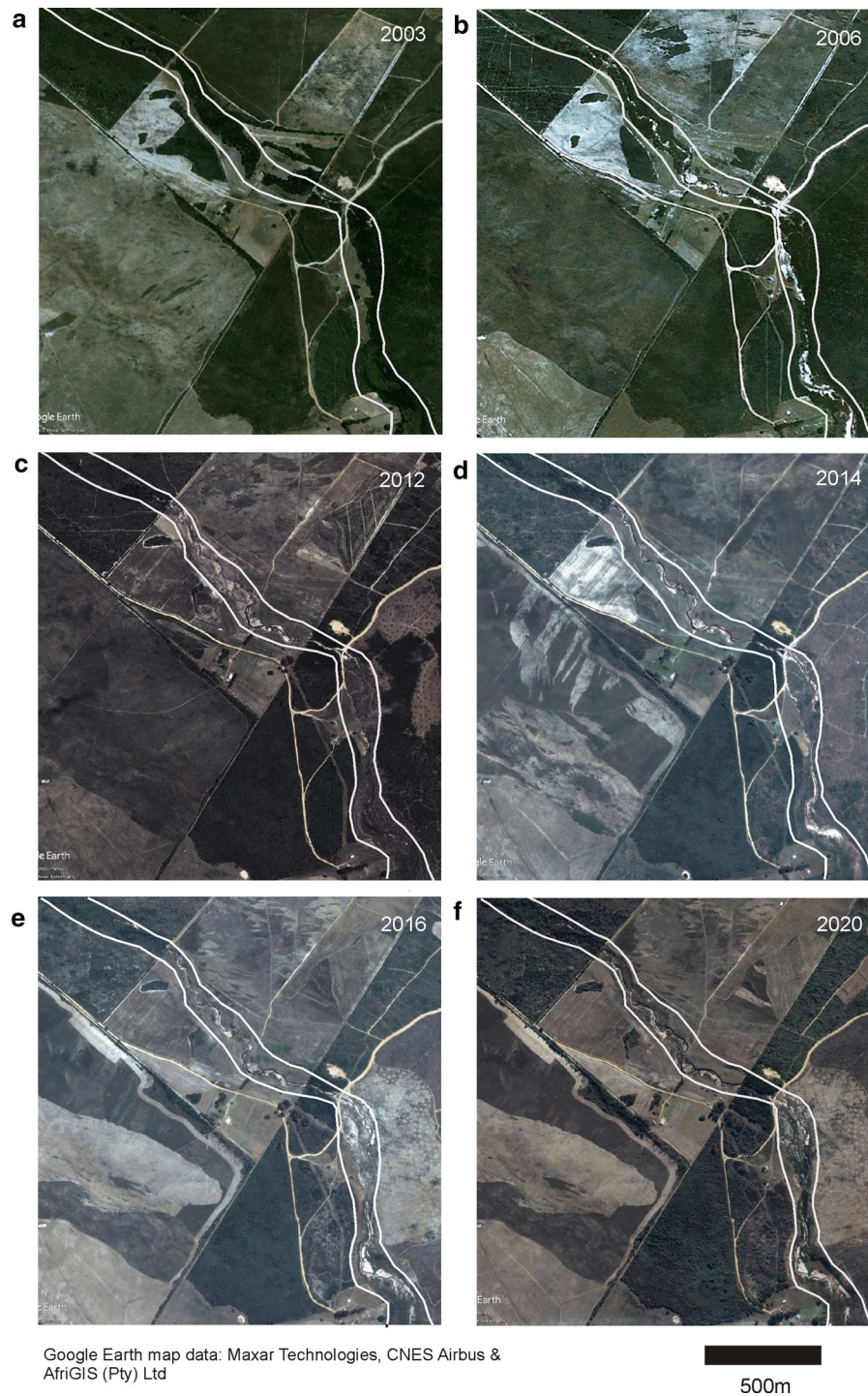*Upper and lower Kiersgat wetland reach*

The resolution of images prior to 2000 relative to the width of the Kiersgat reach prevents detailed mapping in GIS, although it is possible to broadly describe the changes. By 1938, a gravel road had been built across the Kiersgat wetland arm to provide access to a farmstead on the wetland boundary and there were indications of wetland disturbance. A vegetated channel was visible propagating upstream from the road, but toward the northern end of the upper Kiersgat

reach, the channel was laterally eroding via meandering, as could be seen by extensive patches of reflective alluvium. Immediately downstream of the road, erosion of the wetland in the form of a channel was visible. By 1961, the channel had become fully vegetated above and below the road. However, small to large depositional bars and floodout features were visible immediately below the previously meandering section and the road.

By 1989, agricultural activities had encroached into the wetland boundary in the upper Kiersgat reach, and the drainage line was vegetated with invasive alien *Acacia saligna*. There was no prominent channel. The trajectory of increasing agricultural encroachment continued to 2003. In April 2005, 293.5 mm of rain fell over 4 days (recurrence interval 27 years), an event which was associated with multiple landslides in the catchment. This event resulted in dramatic erosion of the upper Kiersgat; wetland vegetation was eroded and an actively meandering channel excavated a gully ∼ 30 m wide in which the channel became inset. Eroded sediment accumulated just downstream of the road and this portion of the wetland remained vegetated with *Acacia saligna*. Toward the confluence with the Boskloof arm, the channel re-emerged, again actively meandering and depositing sand sheets on its newly created floodplain.

