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Valley morphology and sediment cascades within a wetland system in the KwaZulu-Natal Drakensberg Foothills, Eastern South Africa

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ABSTRACT

Sedimentological connectivity within drainage systems may be controlled spatially by 'pockets' of intact valley fill, alluvial fans impinging laterally on mainstem rivers, floodouts impinging longitudinally on valley floors, and downstream resistant rock bands and their effect on valley width. Where local conditions favor prolonged inundation of the uppermost ~0.5 m of the sediment surface, these environments of deposition host wetlands that provide several ecosystem services to society. In this paper, we examine the long-term (millennia), large-scale mediation of connectivity by geological and geomorphological controls, highlighting the relationship between drainage disconnectivity and wetland origin, and appraise ongoing rehabilitation efforts in light of the long-term natural dynamic. The paper uses a wetland system in the KwaZulu-Natal Drakensberg Foothills, eastern South Africa, as a case study, focusing particular attention on part of the system in which cut-and-fill processes are evident, and proceeds, using observations from this and other similar wetland systems in the region, to discuss successive breaks in connectivity with increasing spatial scale and time. Implications for valley morphology are discussed, and channel incision is shown to play an important role in long-term valley and wetland morphodynamics in certain geomorphological settings, creating a diversity of geomorphological features and hydrological regimes. Thus, rehabilitation practitioners should focus on interventions that improve or stabilize desired functional outcomes, rather than on restoring or maintaining what is perceived to be 'the natural dynamic' in which erosion is absent.

1. Introduction

Ferguson (1981: 90) poignantly described the nature of sediment delivery by referring to river channels (and floodplains, where channels are laterally active) as "a jerky conveyor belt for alluvium moving intermittently seawards". Episodic and intermittent sediment delivery through drainage systems has since been studied in a variety of settings internationally, over a range of temporal and spatial scales. River channel studies have focused on the movement of 'sediment slugs' (Lisle et al., 2001; Kasai et al., 2005), and 'sediment waves' (James, 1989, 1991), and the effects of in-channel storage on catchment sediment yield (e.g. Walling et al., 2003, 2006), and sediment delivery ratios (e.g. Walling et al., 2001, 2002). Other studies have focused on 'coupling'; the degree of connectivity between components of a system (Brunsden and Thornes, 1979), particularly as it refers to sediment delivery from hillslope to stream channel (e.g. Fryirs and Brierley, 1999; Harvey, 2001; Betts et al., 2003). Fryirs et al. (2007a,b) expounded and synthesized notions of coupling and sediment cascade disconnectivity, using the terms 'buffer' and 'barrier' in describing disruption to longitudinal and lateral linkages in sediment delivery by valley alluviation within depositional landscape settings.

From a geomorphological perspective, wetlands are environments of deposition, and many of the world's wetlands occupy the depositional landscape settings of disconnected drainage systems. In South Africa, valleys cut into lithologies of the Late Carboniferous to Late Jurassic Karoo Supergroup host wetlands in settings where incision is impeded, such as upstream of resistant dolerite intrusions (Tooth et al., 2002, 2004). These intrusions form stable local base levels, and locally restrict valley width, slowing the rate of sediment delivery to downstream reaches of the rivers they cross, as sediment is stored upstream within floodplains, and reworked by meandering rivers over ~10s ka (Tooth et al., 2007). Within this period, local vertical levee and alluvial ridge accretion on floodplains impounds adjoining valleys, resulting in tributary deposition and the formation of tributary valley-fill wetlands (Grenfell et al., 2008). Channels within these tributary wetlands typically attain discontinuity toward their

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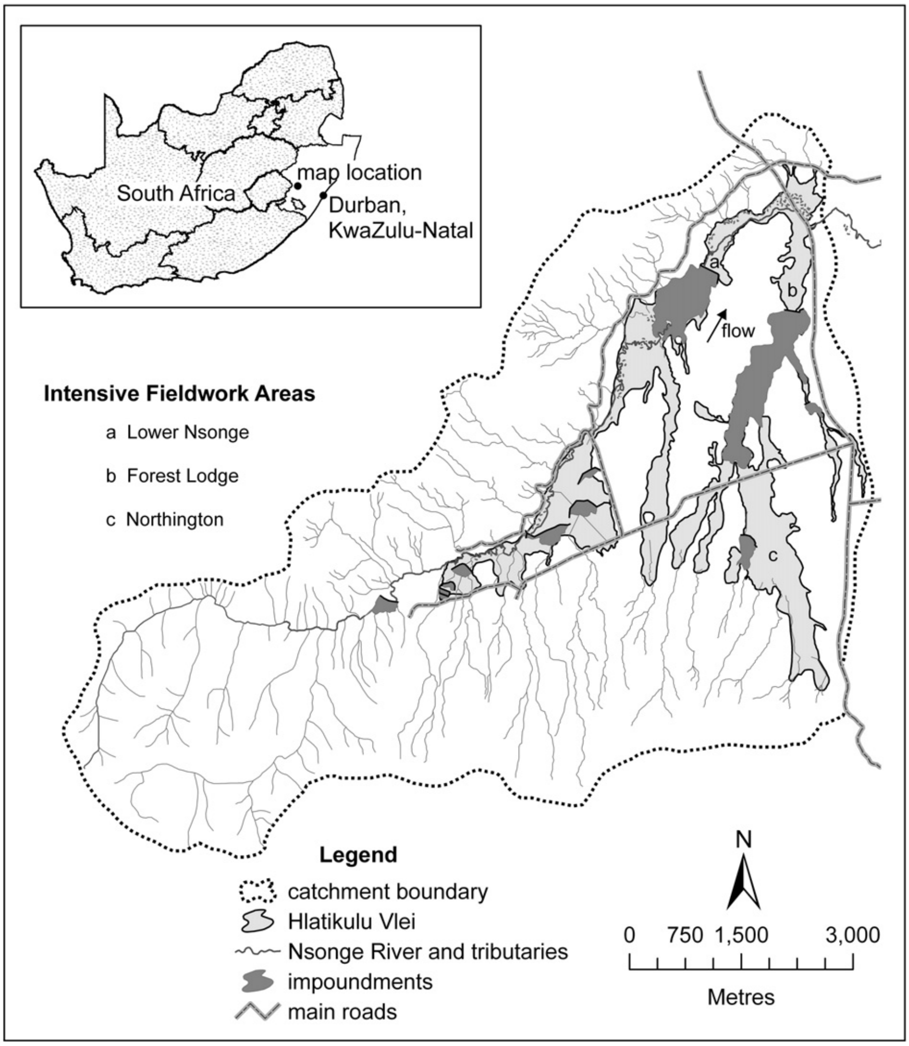

Fig. 1. Hlatikulu Vlei and surrounding catchment, showing the location of study sites, the Nsonge River and tributaries, impoundments, and main roads.

confluence with the trunk (floodplain) river, effectively decoupling tributary and trunk landscape units (similarly described by Fryirs and Brierley, 1999; Harvey, 2002, and Kasai et al., 2005). The Karoo dolerite intrusions thus act as sedimentological 'barriers', disrupting longitudinal linkages in sediment delivery, while the floodplain-impounded tributary valley-fill wetlands act as 'buffers', disrupting both longitudinal and lateral linkages in sediment delivery (Fryirs et al., 2007a,b; Grenfell et al., 2008).

This paper describes another form of sedimentological buffer observed within Hlatikulu Vlei, a wetland system in the KwaZulu–Natal Drakensberg Foothills, eastern South Africa, in a geomorphological setting apparently analogous to that of the 'cut-and-fill' features (*sensu* Nanson and Croke, 1992), described by Brierley and Fryirs (1998, 1999), and Fryirs and Breirley (1998) in Australia. The paper considers implications of the recorded geomorphological processes for valley morphology, and the long-term (millennia), large-scale mediation of connectivity by geological and geomorphological controls, and it contributes to a growing literature on the geomorphological origin and dynamics of wetlands. Understanding geological and geomorphological controls on the dispersal of water and sediment is critical to understanding wetland origin, particularly in southern Africa, where yearly atmospheric demand for water generally greatly exceeds yearly precipitation (Schulze, 1997), and many rivers are in a long term state of incision (McCarthy and Hancox, 2000; Tooth and McCarthy, 2007).

2. Regional setting

Hlatikulu Vlei is a 7.31 km^2 wetland system located ~150 km northwest of Durban in the KwaZulu-Natal Drakensberg Foothills (Fig. 1). The wetland system occupies approximately 13% of its 56.86 km^2 catchment, the median annual runoff from which is estimated to be 12.3 million m^3 (Schulze, 1997). Mean annual precipitation and mean annual potential evaporation (A-pan equivalent) for the catchment are estimated at 954.3 mm and 1677.0 mm, respectively (Schulze, 1997). The climate of the region is described by Mucina and Rutherford (2006, p. 424) as "a cooler, submontane form of warm-temperate climate", with a mean annual temperature of ~15 °C, and 26 frost days per year. Summers (December–February) are warm and moist, with common occurrence of both orographically and convectionally derived rainfall events of high intensity (Tyson and Preston-Whyte, 2000). Winters (June–August) are cool and dry with sporadic snowfalls.

