Geomorphic origin and dynamics of deep, peat-filled, valley bottom wetlands dominated by palmiet *(Prionium serratum)* – a case study based on the Goukou Wetland, Western Cape.

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Abstract

The Goukou Wetland is a 700 ha unchannelled valley bottom wetland near the town of Riversdale in the Western Cape of South Africa. The wetland is approximately 16 km long and between 200 and 800 m wide, with peat deposits up to 8 m deep that get progressively shallower downstream. The Goukou Wetland is one of the last remaining intact peatlands of significant size in the Western Cape. However, there is increasing human pressure on these peat wetlands, where the dominant plant is palmiet (*Prionium serratum)*, which is endemic to the Western and Eastern Cape Provinces of South Africa. Palmiet is viewed as a problem plant by farmers as it is believed to block waterways and promote inundation of arable land and infrastructure. Many landowners therefore actively remove palmiet from peatlands, threatening the integrity of these wetlands.

Although the hydrogeomorphic origin of large, non-peat floodplain and valley bottom wetlands has been investigated in South Africa, unchannelled valley-bottom wetlands with deep peat accumulations are rare features and have not been well studied. The hydrogeomorphic factors leading to peat accumulation have been documented elsewhere in Southern Africa, where aggradation due to sedimentation along trunk streams may block a tributary stream, elevating the local base level of the tributary, creating the accommodation space for organic sedimentation. Alternatively, sedimentation along a trunk stream at the toe of a tributary stream may similarly block a trunk stream, promoting organic sedimentation along the trunk stream upstream of the tributary. This pattern of peat accumulation is associated with declining peat thickness upstream of the blocked valley. In the case of the Goukou Wetland, however, peat depth and organic content was found to increase consistently upstream from the toe to the head of the wetland.

The Goukou Wetland was graded along its length, with gradient increasing consistently upstream in response to longitudinal variation in discharge. There was no clear relationship between peat formation and tributary streams blocking the wetland. Instead, the distribution of peat and the extent of the wetland appeared to be controlled by the plant palmiet, whose clonal nature and robust root, rhizome and stem system allowed it to grow from channel banks and islands into fast-flowing river channels, slowing river flows and ultimately blocking the channel. The

promotion of diffuse flows within the dense, monospecific stands of palmiet creates conditions conducive to water retention and peat accumulation. By growing across the full width of the valley floor, the plant is able to constrict the stream, trapping sediment and slowing flows such that the fluvial environment is changed from a fast flowing stream to one with slow, diffuse flow. These processes appear to lead to the formation of organic sediment, accumulating to form a deep peat basin. The sustained input of water from the folded and fractured quartzite lithologies of the Cape Supergroup that make up the Langeberg Mountains, which provide the bulk of the water supply to the wetland, is also important in promoting permanent flooding in the wetland.

A feature that characterized the wetland was the fact that bedrock across the valley beneath the peat deposits exhibited a remarkably uniform elevation. This suggests that over long periods of time (tens to hundreds of thousands of years), bedrock has been laterally planed across the valley floor. It is proposed that valley widening associated with lateral planning of Uitenhage Formation rocks has taken place during periods of episodic very high flows. During these episodes, erosion cuts into the peat wetland and valley sides, cutting to bedrock and planing the valley floor to a uniform elevation for a given distance from the head of the wetland. Periods of episodic degradation are followed by periods of renewed peat accumulation associated with palmiet establishment, such that the wetland valley is shaped by repeated cycles of cutting and filling.

Palmiet can be considered an “ecosystem engineer” that is integral to the formation of these deep peat basins. Removal of palmiet from these systems is likely to have negative consequences for the wetland and its functions in that water storage will be reduced, erosion will increase dramatically, and the water-purification function of the wetlands will be lost. Management of these wetlands, which are close to the geomorphic threshold slopes for their size, is therefore essential if they are to be preserved for the benefit of human well-being.