The historical pattern of dramatic erosion and subsequent formation of sand flats immediately downstream, followed by revegetation (albeit with alien invasive species more recently), is repeated three times in the lower Kiersgat in the last 20 years (Fig. 4).

Fig. 4 Geomorphic change in the upper and lower Kiersgat wetland reach as shown in Google Earth high resolution imagery between 2003 and 2020. Erosion occurs within gullies, while areas of deposition adjacent to the gully and floodout deposits may be recognised by the highly visible white sand characteristic of the region

While the upper Kiersgat now appears to be locked into a phase of lateral valley expansion, the lower Kiersgat revegetated by 2012 following the 2005 floods. Channels re-formed following floods in 2013 (78.5 mm, recurrence interval 6.23 years) which coincided with local removal of alien invasive *Acacia saligna*. By 2020, there were indications that channel expansion and deepening had halted, and that vegetation cover was re-establishing.

Boskloof wetland arm

In 1938 and 1961, the Boskloof wetland arm was completely intact with native vegetation dominated by *Prionium serratum*. By 1989, textural variation indicated some vegetation disturbance immediately downstream of a more formalised road crossing although farming had not encroached within the wetland boundary. Following the April 2005 flood, 70% of the wetland vegetation was either eroded or inundated with sand sheet deposits characterised by a multi-distributary channel network that covered the entire wetland width. Vegetation cover was re-established by 2012, although textural characteristics indicated that it was not native vegetation (Fig. 5). Following a 78 mm event in 2013, a single channel became strongly entrenched through the centre of the wetland. It is notable that the western slopes of the wetland's local catchment had been recently cleared of alien vegetation. The channel flooded-out toward the southern confluence with the Kiersgat wetland, where natural vegetation was established. Between 2014 and 2020, the channel stabilised and the invasion of alien *Acacia saligna* trees within the wetland became a primary concern for wetland persistence.

Pietersielieskloof wetland

Due to the size of the wetland and features in the wetland below the confluence of the Kiersgat and Boskloof Arms, it is possible to map historical change in more detail (Fig. 6). In 1938, the wetland is fully intact, there is evidence of channelisation toward the southern end where the system approaches its confluence with the Nuwejaars River but this is likely natural. In February 1940 and October 1948, the fourth and second largest rainfall events on record occurred, delivering 48% and 68% of the mean annual rainfall in 3 and 7 days respectively (Table 1). Nevertheless, the

1961 aerial photographs indicate no observable change to the wetland which remains intact. By 1989, the earlier channels had become more distinct, potentially indicating wetland desiccation or reflection from sand sheet deposits. Between 1989 and 2003, the central portion of the wetland was reclaimed for agriculture and a drain was dug on the western boundary.

The response of the Pietersielieskloof to the April 2005 rainfall event was dramatic, the drain was completely infilled by a massive sand sheet deposit which covered 90% of the wetland surface. A new straight channel incised down the centre of the wetland. 11 years later, wetland vegetation had re-established at the northern confluence, while the central portion was converted to pasture and some sand sheets remained unvegetated. The channel remained a prominent feature, although it had migrated toward the eastern boundary. The entire eastern margin of the system was infested with alien invasive *Acacia saligna*. The system remained in a similar state in early 2020.

Wetland morphology

Valley longitudinal slopes calculated from the 2005 orthophotographs indicate that the systems are very steep relative to other wetlands of similar catchment size (Ellery et al. 2011). The average valley longitudinal slope for the combined Blomkloof and Kiersgat arm is 1.91%, which is double what one would expect for an intact wetland of comparable size based on the empirical model of Ellery et al. (2011). The Boskloof arm has a valley slope of 1.53%, while below the confluence at Pietersielieskloof, the slope is reduced to 0.78% (Fig. 1). The reduction in slope downstream is consistent with the effect of an increase in catchment area.

Figure 7 provides the detailed longitudinal morphology of the lower Kiersgat reach which has undergone several phases of disturbance and associated erosion since 1938. The pre-existing wetland (as indicated by the elevation of the top of the left and right banks) is highly uneven, and field observations identified several lobate floodout shapes through which the gully has more recently eroded (Fig. 8, cross-section 4 and 7). The average slope of the lower Kiersgat reach left bank, representing a pre-erosion surface, was 1.6%.

Fig. 5 Geomorphic change in the Boskloof wetland reach as shown in Google Earth high resolution imagery between 2003 and 2020

The thalweg profile is marked by five different process zones of different slopes. Immediately above the road, the thalweg slope is 1.7%. It is likely that upstream of the road is aggradational, as limited channel development at cross-section 1 indicates. At cross-section 2, the channel has been artificially excavated to limit flooding of the road (Fig. 8). There is a steep drop off downstream of the road due to