The KwaZulu-Natal Drakensberg Foothills are underlain by lithologies of the Karoo Supergroup (Fig. 2). In the region of Hlatikulu Vlei, valley floors are typically underlain by fine- to medium-grained

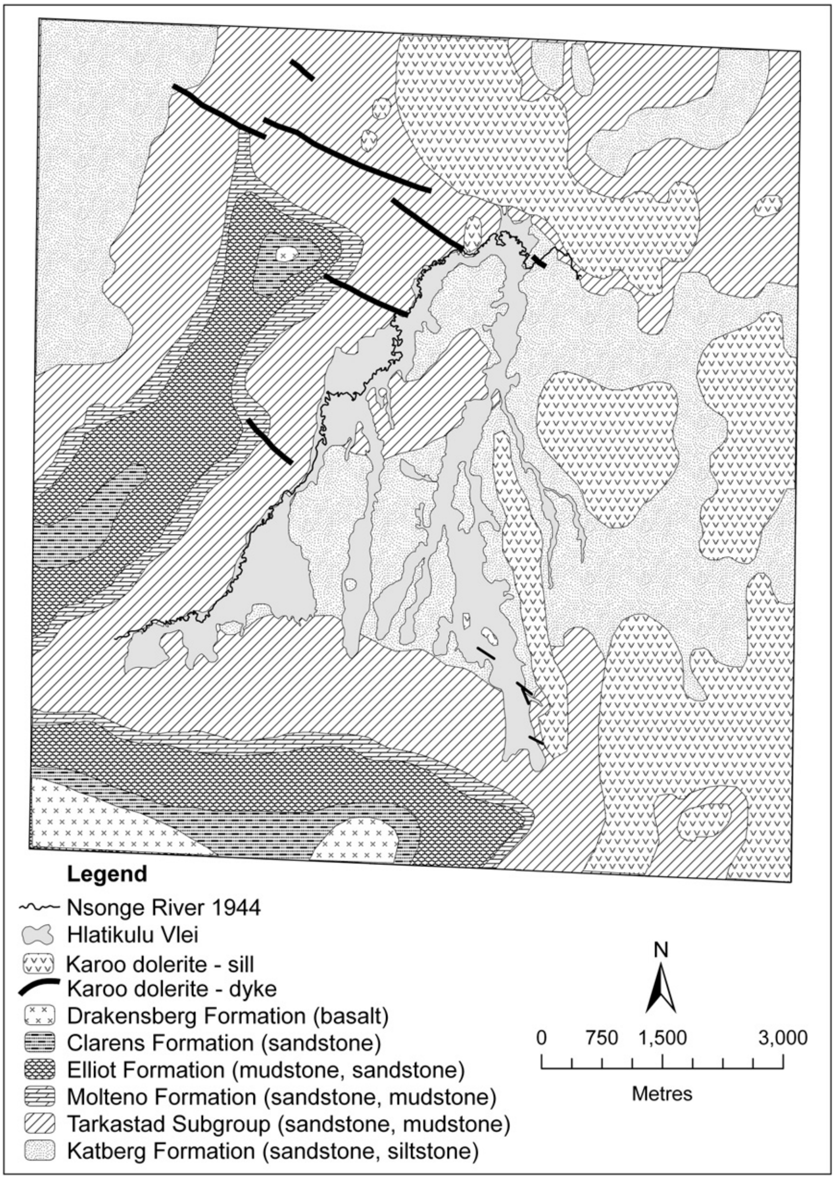

Fig. 2. Geology of Hlatikulu Vlei and surrounds, illustrating the Tarkastad Subgroup/Katberg Formation sandstone/siltstone/mudstone underlying the wetland system, and typical lithology of the KwaZulu-Natal Drakensberg Foothills surrounding the system (digitised from the South African Geological Survey map of the geology of Hlatikulu Vlei in Begg, 1989, verified in the field).

sandstones, siltstones, and mudstones (Tarkastad Subgroup and Katberg Formation, Fig. 2). Several Karoo Supergroup sedimentary formations overlie the Tarkastad Subgroup/Katberg Formation to produce the Foothill relief that typically attains elevations of 1500 to 1900 m, with the basalt-capped high Drakensberg range rising a further ~1000 m above the Foothills to the west (not pictured in Fig. 2). The regional dip on the Karoo sedimentary rocks is ~4° west. Some of the higher peaks in the Foothills are capped by basalt (Fig. 2), but most of the basalt cap at lower elevations has been removed by erosion. Geomorphic evolution of the Drakensberg region during the Miocene and Pliocene involved episodes of intense uplift followed by periods of stasis and erosion (Partridge and Maud, 1987; Partridge, 1998). Uplift rejuvenated rivers of the region, which, during periods of stasis that followed, resulted in the removal of substantial thicknesses of Karoo Supergroup sedimentary rocks and widespread river superimposition onto underlying resistant dolerite dykes and sills (Wellington, 1941, 1955; King, 1955, 1963; Partridge and Maud, 1987, Partridge, 1998).

Approximately half of the Hlatikulu Vlei catchment lies within the statutorily protected uKhahlamba Drakensberg National Park, and is vegetated by dense 'Drakensberg Foothill moist grassland', with patches of 'northern afrotemperate forest' on south-facing slopes, generally within ravine and crag settings (Mucina and Rutherford, 2006). Outside the National Park, many slopes are planted with gum and pine plantations, while lowlands have to a large extent been converted from former grassland or herbaceous palustrine wetland to pasture or cropland. The vegetation of Hlatikulu Vlei is diverse and has been described in detail by Guthrie (1996). In general, temporary to seasonal wetland at the outer margin of the system is dominated by grasses such as *Setaria sphacelata* and *Arundinella nepalensis*, and grades to seasonal to permanent wetland dominated by sedges such as *Cyperus denudatus*, *Carex acutiformis* and *Carex cognata* (within lower elevation floodplain backswamp and valley floor settings). Scattered stands of *Typha capensis* and *Phragmites australis* compete for dominance in flooded depressions and oxbow lakes within the more permanently flooded parts of the system. River banks have been colonised in places by *Leucosidea sericea* thicket, a common feature of many rivers in the region, and in places by exotic willows (*Salix* spp.).

3. Methods

Geomorphological features (e.g. abandoned channels, oxbow lakes, gullies, and floodouts) of the wetland system were mapped using rectified and georeferenced aerial photography, and verified in the field. Longitudinal and across-valley profiles of the valleys occupied by the wetland system were plotted using contour crossings from 1:10 000 scale orthophotographs (5 m elevation interval) and 1:50 000 scale topographic maps (20 m elevation interval), to illustrate variations in river and wetland longitudinal slope, and valley width and morphology through the system. Further across-wetland, down-valley, and channel geometry profiles were determined by automatic level (dumpy) survey. Along the across-wetland survey lines, sediment cores were extracted using gouge corers and soil augers, to characterize the nature and thickness of wetland sedimentary fill. Core locations were recorded using a Trimble GeoExplorer XT GPS (0.3–0.6 m precision in x and y, 0.7–1.0 m precision in z, following post-processing differential correction using a remote base station), for later incorporation into a GIS.

Field sampling effort was stratified by wetland hydrogeomorphic unit (using the classification of Brinson, 1993, adapted for South African wetlands by Kotze, 1999, and Ewart-Smith et al., 2006), in order to capture the range in geomorphological/sedimentological environments represented within the system. The hydrogeomorphic units chosen for intensive field study are shown in Fig. 1. The ‘Lower Nsonge’ site (a, Fig. 1), a floodplain wetland associated with the Nsonge River, extends from the wall of the impoundment on the Nsonge River, to the distal downstream end of Hlatikulu Vlei. The ‘Forest Lodge’ (b, Fig. 1) and ‘Northington’ (c, Fig. 1) sites are valley-

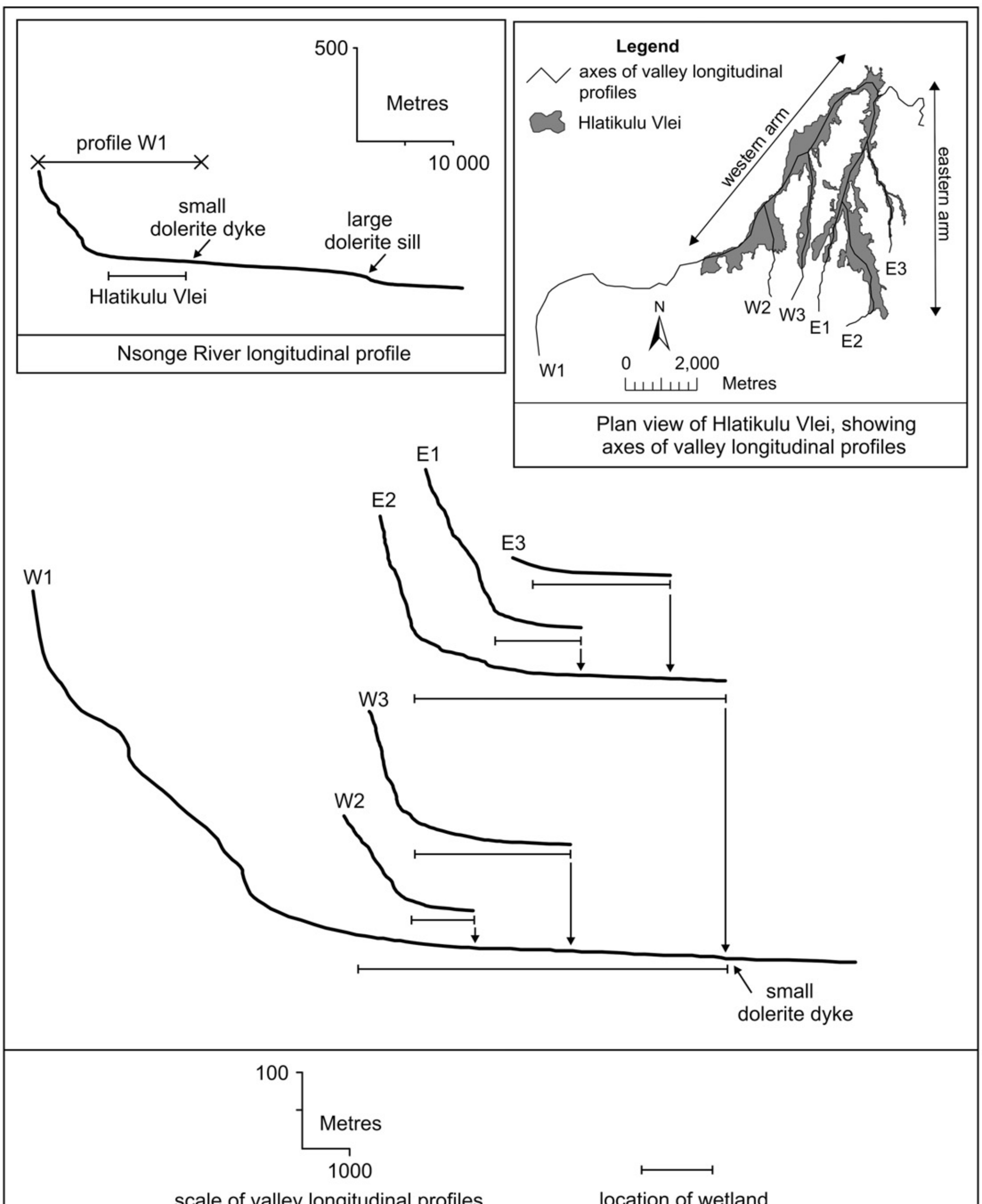

Fig. 3. Longitudinal profiles of the Nsonge River valley, and main drainage axes of Hlatikulu Vlei, showing points of superimposition upon underlying dolerite intrusions.

bottom wetlands, distinguished from each other for the purposes of the geomorphological/sedimentological work as having different channel environments. The Forest Lodge wetland extends from the wall of the large eastern impoundment, to the wetland's confluence with the Lower Nsonge floodplain, while the Northington wetland comprises the upper eastern part of Hlatikulu Vlei, upstream (south) of the road crossing (Fig. 1).