Acknowledgements

The following are gratefully acknowledged for their assistance and support: Professor Ellery, the multiple landowners along the Goukou River who allowed access to the wetlands, Wim Filmater, Damian Walters, Garth Alistoun, Rebecca Joubert, Debbie Bekker, Jurie Viljoen, Heidi Nieuwoudt, Mireille Lewarne, Phillip Desmet, Hans King, Jan Sliva, Piet-Louis Grundling.

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1. INTRODUCTION

1.1 Background

1.1.1 Wetland formation in southern Africa

There has been significant progress over the last decade towards a deepened understanding of how South Africa's diverse wetlands have formed and why they occur where they do in the landscape. While the fundamental importance of hydrological factors in forming and controlling wetlands has been well established in global wetland literature (Mitsch and Gosselink, 2000), McCarthy and Hancox (2000) and Ellery *et al.* (2009) have underscored the significant influence of geomorphological factors on water distribution and retention in the landscape, specifically with regard to wetland distribution, structure and function.

Key events of geomorphological significance include the multiple uplift events which took place in southern Africa over the last twenty million years, where the interior escarpment parallel to the southern coastline rose by approximately 400 m in the southern Cape (McCarthy and Rubidge, 2005; Marker and Holmes, 2010). This uplift has created a strongly erosional landscape, such that most coastal rivers are in a state of incision (Dollar, 1998; McCarthy and Rubidge, 2005; Marker and Holmes, 2010). Furthermore, uplift has elevated the southern African sub-continent to produce a land surface with a mean altitude of about 1000 m above mean sea level such that it is situated at a much higher mean altitude than other continents that have not experienced recent mountain-building through tectonic processes (McCarthy & Rubidge 2005). This unusually high elevation means that South Africa is a landscape of rapid runoff and erosion, thus reducing the likelihood of wetland formation (Ellery *et al.*, 2009).

Although some regions of South Africa are indeed rich in "pans" or depressional wetlands, these are most commonly shallow remnants of ancient floodplains or deflationary in origin, and are not due to glaciation, as is the case in high northern latitudes (McCarthy *et al*, 2007; Ellery *et al.*, 2009). While some wetlands may have groundwater replenishment as a supplementary source of water as described in other semi-arid regions of the world (Knighton, 1998; Tooth and McCarthy, 2007), given the predominantly erosional landscape driven by incising rivers and the semi-arid climate described above, it can be anticipated that comparatively few wetlands in South Africa are driven by precipitation alone and that the majority occur in close association with, or are driven by, fluvial systems (Ellery *et al.*, 2009). Much can therefore be understood through examining southern African wetlands from the perspective of fluvial geomorphology.

Given that wetlands in South Africa are generally integrated within fluvial systems, erosion of and deposition within wetlands will occur in relation to variation in velocity and discharge in a manner similar to rivers. Theoretically, a river would display a logarithmic longitudinal profile, as overall discharge increases downstream (Knighton, 1998; Ellery *et al.*, 2009). This relates to the fact that small streams, even with high velocities, do not have the capacity to erode and transport large volumes of sediment, and therefore typically occur on steep slopes. As tributaries join the trunk stream, discharge increases and the capacity of the trunk to erode and transport sediment increases, such that erosion lowers the longitudinal slope to a point where slope, velocity and discharge are roughly in equilibrium (Knighton, 1998; Ellery *et al.*, 2009).

The ocean is regarded as the ultimate base level for rivers, as it is the lowest point on the river longitudinal profile. At base level, stream gradient approaches zero, velocity declines and the stream is no longer able to carry sediment, leading to deposition (Knighton, 1998). The presence of local base levels remote from the coastline will be reflected on the river longitudinal profile as relatively flat sections interrupted by "steps" associated with valley narrowing (Grenfell *et al.*, 2010). Schumm (1979) and Knighton (1998) have identified a number of potential factors driving local base level in rivers, such as bedrock outcrops, interactions of the trunk stream with tributary streams, active local tectonic activity and valley morphology.