severe headcut erosion, illustrated by a break in slope in Fig. 7 (Fig. 8, cross-section 3 and 4). Lateral and vertical erosion in this reach has resulted in the formation of a sediment slug (defined as a body of clastic material that moves downstream over time periods longer than the event-scale, Nicholas et al. 1995), the surface of which has a slope of 1.45%. The sediment slug appears to locally reduce lateral gully
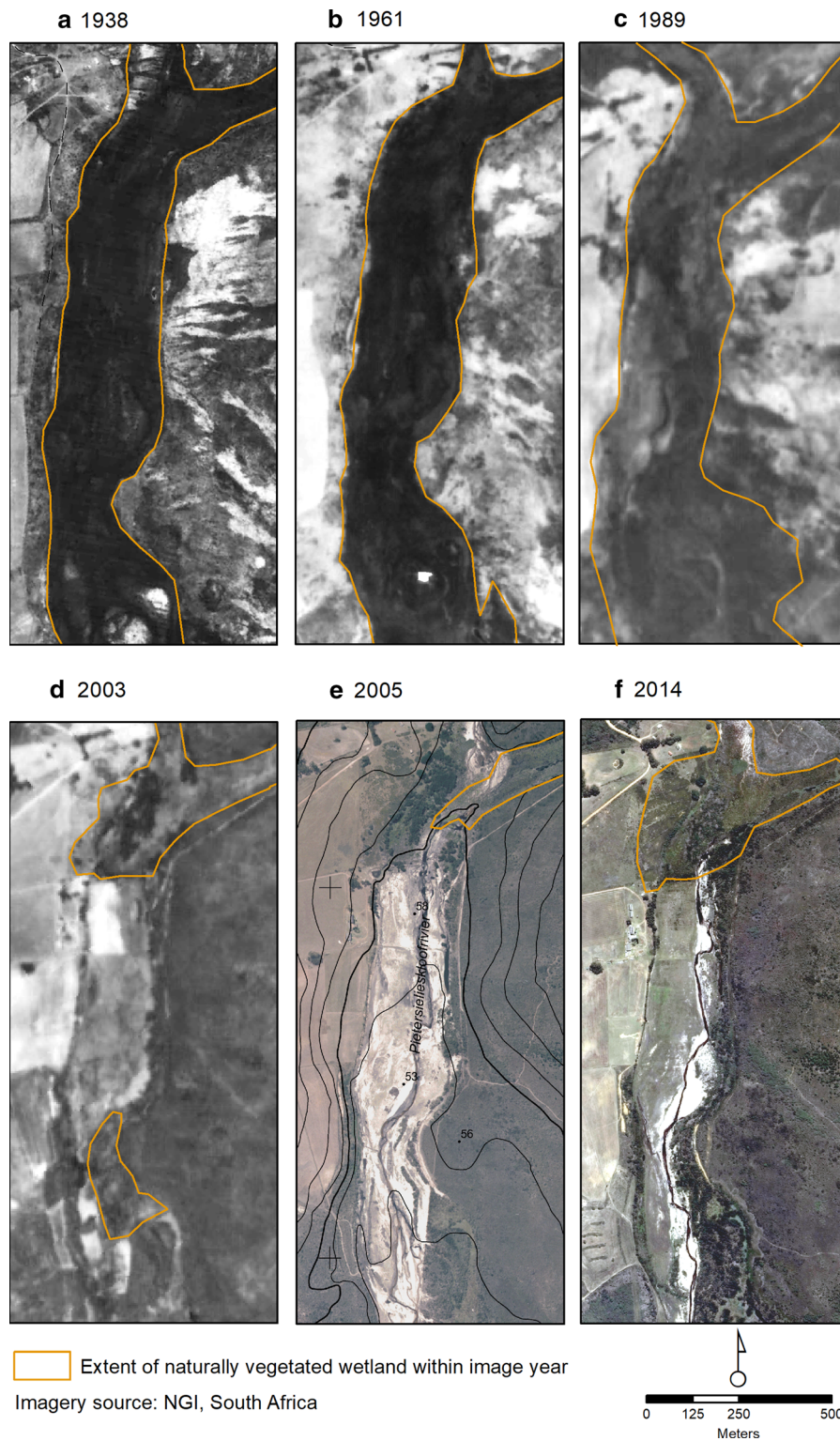
Fig. 6 Geomorphic change in the Pietersieliekloof wetland below the Kiersgat and Boskloof confluence as shown in NGI imagery from 1938 to 2014
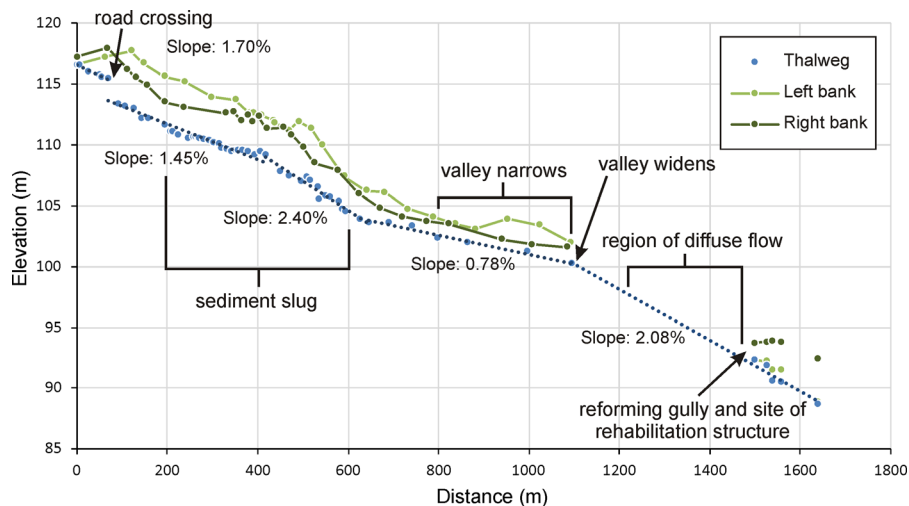
Fig. 7 Detailed DGPS survey of the lower Kiersgat reach, the elevation of the left and right bank and thalweg are shown. Slopes are for thalweg sub-reaches