Sediment samples within selected cores were taken at 0.5 m depth intervals, and where sandy/gravely layers or other features of interest were encountered. Particle size distribution (% clay, silt and sand) was determined by the pipette method (Briggs, 1997). Samples were classified (e.g. as clay or sandy clay) using the USDA soil texture triangle and associated nomenclature (Richardson and Vepraskas, 2001). D_{50}s of samples comprising >50% sand, as well as the sandy/gravely layer samples were determined by dry sieving in a vibrating sieve stack. D_{50} values were interpreted (e.g. as fine sand or coarse gravel) using the Udden–Wentworth scale and associated nomenclature (Gordon et al., 2004). Loss on ignition (Heiri et al., 2001) was used to determine the organic matter content (percentage by mass) of samples from selected cores.

At the Northington site, an EG&G Geometrics G-856 proton precession magnetometer was used to determine the location of dolerite intrusions buried beneath wetland sediment. Karoo dolerite partly comprises ferruginous magnetic minerals such as olivine, pyroxene, and amphibole, and therefore produces a disturbance in the magnetic field measured by a magnetometer. Magnetometer reading locations were recorded using the Trimble GPS in a grid covering the Northington wetland. At each location, readings were taken repeatedly until a consistent output was attained, which was then recorded. Magnetic field intensity (gammas) was classified using the 'natural breaks (Jenks)' method in ArcGIS 9.2, whereby class breaks are determined by grouping similar data values, with groups separated at large differences in the data values. This classification allowed mapping of zones of similar magnetic field intensity, which guided interpretation of the underlying lithology.

4. Results

Hlatikulu Vlei occupies two main drainage lines (the western and eastern arms, Fig. 3 plan view inset) that coalesce immediately

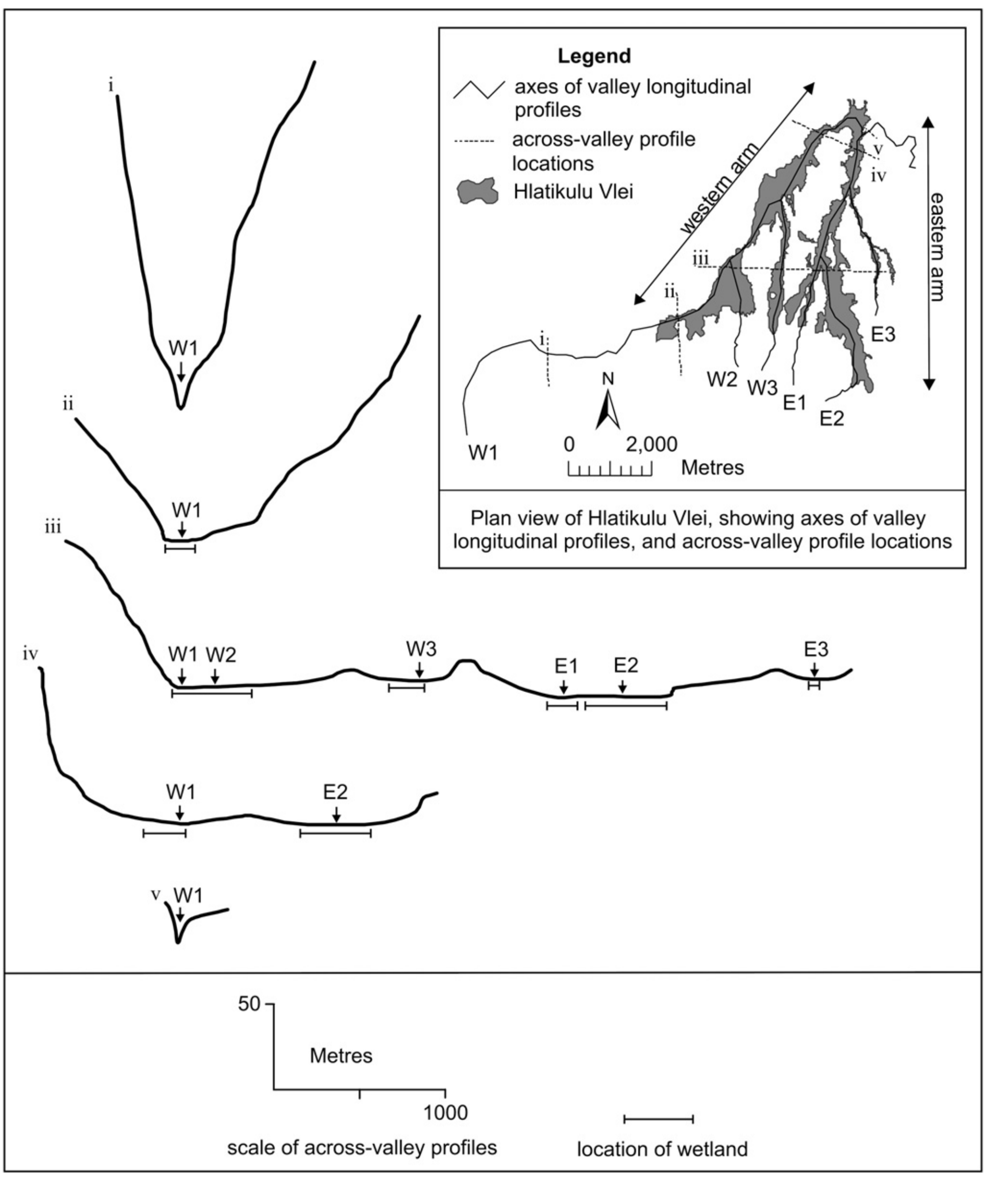

Fig. 4. Across-valley profiles of the Nsonge River valley, and main drainage axes of Hlatikulu Vlei, illustrating variation in valley width through the system.

upstream of a small dolerite dyke (Figs. 2 and 3 profile inset), and an array of smaller drainage lines. The western arm of the system occupies part of the valley of the Nsonge River, which rises at an elevation of 2040 m amsl, and flows north and then east before entering the system at ~1590 m amsl, by which point the river has attained 3rd order. The Nsonge River valley upstream of the system follows a steep (ave. slope 6.61%), stepped profile, while average slope through the wetland system is substantially lower at 0.38% above the Lower Nsonge study site (Fig. 1, a), to 0.25% within the study site (Fig. 3, profile W1). There is a minor increase in slope through the dolerite dyke at the toe of the system (to 0.3%). After this, an average valley slope of 0.25% is maintained to the point at which the river crosses a large dolerite sill (Fig. 3 profile inset), where there is a step increase in slope (to 4%).

Tributaries to the main western and eastern arms rise at elevations of 1595–1770 m amsl (Fig. 3, profiles W2, W3, E1, and E3), and flow north, entering the system at 1580–1600 m amsl. With the exception of E3 (ave. slope upstream of the system 2.32%), these tributaries follow steep (ave. slope 8–16%), stepped profiles in their upper reaches, while average slope through the wetland system is 0.48–1.40%. Drainage within the main eastern arm of the system (Fig. 3, profile E2) rises at an elevation of 1775 m amsl, and flows north to the toe of the system. Profile E2 has three distinct average slopes: 19.60% upstream of the system, 2.10% through the Northington study site (Fig. 1, c), and 0.23% through the Forest Lodge study site (Fig. 1, b).

In cross-profile, valleys upstream of Hlatikulu Vlei are confined, and generally broaden through the wetland system (Fig. 4, profiles i to iv). The Nsonge River valley is broad through the Lower Nsonge

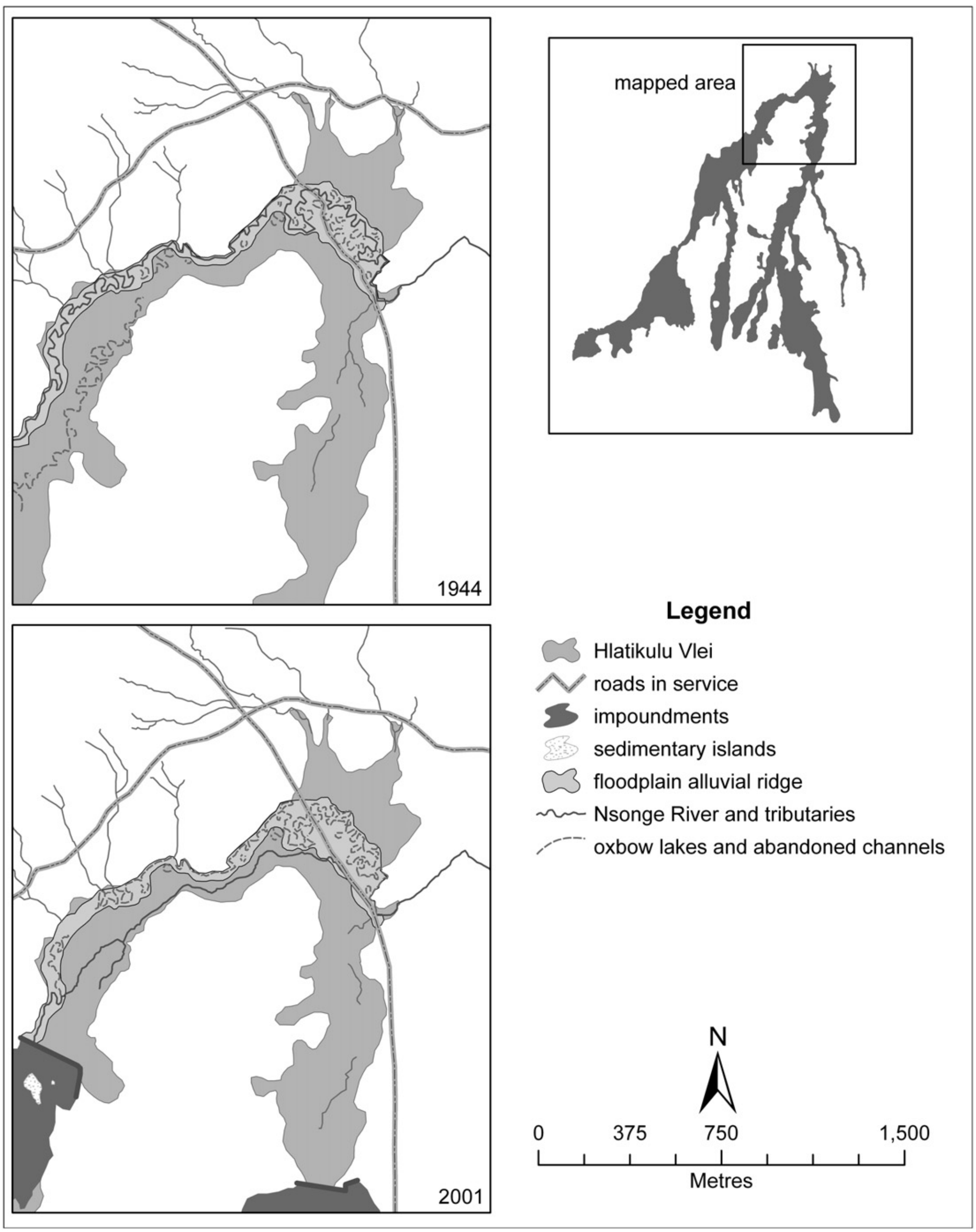

Fig. 5. 1944 and 2001 views of the geomorphology of the Lower Nsonge and Forest Lodge study sites (refer to Fig. 1 for study site locations), illustrating the meandering Nsonge River atop an alluvial ridge, oxbow lakes and abandoned channels, the recent avulsion (2001), impoundments (2001), and the discontinuous tributary within the Forest Lodge wetland.

floodplain (Fig. 4, profile iv), but confined where the river is superimposed upon the small dolerite dyke at the toe of the system (Fig. 4, v). Through confined valley reaches, the Nsonge River follows an essentially straight course with sinuosity (P) ~1–1.2 (Fig. 5, 1944 view). In contrast, through broad valley reaches, the river follows a tortuously meandering course (P~2–3), and is situated on an alluvial ridge that is elevated 0.5–1.5 m above adjacent backswamp (Fig. 5, 1944 view). It is this meandering planform to which the river likely owes its name ('Nsonge' is an isiZulu word for 'bent' or 'twisted'). In the 1944 view (Fig. 5), an abandoned meander belt (~1 km in length) is evident adjacent to the meandering Nsonge River, as are numerous oxbow lakes. The 2001 view (Fig. 5) illustrates recent avulsion and abandonment of the 1944 meandering course by processes considered in detail in a separate study. The density of oxbow lakes is highest through the Lower Nsonge study site (12 per 1 km of channel, compared to 5 per 1 km of channel for the entire floodplain), suggesting that meander cutoff is a frequent and active process of channel change in this part of the floodplain. The narrow necks of oxbow lakes indicate that neck cutoff is more common than chute cutoff in this setting.

A series of cores taken along surveyed profile A indicate that the mudstone bedrock surface is near-planar (Fig. 6). Floodplain alluvium generally fines upwards from basal gravels and sands above weathered mudstone. The fining-upwards succession illustrated in core A4 is a result of abandonment of the 1944 channel course. Ash content typically decreases (i.e. organic matter content typically

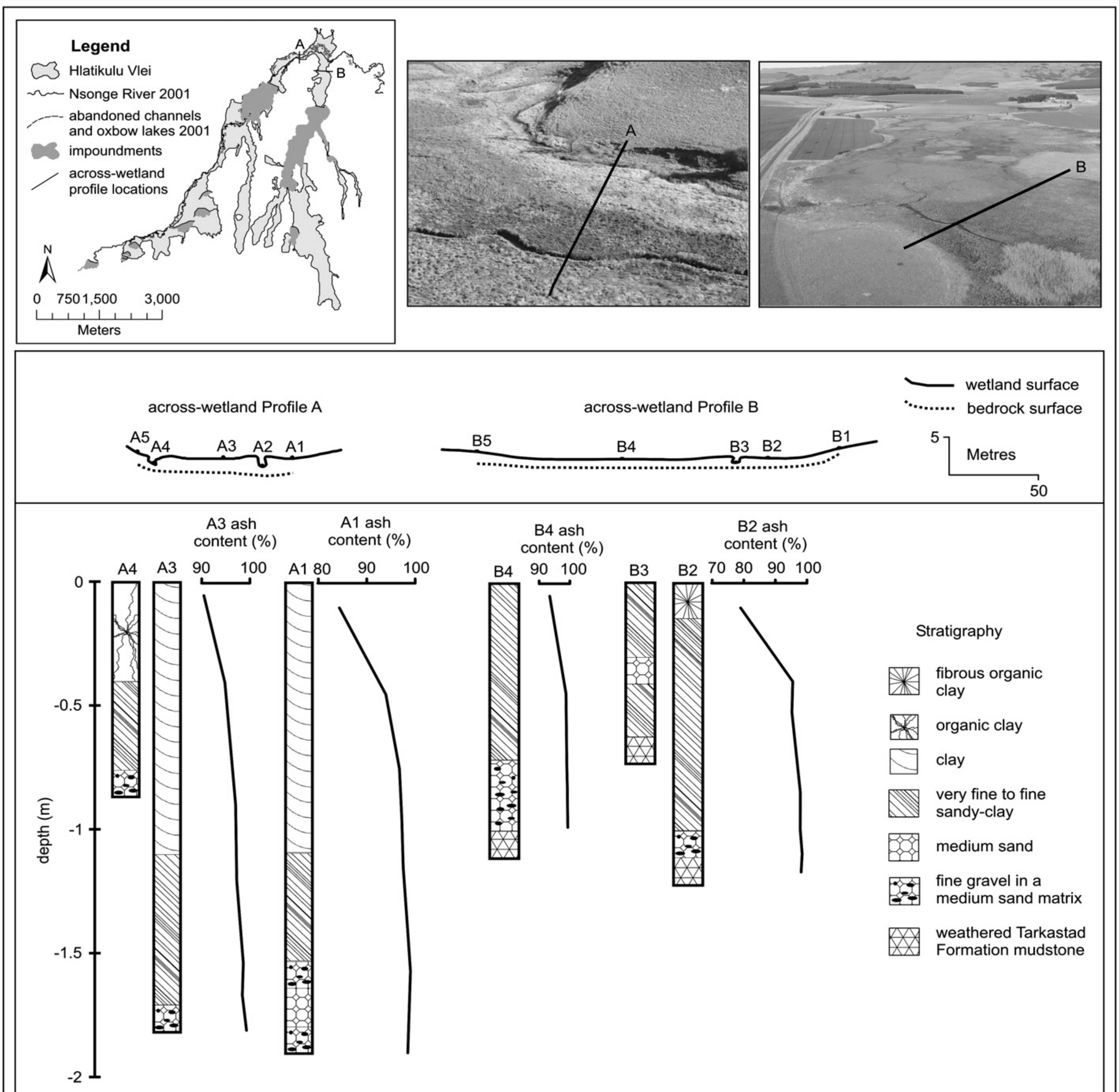

Fig. 6. Wetland and bedrock surface morphology, and location, texture, and ash content of cores taken within the Nsonge River floodplain, and Forest Lodge valley-bottom wetlands.