erosion at cross-sections 5 and 6, as demonstrated by the reduced cross-sectional area and longitudinal slope, while downstream, the prograding face of the sediment slug is steepened (2.40%). Below the sediment slug, the wetland narrows and the slope is reduced to 0.78% (Fig. 8, cross-sections 8 and 9). The gully becomes shallower and the valley widens toward the confluence with the Boskloof arm. At this point, the wetland transitions from channelled flow to a diffuse flow over a large floodout associated with aggradation within a diffuse channel network (Fig. 8, cross-section 10 and 11). This is associated with thalweg steepening (2.08%).

Wetland sedimentology

The sedimentology of profiles sampled within the Upper Kiersgat (UK) reach were generally low in organic content (< 6%), and were dominated by medium to coarse sand (Fig. 9). UK 2, the longest of the exposed profiles, comprises a series of depositional sequences which are sometimes truncated by erosion. The most recent deposit comprises a sediment sequence of 112 cm, with fine sand at the base followed by a massive deposit of coarse sand, topped with fine sand assumedly deposited during the waning flood phase. Another sequence of almost a metre is preserved between 265 and 355 cm, including a layer of gravel in a coarse sand matrix.

Sediment profile UK 5 was sampled on the opposite gully wall at the same location as UK 2 (Fig. 2). Despite the spatial proximity, there is massive differentiation in sedimentology, indicating that different sedimentary environments are represented. The base of the sequence is underlain by gravel within a coarse sand matrix, indicating a fairly high energy environment. The onset of a wetland environment is indicated by 1 m of gleyed fine sand with an organic content of 27%, the base of which dates to 5530 ± 42 years BP (Table 2). This is overlain by sediment which fines upward from medium to fine sand. High organic content at the top of the sequence in addition to gleyed sand, indicate that wetland conditions were locally re-established. A comparison of the two sedimentary sequences at UK 2 and UK 5 suggests that the depositional phase from 5530 years BP accumulated in a topographic low, most likely in the form of an infilling gully as is seen currently at cross-sections 9 and 10. UK 2 appears to represent a fairly stable floodout feature with massive sand deposits that manifest in planform as sand sheets. These are seen on current aerial photography as highly reflective expanses with little or no vegetation. Critically, wetland formation occurs within infilling gully features, and floodout features are fairly low in organic content.

UK 3 is similar to UK 2, with portions of flood events preserved, including a massive medium sand deposit at the base which is just under 1m deep. Immediately upstream UK 4 is more homogeneous,
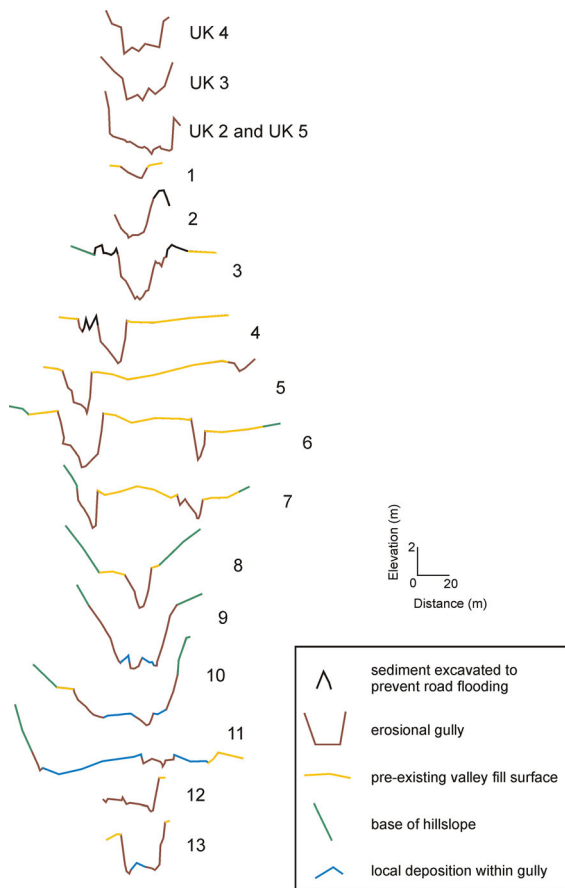
Fig. 8 A selection of cross-sections across the Upper and Lower Kiersgat reach. Due to expansive infestations of *A. saligna* as well as the occasionally very broad valley, it was not always possible to survey to the base of the hillslope. The location of each cross-section is indicated in Fig. 2

comprising 1.5 m of a well-sorted upward coarsening sand sequence. UK 1 was sampled from an organic rich layer that was exposed by erosion and was in situ on the gully floor. This wetland surface was dated at 3311 ± 30 years BP and was buried by 2.5 m of medium to coarse sand deposits before exhumation by gullying.

Overall, the sediment profiles represented in the Lower Kiersgat reach are more homogenous than those in the Upper Kiersgat. The deposits at LK 1 and LK 2 are fairly homogenous, characterised by massive deposits of fine to medium sand. Organic contents are typically less than 5%. At LK 3, a gravel with coarse sand matrix deposit is overlain by a gleyed organic lens (organic content 62%) which is approximately 15 cm thick at its centre. This is topped by extremely

well-sorted sand deposits. The abrupt change in the energy of the depositional environments suggests that this organic deposit accumulated within a depression created by gully erosion.

The sedimentary profile at Blomkloof is the only location where the wetland is intact. The upper 145 cm of the sequence consists of weakly consolidated fibrous peat deposits, the base of which was dated at 814 ±26 years BP. This is underlain by well sorted medium sand with extremely low organic content.

At Boskloof, a 6 m deep sediment profile is exposed in an active gully while palmiet and other wetland vegetation still grow on the adjacent pre-eroded wetland surface. The lower 2 m of the exposure comprise well-sorted medium sand, with organic contents less than 3%. The uppermost portion of this basal sequence coarsens slightly, with gravel supported by the sand matrix. The sequence is overlain by 0.5 m of organic, gleyed sand with an organic content of 43%. This organic rich deposit was dated at 6098 ±45 years BP. This is topped by 3.5 m of alternating medium and coarse sand with minor amounts of gravel. The top 1.5 m, immediately below the current wetland surface, fines substantially to medium silt.

In each of the cases where dating was undertaken due to locally high organic contents, the underlying material was a unit of gravel (between 2 and 15%) supported by a sand matrix. This suggests a sudden shift from a high to low energy environment, consistent with an environmental interpretation of an incisional gully that is beginning to infill.

Discussion

Spatial and temporal patterns of incision and aggradation

The sedimentology of the Pietersflieskloof palmiet wetlands marks them as dissimilar to those of the Krom (Pulley et al. 2018). Peat accumulations do not extend across the valley, and appear to only occur in thalweg positions as part of the early phase of channel fill (post-impoundment of a gully by downstream floodout formation). This is well demonstrated by the rather different profiles represented at UK 2 and UK 5 which are on opposite banks of the same gully site. Massive sand deposits represented in the profiles that are typically between 0.8 and 1 m in depth must be
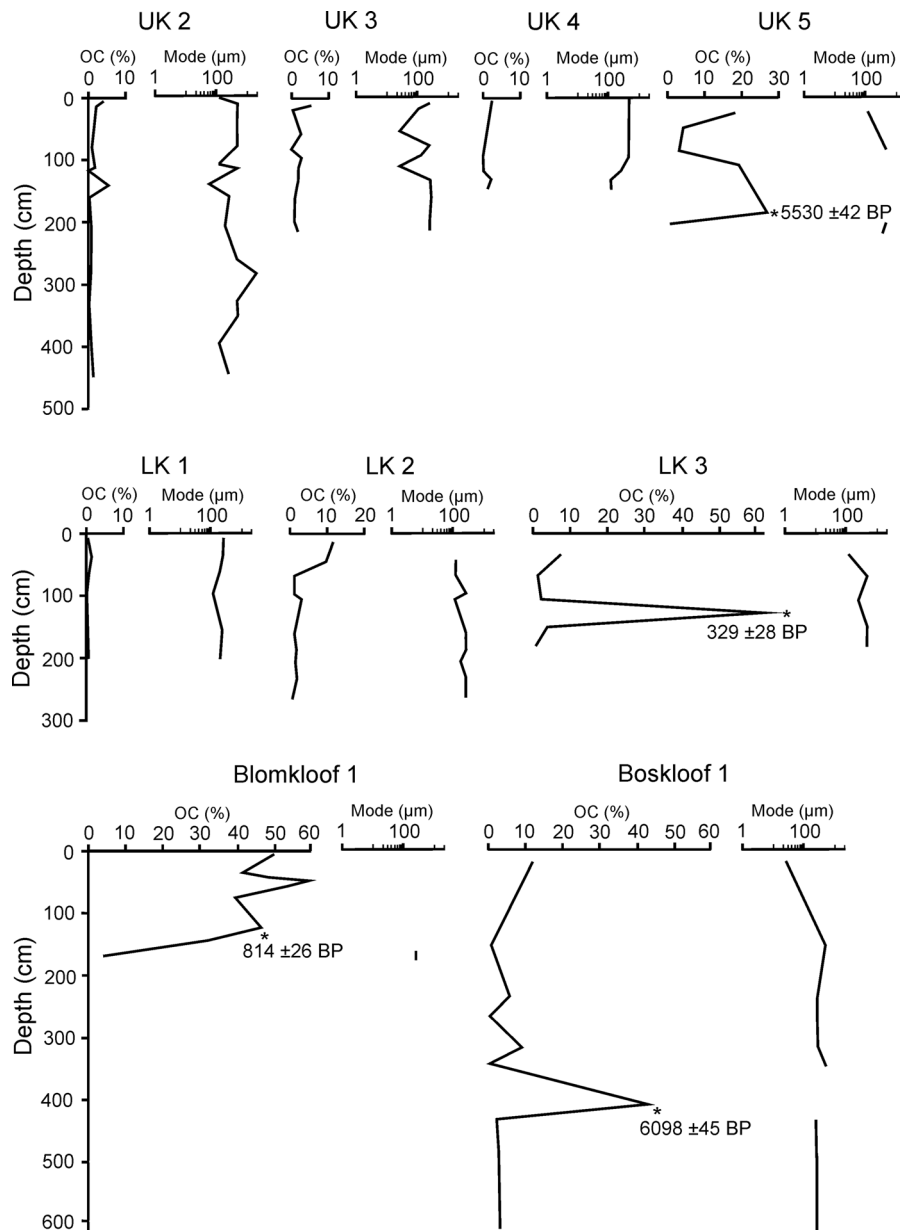
Fig. 9 Organic content (%) and modal particle size (for samples < 30% organic content) profiles for all sample sites. The same scale is used for each to allow for comparison. The location of each sample site is shown on Fig. 2. A profile is not shown for UK 1, as this sediment sample was taken from an exposed in-situ valley floor