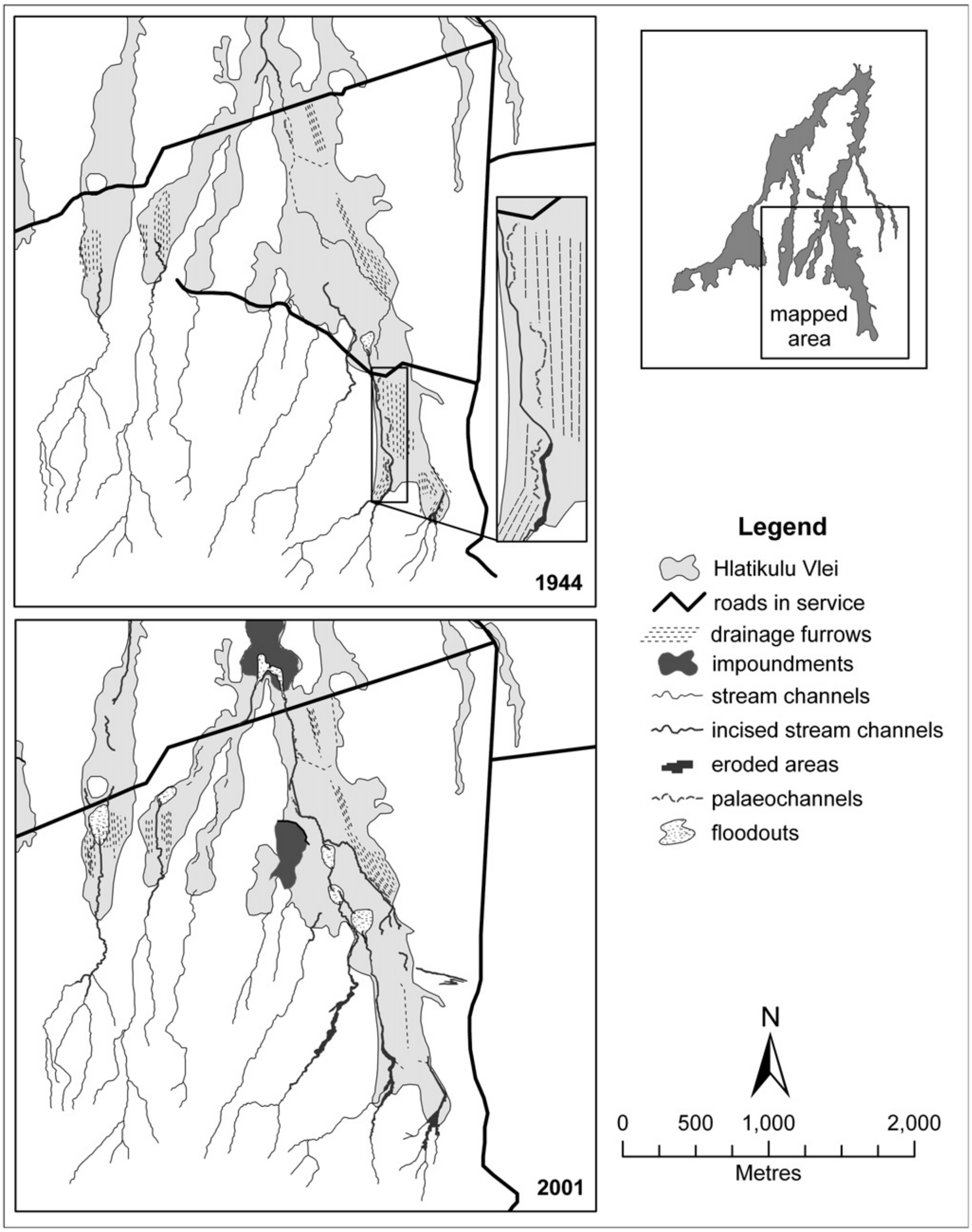

Fig. 7. 1944 and 2001 views of the geomorphology of the Northington study site, illustrating roads, impoundments (2001) and drainage furrows, as well as stream channels, incised stream channels terminating in floodouts and re-forming downstream, palaeochannels, and areas of wetland or valley surface erosion.

increases) towards the wetland surface, but true peat is generally not encountered within the floodplain, and clastic sedimentation predominates.

Flow within the Forest Lodge study site is mostly diffuse, although low flows are retained in channel segments of a discontinuous stream course (Fig. 5). The inefficiency of this stream style relative to that of the Nsonge River in the western arm is inconsistent with the basal gravel and sand stream bed and point bar deposits recorded in cores taken in the lower eastern arm, and with the natural levees (features of overbank deposition) flanking the channel in profile (Fig. 6). The series of cores taken along surveyed profile B indicate a planar mudstone bedrock surface. As at Lower Nsonge, alluvium in this part of the system generally fines upwards from basal gravels and sands above weathered mudstone, and ash content typically decreases (i.e. organic matter content typically increases) towards the wetland surface, with true peat rarely encountered.

The Northington site is characterized by geomorphological features that are not evident elsewhere in the system (incised streams that terminate at small 'floodouts', *sensu* Brierley and Fryirs, 2005, and reform downstream, Figs. 7 and 8). Incision is conspicuously located in parts of the wetland historically subject to high soil disturbance and flow concentration by excavated cambered beds ('ridge and furrow' development) and drainage furrows, particularly evident in the 1944 view (Fig. 7). Palaeo-stream style within the Northington site is suggested in the small sinuous channel, now dissected by stream incision (Fig. 7, 1944 view, enlarged). Channel incision and floodout formation increased between 1944 and 2001 (Fig. 7). Since 2001, an incisional avulsion has initiated from the western incised stream (Fig. 7) towards the uppermost terminal floodout on the eastern incised stream. The avulsion is oriented obliquely to the stream terminus, across the floodout face. Headward progression of this avulsion will divert the course of the eastern incised stream to the western incised stream, hydrologically and sedimentologically isolating the uppermost terminal floodout.

Core C1, taken at a palaeo-ridge of the small sinuous palaeochannel (Fig. 9, across-wetland profile), illustrates deposition of a fine sandy-

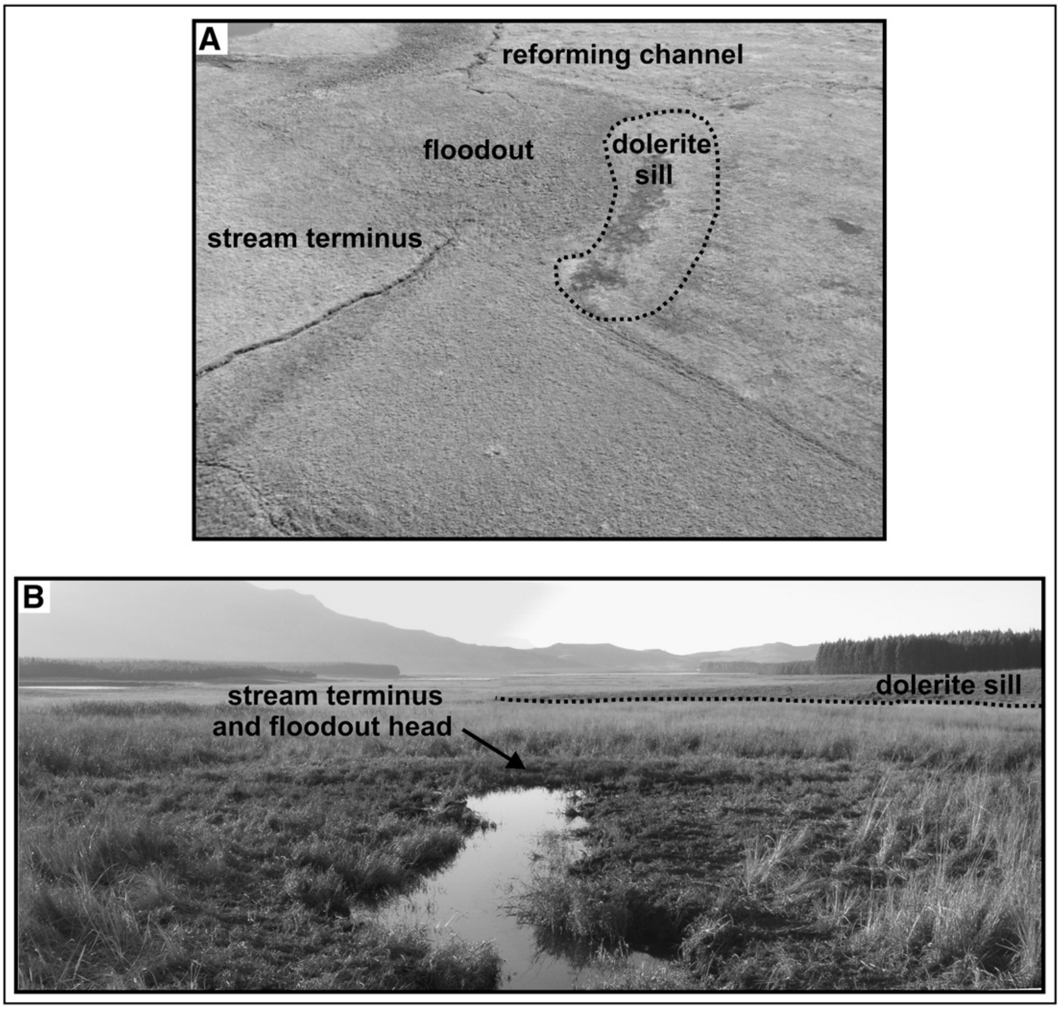

Fig. 8. Oblique aerial (A), and ground-level (B) photographs of a floodout near an outcropping dolerite sill within the Northington wetland.

loam to silty-clay fining-upwards succession of wetland alluvium (channel and alluvial ridge deposits), over organic clay (palustrine marsh deposits). Core C2, taken near the apex of the uppermost terminal floodout, illustrates deposition of a medium sand to silt fining-upwards succession, with interlaminations of fine gravel in a medium sand matrix (floodout deposits), over fibrous-organic and organic clay (palustrine marsh deposits). Auger holes indicate a laterally near-planar bedrock surface (Fig. 9, across-wetland and across-floodout profiles), that is longitudinally stepped (Fig. 9, valley longitudinal profile).

Magnetic field intensity over the Northington study site varied from 7047–17314 gammas (for 175 consistent-output data readings). Readings taken over sedimentary rock outcrops located far from dolerite outcrops were typically ~15000 gammas, while readings taken directly over dolerite outcrops were typically ~8000 gammas. There is a general west–east decline in magnetic field intensity over the site (Fig. 10), driven by proximity to the large dolerite sill outcropping near the eastern wetland margin. However, the magnetometer survey suggests that smaller dolerite intrusions, which intermittently crop out within the wetland, extend across the wetland beneath sedimentary fill (Fig. 10). Intrusions cross beneath the incised stream channel in close proximity to floodout apexes (Figs. 10 and 11). The incised stream feeding the uppermost floodout decreases in depth downstream, before channel flow is terminated altogether at the floodout (Fig. 11, longitudinal profile). Ratios of wetted cross-sectional area to bankfull cross-sectional area for this channel generally increase downstream, reaching a value of 1 (Fig. 11, longitudinal profile), reflecting channel impoundment by the lobate floodout (Fig. 11, across-floodout profiles).

5. Discussion

5.1. Wetlands within wetlands

Hlatikulu Vlei is a geomorphologically diverse wetland system, comprising low-gradient meandering-river floodplains, low-gradient floodplain-impounded valley-fill wetlands with diffuse flow and discontinuous channel networks, and relatively higher-gradient headwater valley-fill wetlands with discontinuous gully-floodout complexes. Each wetland type is characterized by different geomorphological features, and a different geomorphological dynamic.

5.1.1. Floodplains and floodplain-impounded valley-fill wetlands

The Nsonge River and floodplain exhibit many geomorphological features (e.g. abandoned meander belts, oxbow lakes, and low alluvial ridges) in common with the Klip River and associated floodplain wetlands described by Tooth et al. (2002, 2004), and the Mooi River and floodplain within Stillerust Vlei described by Grenfell et al. (2008). Although smaller than the Klip and Mooi (both 5th order rivers), the Nsonge meanders extensively within a relatively broad, low gradient valley located upstream of a small dolerite dyke, and follows a straight, angular course in a confined valley where it is superimposed upon the dyke. Floodplain fill predominantly comprises a fining-upwards succession of alluvium above basal sands and gravels

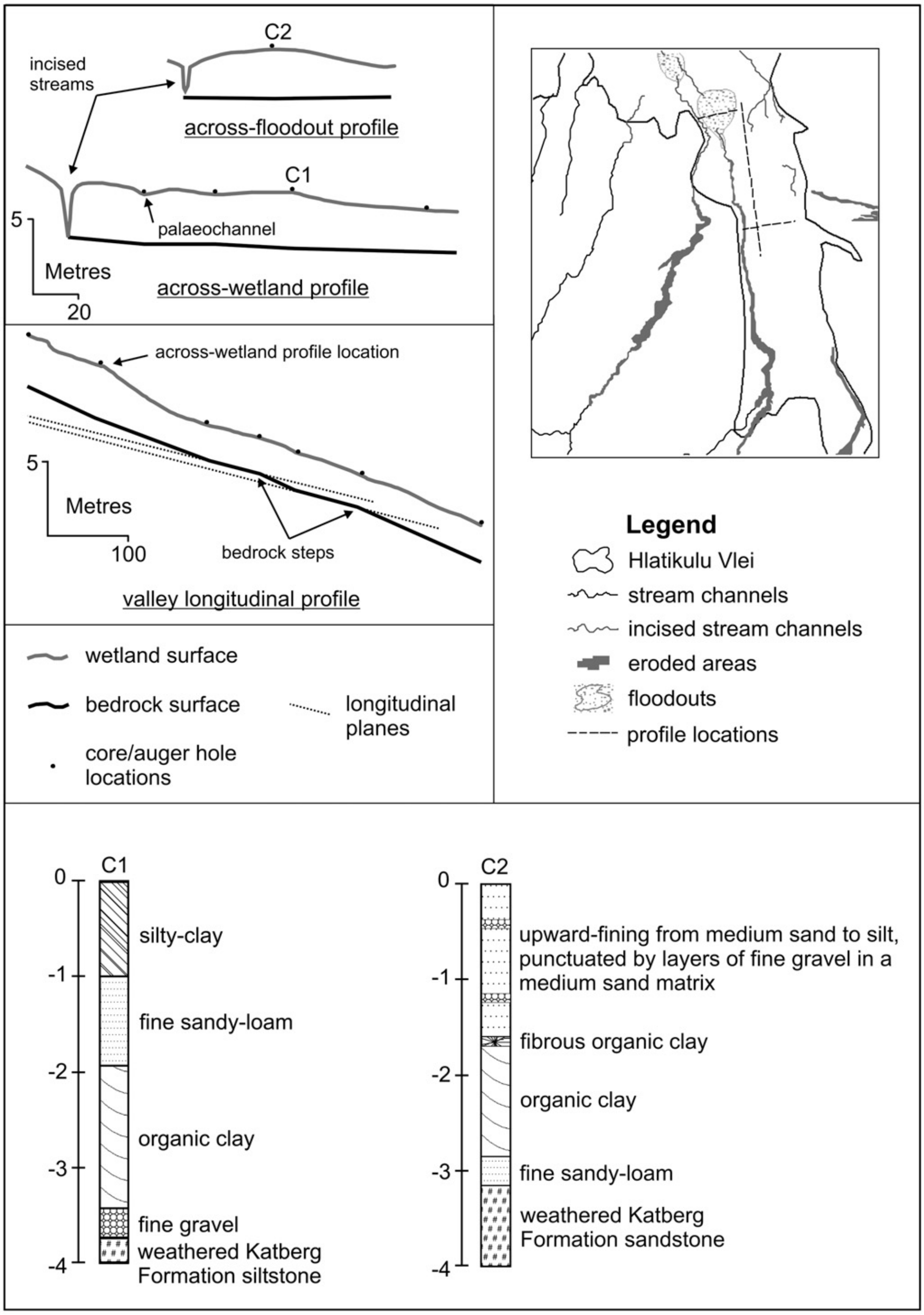

Fig. 9. Wetland and bedrock surface morphology, and location and texture of cores taken within the Northington valley-bottom wetland.

(preserved point bars) and weathered sedimentary rock, a stratigraphy characteristic of floodplains with laterally-planing, mixed bedrock-alluvial rivers, in a landscape that is in a state of long term incision (Tooth et al., 2002). Features of local vertical accretion (e.g. levees) are not preserved within floodplain fill, suggesting reworking of fill by lateral migration (Tooth et al., 2002). Thus, the processes of wetland origin and dynamics operative within the Nsonge River floodplain generally conform to the model proposed by Tooth et al. (2002, 2004).

The presence of channel-flanking levees and river bed and point bar deposits within the Forest Lodge valley-bottom wetland, and the planar nature of the bedrock across the valley in this area indicate that the lower eastern arm of Hlatikulu Vlei also once hosted a small, laterally migrating stream. Following superimposition of the Nsonge River upon the dolerite dyke, it is likely that the lower eastern arm initially shared the local base level that formed, and developed by the same set of processes as the western arm, to be later overwhelmed by the greater rate of trunk river floodplain development, a process discussed in detail in Grenfell et al. (2008).

5.1.2. 'Cut-and-fill' valley-bottom wetlands

While it may be tempting to associate the stream incision and consequent floodout formation within the Northington site with recent agricultural activities, the laterally planed and longitudinally stepped imprint left on underlying bedrock suggests that incision and floodout formation within this part of the system are natural,

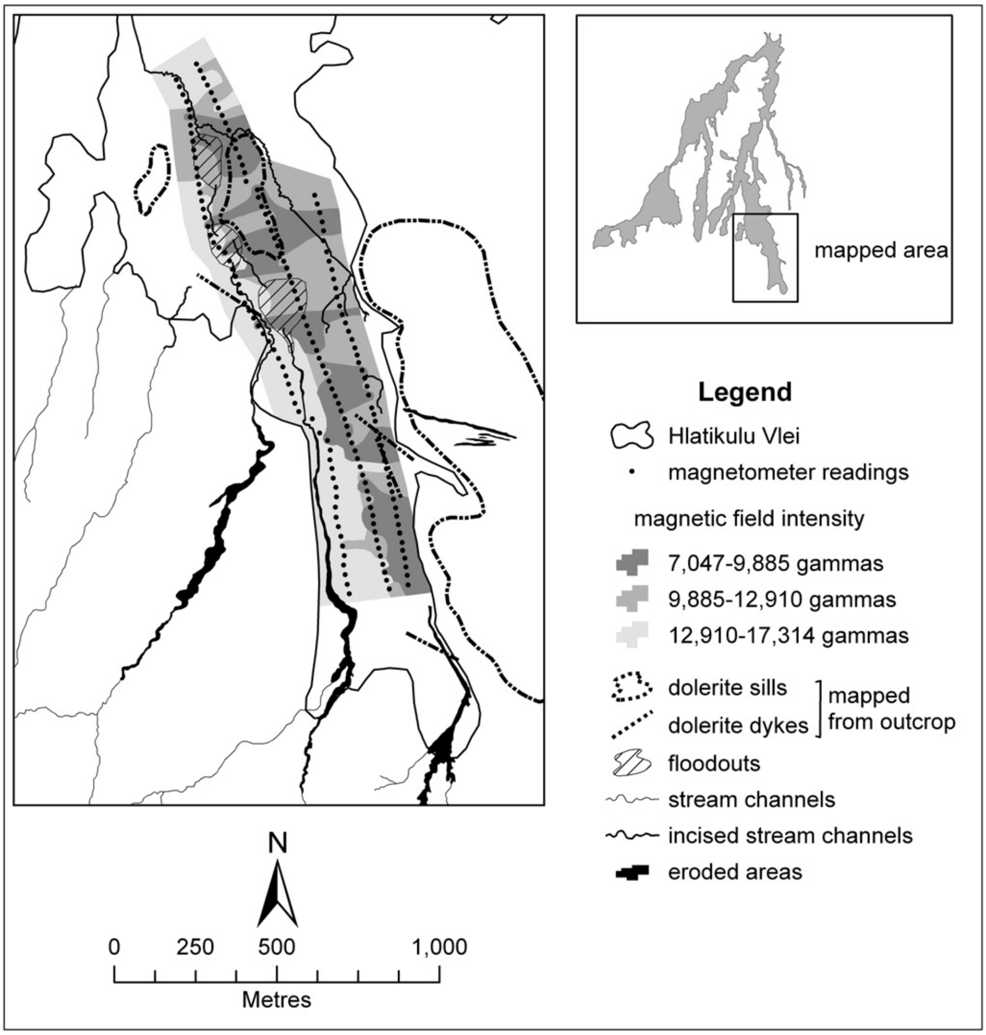

Fig. 10. Magnetic field intensity mapped for a large portion of the Northington wetland, with the location of erosional and depositional features, and outcropping dolerite intrusions overlaid.

temporally repetitive phenomena. Past agricultural activities simply accelerated the onset of incision. Planation and export of bedrock within the wetland occurs by oblique avulsions that may be driven by steepening of a floodout surface and the crossing of a threshold of slope stability (e.g. Prosser, 1994; Bull, 1997), through capture by lateral extensions of adjacent incised streams, or by these processes in combination. It is likely that these processes contribute to progressive valley deepening and widening to the same extent that lateral planing by meandering rivers does in the mixed bedrock-alluvial floodplains described by Tooth et al. (2002, 2004). A logical progression of this argument is that channel incision within these wetlands plays an important role in long-term valley and wetland morphodynamics. Stream incision and gully formation is therefore an integral component of wetland formation, morphology, spatial heterogeneity and dynamics, and in this case has created a broad, flat, sediment-filled valley with a low longitudinal slope that is seasonally flooded for sufficient duration to produce anaerobic conditions in the soil. Locally, within depressions that are a product of sedimentation related to floodouts, flooding is permanent in a situation where rainfall is strongly seasonal. Erosion is a component of the natural dynamic.