analogous to modern floodout deposits. Following incision, wetland formation and the first site of palmiet recruitment seems to originate from within an infilling gully impounded by the floodout, rather than on the floodout itself.

In the Pietersieliekloof it was not possible to verify the duration of previous erosional phases. More

recently however, historical aerial photography indicates that the Kiersgat reach has been locked in a sequence of incisional events since 1938. While there has been some deposition in the form of floodouts and vegetation cover has returned (although likely non-native), the overall theme has been one of vertical and lateral erosion. The most recent phase of incision

Table 2 Sample location, characteristics and radiocarbon ages for sediment samples dated by DirectAMS

| Laboratory code	Sample name	Description	Location	Sample depth (cm)	Radiocarbon age	
					BP	1σ error
D-AMS 032031	Blomkloof 1 (140–150)	Organic rich layer above sandy valley floor	Blomkloof	140–150	814	26
D-AMS 032033	Boskloof 1 (410–415)	40cm thick peat layer buried within clastic deposits, underlain by m sand	Boskloof	410–415	6098	45
D-AMS 032032	UK 1 (40–50)	Exposed peat deposit on valley floor, 2.50m below gully bank top	Kiersgat	280–285	3311	30
D-AMS 032035	UK 5 (180–190)	Base of 1.3m thick organic gleyed clay, underlain by clean f sand, overlain by cobbles in a sand matrix	Kiersgat	180–190	5530	42
D-AMS 032034	LK 3 (125–135)	20cm thick peat layer, underlain by c sand, overlain by m sand	Kiersgat	125–135	329	28

began prior to 1938 in the Kiersgat reach, while in the Boskloof reach it began between 1961 and 1989. Radiocarbon dating allowed the onset of previous fill phases to be documented. This was possible because sediment cores and profiles consistently revealed that organic deposits were underlain by gravel in a sand matrix, indicative of a high energy gully environment. The chronology presented therefore captures the periods of transition from a high energy gully to a low energy depositional environment.

Phases of aggradation varied in length from ∼ 300 years in the lower Kiersgat reach to more than 6000 years in the Boskloof reach (Fig. 10). The dates provide a system-scale indication of the temporal variation in cut-and-fill processes within a single wetland drainage line. The headwater reach at Blomkloof is relatively young (814 years BP), and the 1.5m deep organic deposit reflects both local hydrology (permanently saturated, potentially due to groundwater recharge at base of mountains) and low rates of

sediment supply. In contrast, the Boskloof reach is characterised by a prolonged phase of aggradation since 6098 years BP that has resulted in over 4m of alluvial fill. In the Kiersgat, three erosional phases followed by aggradation could be recognised, dating at 329, 3311 and 5530 years BP. However, none of these phases was represented in more than one location, suggesting that phases of erosion and subsequent deposition were spatially segregated, a view that is consistent with cut-and-fill processes as described by Patton and Schumm (1975). In contrast, the current phase of incision is synchronous across the drainage line. This synchronicity is unprecedented in the sedimentological record (Fig. 10); never before during the Holocene has more than one reach actively incised at any one time. Prosser (1991) describes a similar pattern of unprecedented widespread erosion following European settlement in similar dryland wetlands that were also characterised by intrinsically controlled local episodes of gullying.

Implications of the catchment context for geomorphic processes

In the absence of anthropogenic drivers prior to 1700, incision in the Pietersieli.eskloof system is likely driven by exceedance of a geomorphic threshold slope. However, the current phase of unprecedented synchronous incision suggests that other factors may be responsible for regionally accelerating threshold exceedance. The catchment has been altered in the last
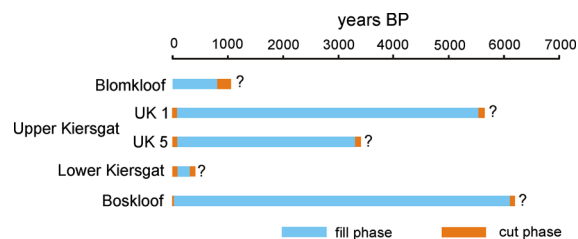
Fig. 10 Timing and duration of known cut and fill phases in the Pietersielieskloof drainage lines

century, changing from largely natural fynbos shrub, to open grassland pastures and wheat fields that are seasonally fallow, with intervening patches of invasive alien vegetation. This has likely altered the hydrological regime of the catchment and wetland. In addition, road crossings have channelized flow through culverts, while road maintenance crews routinely remove sediment accumulating adjacent to roads to prevent flooding. This has the effect of increasing the catchment's quick flow response, while reducing connectivity in terms of the longitudinal sediment supply.