The fact that channel and levee deposits of the small sinuous stream within the Northington wetland are superimposed upon palustrine marsh sediments suggests that this stream is more similar to a true alluvial river, than bedrock-planing mixed bedrock-alluvial rivers such as the Klip, Mooi, and Nsonge, and is thus not responsible for the near planar across-wetland bedrock profile. Overall, the Northington wetland could be considered a South African analogue of the 'cut-and-fill' systems described by Brierley and Fryirs (1998, 1999), and Fryirs and Breirley (1998) in Australia. The sinuous stream is thus a remnant feature of a 'fill' cycle, temporally punctuated by 'cut' cycles in which stream incision and floodout formation dominate.

Within the Northington wetland, loss of stream confinement and consequent floodout formation is strongly associated with stream superimposition upon underlying Karoo dolerite intrusions. Observations of floodouts in similar wetland systems in KwaZulu-Natal suggest that floodouts in these systems may be spatially determined by other means, such as laterally-impinging alluvial fans (Fig. 12, A, B), but may also result simply due to transmission loss, or a break in channel gradient (Brierley and Fryirs, 2005; Tooth and McCarthy, 2007, Fig. 12, C–F).

Controls on the transition from 'fill' to 'cut' cycles in such systems are a subject of ongoing debate (Brierley and Fryirs, 1999). The work of Tooth et al. (2004), and Tooth and McCarthy (2007) suggests that incision within wetlands over much of the South African Highveld is related to base level fall through the breaching of dolerite barriers, re-establishing local sedimentological connectivity. However, this work has focused on floodplain wetlands similar to that associated with the Nsonge River at Hlatikulu Vlei. Since the dolerite dyke local base level of the Nsonge River floodplain has not been breached, and the Northington valley-bottom wetland is besides sedimentologically

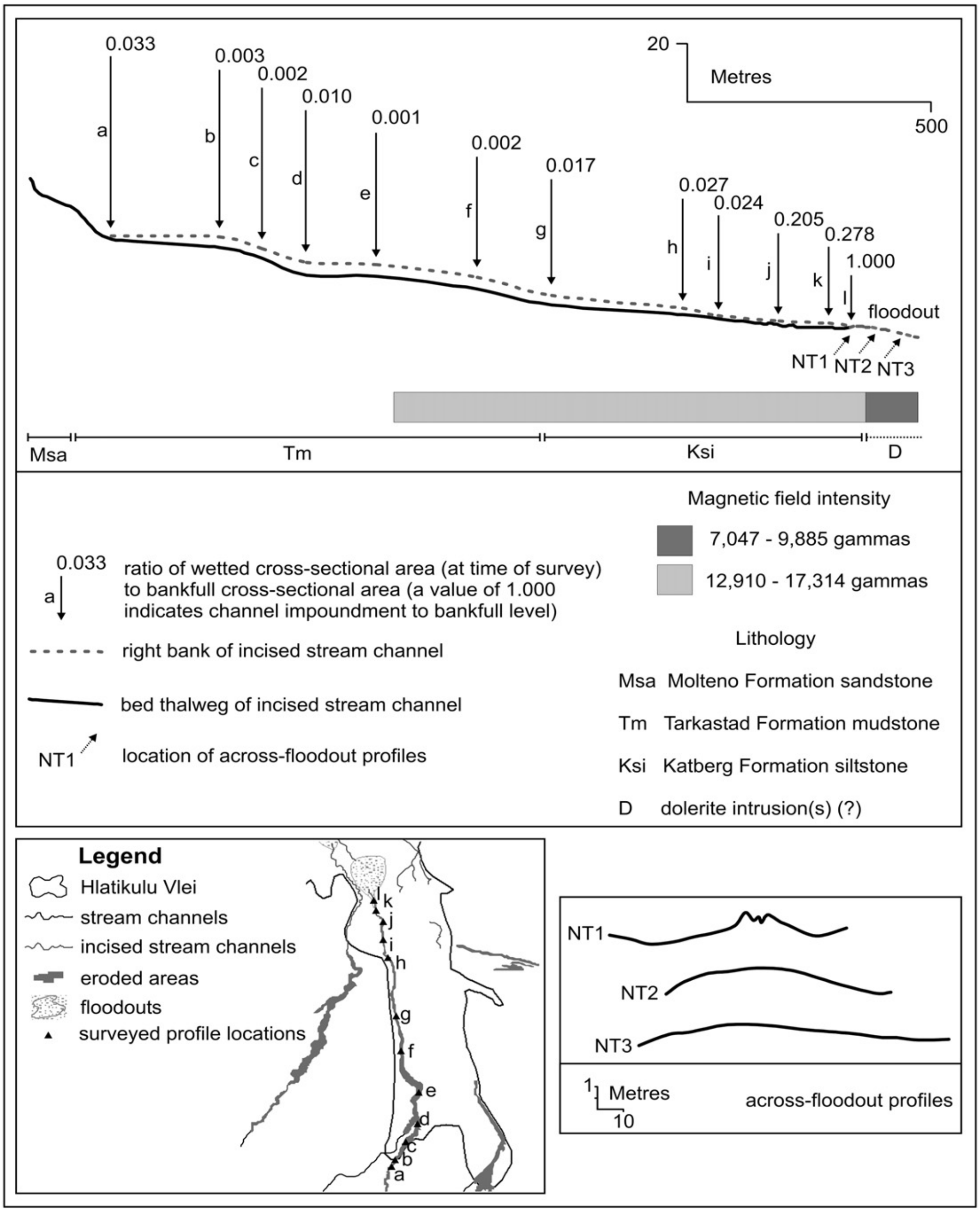

Fig. 11. Longitudinal profile of the incised stream-uppermost floodout within the Northington wetland, with magnetic field intensity and underlying lithology indicated, and across-profiles of the lobate uppermost floodout (lower right inset).

disconnected from the Nsonge River (e.g. Brierley and Fryirs, 1999; Fryirs et al., 2007b), an alternative explanation for wetland incision must hold.

Ongoing investigation of a large sample of similar South African wetlands (Grenfell et al., in review) aims to determine whether such incision is related to the crossing of a geomorphological threshold (e.g. Patton and Schumm, 1981; Schumm, 1979; Prosser, 1994; Bull, 1997). Such a threshold might be crossed artificially through increased discharge from a catchment that has been hardened through urban development, or increased runoff due to removal of catchment vegetation. Alternatively, this may occur naturally through climate change. It is likely that erosion within the Northington wetland resulted because a geomorphological threshold was crossed, and that the crossing of this threshold was accelerated by historical agricultural activities.

5.2. Long-term development of sedimentological disconnectivity, and wetland origin

Wetlands are conventionally considered ‘filters’ of water (e.g. Comin et al., 1996). In connectivity terms, due to their role in the landscape as sedimentological buffers, wetlands are filters of energy (they have ‘filter resistance’, c.f. Brunsden, 2001), decoupling fluvial energy within the drainage network. This decoupling of energy is expressed through, and accentuated by sedimentation, and the accumulation of ‘pockets’ of valley fill. The establishment of wetland vegetation exerts strong feedback control on channel and valley filling, particularly in cut-and-fill settings (e.g. Zierholz et al., 2001), but the fundamental control on the origin of drainage-linked wetlands at the landscape scale, and associated drainage disconnectivity, is the development and maintenance of local base levels (e.g. drainage

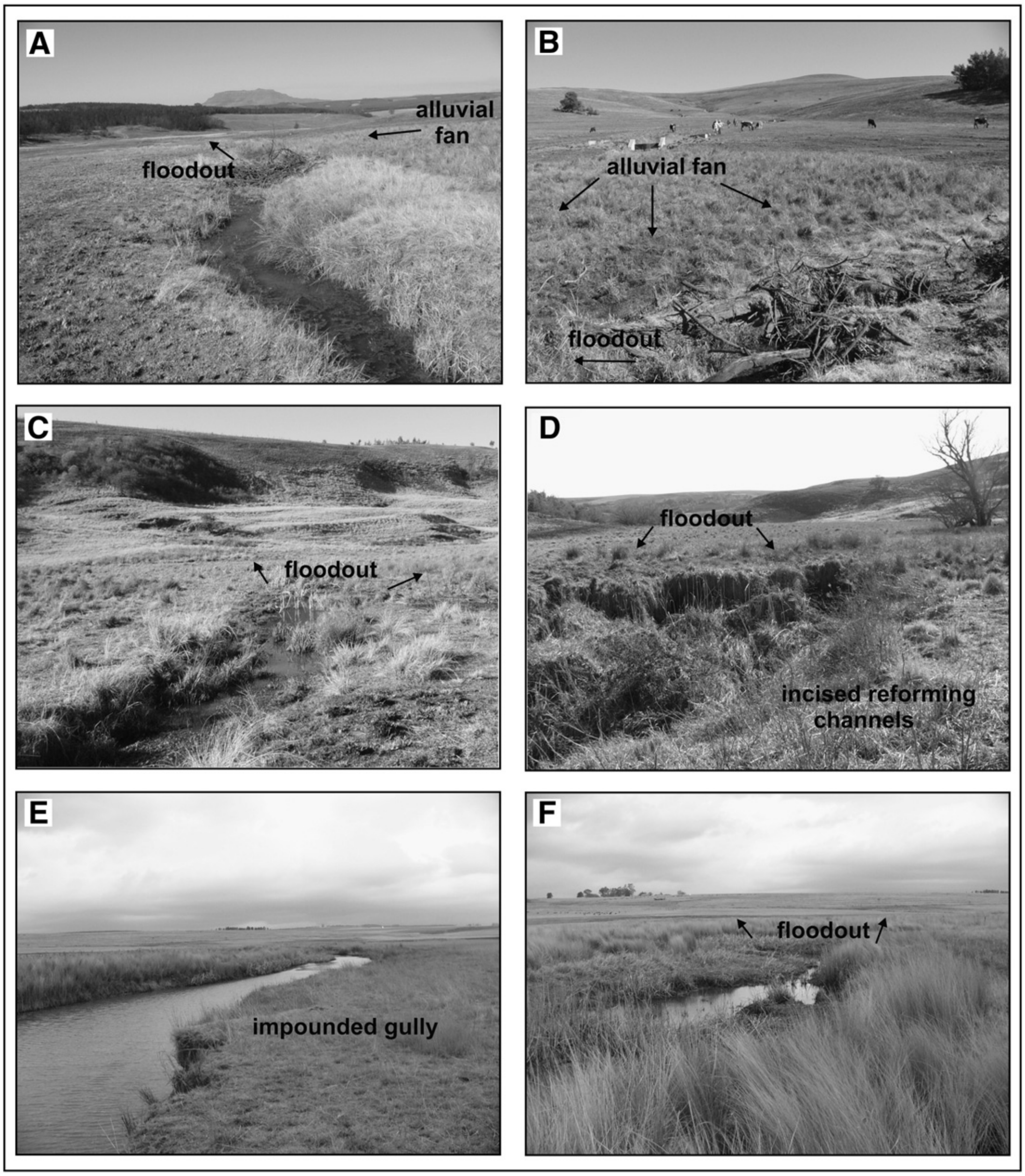

Fig. 12. Photographs of floodouts within the Ntabamhlope Vlei (floodout 1: A, downstream view; B, side view; floodout 2: C, downstream view; D, upstream view), and Blood River Vlei (floodout 3: E, downstream view; F, downstream view), wetland systems in the KwaZulu-Natal interior.