Rainfall data indicates the occurrence of two large rainfall events (February 1940 and October 1948, Table 1) between the aerial photograph image years of 1938 and 1961. Despite the size of these events, neither produced an observable geomorphic impact in the wetland (Fig. 6). A further two major events occur between 1961 and 1989 (Nov 1964 and April 1976, Table 1), once again there is no major change in wetland geomorphic processes. Between 1989 and 2003, the wetland is drained for agricultural use, and a channel flowing through the wetland becomes clearly visible. In April 2005, 211 mm of rain falls within 24 h, generating a massive catchment response. Wetland drainage lines are characterised by a paired response of incision and subsequent widespread deposition of sand sheets. Consideration of the rainfall record in conjunction with the system's geomorphic history indicates that the size of individual rainfall events is not important when considering the geomorphic impact. More frequent, larger rainfall events had very little impact on wetland processes prior to the 1980's, suggesting that there has been a reduction in wetland resilience over the last century.

Flume experiments have shown that it is almost impossible for channels to initiate in valley-bottom wetlands while vegetation is intact (Prosser and Slade 1994; Prosser and Dietrich 1995; Prosser et al. 1995). This is consistent with observations prior to 1980 of the Pietersieliskloof wetland reach (Fig. 6) which remained intact following extremely large rainfall events. This suggests that under 'natural' conditions, given thick vegetation cover, most Palmiet wetlands would remain intact even under extreme, low probability run-off events (as observed here). Instead, gullies would be initiated via headcut erosion from existing channels. Under natural conditions, most valleys are characterised by regions vulnerable to

channel formation. In the case of the Pietersieliskloof wetland system, channels might initiate naturally as reforming channels on the distal regions of floodouts or at points of valley confinement.

Under anthropogenic influences, wetland incision at Pietersieliskloof is likely initiated by road crossings that provide channelled knickpoints from which gullies extend upstream. This is likely exacerbated by land use changes which have altered the hydrology and sediment supply, resulting in accelerated breaching of a geomorphic threshold. The change in catchment land use from native vegetation to pastures and wheat has likely increased the run-off response, reducing infiltration rates and increasing run-off during individual storm events. The catchment mean annual run-off has effectively been increased, increasing the system's vulnerability to erosion.

The catchment context presents a challenge to ongoing wetland restoration attempts in the region. In order to be successful, wetland restoration needs to consider the viability of the catchment in creating an environment conducive to wetland formation. Alien species invasion, specifically *A. saligna* in this catchment, represents a major challenge. Mkunyana et al. (2019) demonstrated that for *Acacia longifolia*, a closely related alien species, water use of trees established along the riparian zone was typically double that of those established on the hillslope and was substantially higher than that of native plants. While it is clear that the removal of alien invasive species, specifically *A. saligna*, is critical for improving the hydrological viability of wetlands (Rebelo et al. 2015), the response of the wetland to changes in peak run-off following land use change indicates that the careful management of run-off following vegetation clearing is essential. In addition to the impact of alien trees on catchment hydrology, *A. saligna* was well established within many wetland reaches in Pietersieliskloof, reducing biodiversity and preventing the re-establishment of wetland vegetation. There appears to be a number of invasion pathways for these species; either gully erosion lowers the water table providing a window of opportunity for terrestrial seeds to establish, or the wetland water table is lowered by enhanced evapotranspiration on the wetland margins, allowing linear encroachment from the wetland edges. As such, Zierholz et al. (2001) further argue that even once a wetland may have recovered geomorphically, land use practices such as furrowing and within

wetland grazing may prevent full ecological recovery. In the case of the Pietersielieskloof, the largest challenges are likely to include the subsequent control of alien invasive species, abstraction of water for irrigation and potentially within wetland grazing.

Natural ecosystem recovery and the current landscape setting

Studies of processes of incision in wetlands in Australia have indicated that while incision may occur very quickly, the process of aggradation and recovery may take substantially longer. For instance, modelling conducted by Brooks and Brierley (2004) for the Cann River Floodplain suggested that it would take 31 000 years to infill a trench that had formed within just 40 years. In South Africa, the tectonic setting, on an uplifted portion of the crust, results in naturally increased sediment loads relative to Australia (Milliman and Meade 1983). However, many systems may be transport-limited due to seasonality and variability in rainfall and flow. Furthermore, rapid infilling may be associated with other challenges. For instance, Zierholz et al. (2001) found that despite fairly rapid infilling, the vegetation assemblages of 'newly created' wetland meadows were quite different from those of the pre-existing meadows, with much lower plant diversity. In addition, the newly created systems tended to be in-stream rather than across the valley floor and thus more narrowly contained than their predecessors.

When considering the potential for natural ecosystem recovery, in addition to considering the catchment context, it is also necessary to reflect on the likely time-period of recovery as this has implications for long-term restoration maintenance as well as future provision of ecosystem services. Given spatial and temporal variability in processes and rates, providing this information has been elusive in many South African wetlands. However, recent radiocarbon dating of the Pietersielieskloof (this study) and the Krom (Pulley et al. 2018) provides insight into recovery rates in these two palmiet dominated systems. A comparison of long-term sedimentation rates and the period over which that sediment accumulated yields a power function that demonstrates that sedimentation rates in these cut-and-fill systems decreases dramatically over time (Fig. 11a). Termed the 'Sadler effect', this power function suggests that sedimentation within these
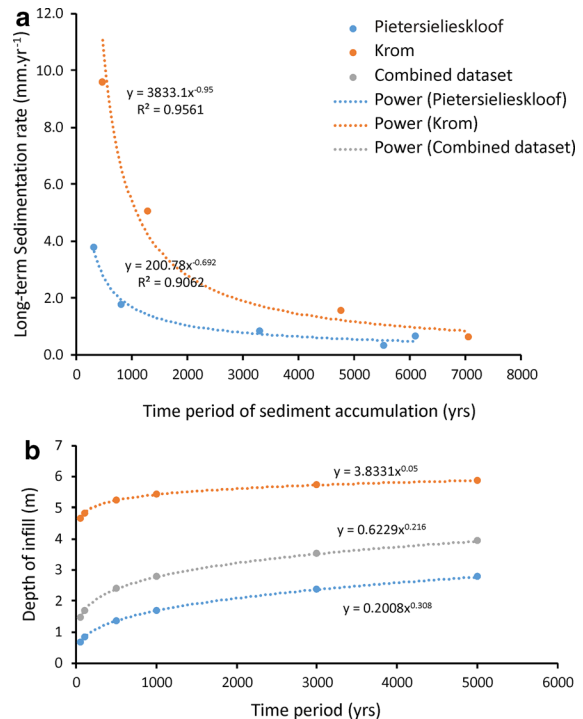
Fig. 11 The relationship between long-term sedimentation rates and the period of sediment accumulation demonstrates that sedimentation rates typically decline over time (**a**). The best-fit line is a power curve for both the Krom (dates from Pulley et al. 2018) and Pietersielieskloof wetland systems. The formulae may be reformatted to express depth of sediment infill over time (**b**)

systems is discontinuous (cyclical or random) (Sadler 1981). This is consistent with preserved sedimentological sequences, which indicate that single events may contribute up to 1 m of sediment in the Pietersielieskloof wetland system. Over prolonged periods of time, the stratigraphic record is disturbed by either hiatuses of no deposition, or erosion (Schumer et al. 2011). As a result, the time taken to 'fill' an erosional gully may be much longer than might be anticipated based on recent sedimentation rates alone. Initial sedimentation rates in the Krom wetland are much higher than those of the Pietersielieskloof wetland; this is likely an indication of higher sediment availability and / or transport capacity.

In order to assess the time required to infill an incised gully, taking into account that long-term sedimentation rates are likely reflect periods of deposition, stasis and erosion, sedimentation rates were converted to depth of infill for specific time periods (Fig. 11b), using the equations provided in

Fig. 11a. These equations provide an estimation of the natural rate of infilling *provided the catchment is undisturbed*. As the Krom system has much higher initial rates of sedimentation, this has a marked impact on the trajectory of recovery. A typical gully in the Krom is ∼5 m deep (Pulley et al. 2018), and at the declining sedimentation rate described in Fig. 11a, would infill within ∼100 years. In contrast, a gully in the Pietersielieskloof system is typically 3 m deep, and would require ∼5000 years to infill.

Despite similarity in vegetation cover (*P. serratum* dominated) and the occurrence of cut-and-fill processes in both systems, there are clear differences in recovery pathways that are likely linked to sediment supply and transport capacity. This has implications for the viability of natural recovery as a restoration option when high value ecosystems are threatened, as a recovery period of 5000 years in the case of the Pietersielieskloof is likely to be considered too long. In contrast, in systems with high sediment supply and rapid initial infilling, the importance of sustaining the longitudinal sediment supply through appropriately designed road crossings and restoration structures is highlighted by the findings presented in Fig. 11.

Conclusion

The current synchronous phase of incision across the Pietersielieskloof wetland system is unprecedented in the last 6000 years, and is likely related to increased hydrological connectivity induced by land use change and ill-designed road crossings. Thus, while processes of erosion and deposition are synonymous with cut-and-fill processes, the current phase of erosion is out of step with the sedimentary record. In contrast with land use changes that tend to promote a rapid stormflow run-off response, the maintenance of road crossings and dams reduce sediment connectivity longitudinally by removing sediment from the dispersal system. Landscape connectivity is key in determining geomorphic recovery potential (e.g. Fryirs and Brierley 2000; Fryirs et al. 2007; Brierley and Fryirs 2009) and in the case of cut-and-fill wetland systems where sediment is integral to gully infilling, artificial impediments to longitudinal sediment transport connectivity prevent natural recovery. Human impacts have resulted in the wetland system attaining a new fixed, altered state which is less resilient and less desirable

than the naturally occurring system, and therefore supports a geomorphological case for the Anthropocene in many South African wetlands (Brown et al. 2013).

As a result, wetland restoration in South Africa is at a philosophical crossroads which has been thoroughly tested by cut-and-fill wetland systems that do not conform to the dominant restoration strategy of halting erosion. As wetland practitioners, either we accept that in some wetlands catchment hydrology and sediment transport regimes have been irrevocably altered and that these wetland systems cannot be returned to their natural state, or we must proactively combine integrated catchment management (e.g. run-off management, alien invasive removal strategies) with the construction of appropriate wetland restoration structures that do not set geomorphic systems into static trajectories.

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