superimposition upon resistant rock bands, or laterally-impinging alluvial fans).

To take the metaphor of filter resistance further, wetlands could be likened to electrical capacitors, storing energy (and matter) at points in the landscape, and releasing it in bursts as erosion thresholds are exceeded (in the case of headwater valley-fill wetlands), or local base levels are breached (in the case of floodplains and floodplain-impounded valley-fill wetlands located upstream of dolerite intrusions). Thus, the intermittent nature of sediment movement through river systems reflects a balance between geomorphological work exerted by the drainage network, and geological resistance (Ferguson 1981).

Many South African rivers are in a long-term state of incision (McCarthy and Hancox, 2000), and prior to river superimposition upon underlying dolerite dykes and sills, would be characterized by high sedimentological connectivity (Fig. 13, t1). Highly resistant dolerite intrusions form stable local base levels on the river profiles they intersect, and locally restrict valley width, promoting upstream sedimentation and floodplain development in wide, low gradient valleys laterally planed by meandering rivers into less resistant Karoo Supergroup sedimentary rocks (Fig. 13, t2). These intrusions thus act as barriers by disrupting longitudinal linkages in sediment delivery to the river downstream (Fryirs et al., 2007a,b, Fig. 13). Floodplain-impounded tributary valley-fill wetlands host discontinuous streams that are unable to perform geomorphological work, and thus act as buffers, disrupting both longitudinal linkages in sediment delivery through the tributaries, and lateral linkages to the trunk rivers and floodplains (Fig. 13, t2).

Similarly, valley-fill wetlands characteristic of the upper portions of Hlatikulu Vlei, such as that of the Northington site, host discontinuous incised streams that terminate in lobate floodouts, and reform downstream, resulting in a sediment cascade that may be likened to a 'jerky conveyor belt' (Ferguson, 1981). These headwater-setting valley-fill wetlands thus act as buffers by disrupting longitudinal linkages in sediment delivery to downstream parts of the system (Fig. 13, t3). Thus, sedimentological connectivity is successively disrupted during the long-term development of wetland systems such as Hlatikulu Vlei (Fig. 13), where the initial break in

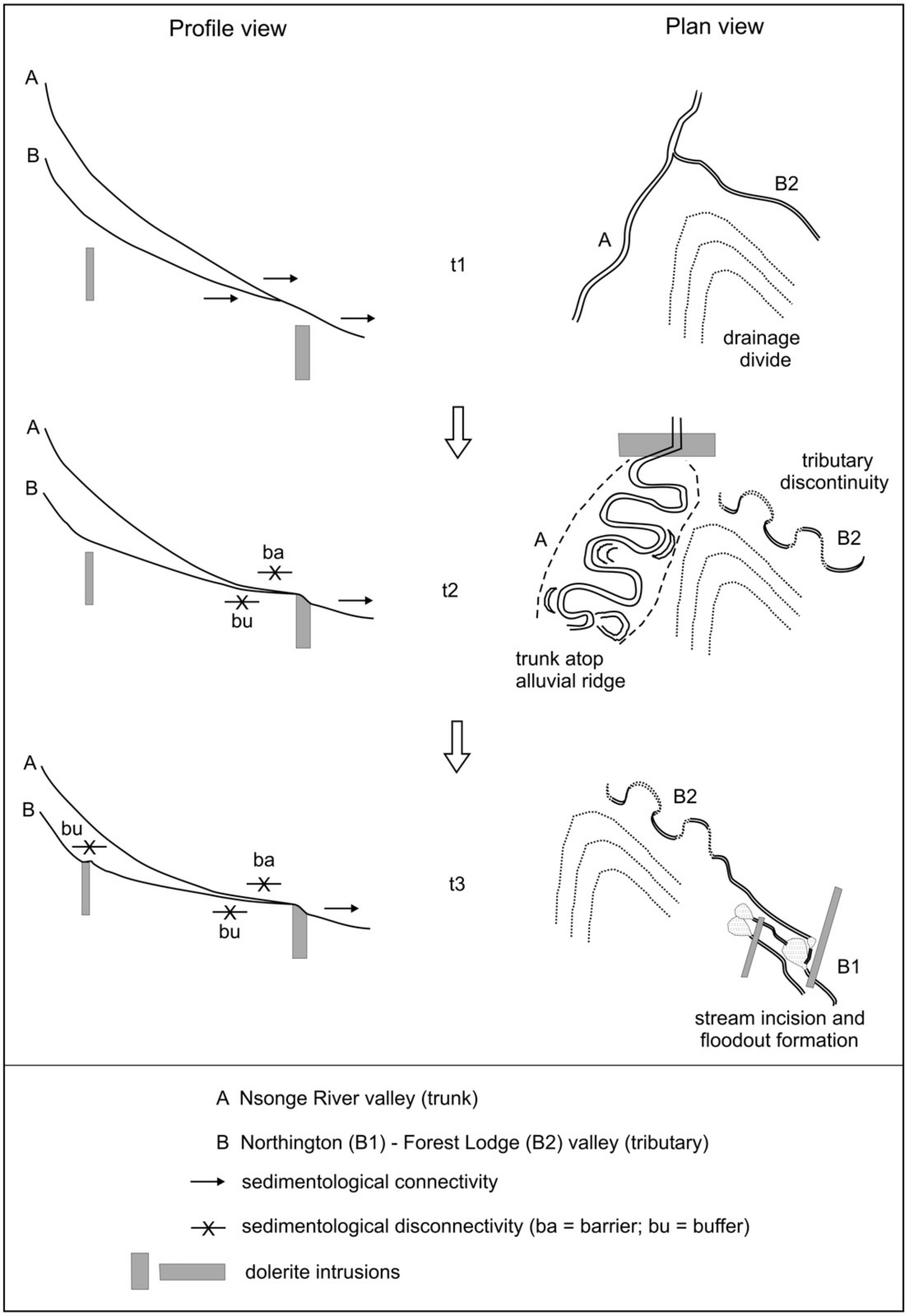

Fig. 13. Conceptual model of long-term development of sedimentological disconnectivity within Hlatikulu Vlei (adapted from Tooth et al., 2002, 2004; Grenfell et al., 2008).

connectivity that followed superimposition of the Nsonge River upon a dolerite dyke initiated a second break in connectivity with the origin of a floodplain-impounded valley-fill wetland. This was followed by headward aggradation up the eastern arm of the system, and a third break in connectivity associated with incised stream superimposition upon underlying dolerite intrusions.

While the cut-and-fill cycle characteristic of the Northington wetland intermittently remobilizes sediment to lower parts of the wetland system, true sedimentological connectivity within the valleys hosting Hlatikulu Vlei will only be re-established once dolerite intrusions at the toe of the system and within the Northington wetland are breached by gradual ongoing vertical erosion (Tooth et al., 2004). This supports the notion that increasing spatial scales of coupling are associated with increasing timescales (Harvey, 2002).

5.3. Implications for wetland rehabilitation

The South African National Government annually invests a large sum of tax-payers money in wetland rehabilitation projects. A large portion of this money is spent addressing stream channel incision and gully erosion that is attributed to past or ongoing agricultural activities or infrastructural development such as road construction. Historically, rehabilitation planners fell victim to erosion tunnel-vision ('gully-vision'?), as the 'problems' that a rehabilitation project might aim to address are often associated with erosion gullies, and effort could be justified as 'addressing the errors of former ways'. As such, although these practitioners made remarkable achievements with available resources and knowledge, they were influenced by mis-perceptions of geomorphological change, and considered all change to be unnatural, unceasing, and having major ecological impact (Schumm, 1994). It is still frequently the goal of conservationists, including practitioners involved in wetland rehabilitation, to reinstate or maintain the natural dynamic. Geomorphologists have long considered cut-and-fill processes to be the natural means by which sediment is transported through drainage systems in arid and semi-arid areas (e.g. Schumm and Hadley, 1957; Patten and Schumm, 1981; Bull, 1997). If erosion is a natural feature of wetlands, what might be the implications for rehabilitation?

There has been a recent shift in rehabilitation planning thinking in South Africa, away from determining whether or not changes such as gully erosion are natural or human-induced, to determining the likely returns in ecological integrity and ecosystem service provision expected for a particular level of rehabilitation effort. However, further emphasis needs to be placed on understanding gully dynamics, and in particular in determining at what stage of gully development (incision/recovery) rehabilitation interventions are likely to be effective (e.g. Schumm, 1994), both in financial and ecological terms. If gully erosion is an important process in wetland formation, morphology and dynamics, rehabilitation practitioners should focus on interventions that improve or stabilize desired functional outcomes, rather than on restoring or maintaining what is perceived to be 'the natural dynamic' in which erosion is absent.

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