Recent research offers evidence that these controls over river form and behavior have also shaped wetland formation and evolution in southern Africa (Table 1.1).

Table 1.1: Current models of geomorphological processes contributing to wetland formation in southern Africa.

Process	Example	Source
Planing of easily weathered and eroded lithologies (such as Karoo Supergroup sedimentary rocks) upstream of a resistant lithology (such as a dolerite dyke)	Klip River floodplain, eastern Free State. Stillerust Vlei, KwaZulu-Natal Drakensberg foothills	Tooth *et al*. (2004), Tooth and McCarthy (2007). Grenfell *et al*. (2008).
Faulted basins	Okavango Delta, Botswana.	McCarthy *et al*. (1997)
Sagging due to deep weathering and volume loss of volcanic rocks	Dartmoor Vlei, KwaZulu-Natal Midlands, South Africa. Kings Flats pan, Grahamstown, Eastern Cape	Edwards (2009). Alistoun (2013).
Tributary impoundment by a trunk	Hlatikulu Vlei blocking Northingtom wetland Umfolozi Floodplain blocking Futululu Wetland Mkuze Floodplain blocking Mdlanzi Wetland	Grenfell *et al*. (2008). Grenfell *et al*. (2010). Ellery *et al*. (2012).
Trunk impoundment by a tributary	Wakkerstroom Vlei, northern KwaZulu-Natal	Joubert and Ellery (2013).

The origin of Highveld wetlands as described by Tooth *et al.* (2004) explains the distribution of floodplain systems in areas dominated by rocks of the Karoo Supergroup. Where such streams cross erosion-resistant lithologies such as dolerite dykes, which act as a local base level, incision of Karoo sediments upstream of the dolerite dyke is not possible, and these streams use their energy to laterally plane the valley, thereby creating wide valleys with broad floodplains. Such dynamic systems typically do not contain substantial peat deposits and are characterized by thin (up to 2 m thick) clastic sediment deposits overlying bedrock.

Dartmoor Vlei in KwaZulu-Natal is a rarely-described situation where Edwards (2009) attributes peat formation to sagging resulting from long-term deep weathering of a dolerite sill on the African Erosion Surface. Peat has formed within the portion of the wetland in which sagging has taken place.

In Hlatikulu Vlei, a headwater-setting floodplain wetland in the southern Drakensberg of KwaZulu-Natal, Grenfell *et al.* (2010) have described the situation of a mainstem (trunk) stream obstructing a tributary stream, elevating the tributary base level at its confluence with the trunk, thus promoting flooding and peat formation at the toe of the tributary valley. Given the reduced slope, the tributary is unable to transport clastic sediment to the toe of the valley where peat has formed. In two further studies in coastal northern KwaZulu-Natal, the Umfolozi and Mkuze rivers were both also found to obstruct tributary streams. In both of these cases, lakes developed in the tributaries which were blocked by natural levee development on the mainstem (Ellery *et al.*, 2012). Finding no evidence for lithological controls in the system, the authors proposed that the overall base control for the Mkuze system is the sea, with overall incision and valley widening in the system matching the decline in sea level change during and following the last Ice Age, thus playing a role in overall wetland and peatland evolution (Ellery *et al.*, 2012).

In the middle reaches of Wakkerstroom Vlei, in the northern Drakensberg foothills in KwaZulu-Natal, it was the tributary streams that were found to block the trunk valley through sediment deposition in the form of large alluvial fans (Joubert and Ellery, 2013). The alluvial fans caused the slope of the trunk stream to be lowered in an upstream direction, causing the middle reaches of the wetland to experience diffuse flows and prolonged flooding, giving rise to peat formation (Joubert and Ellery, 2013).

1.1.2 Sedimentary fill and peat in wetlands

Wetlands within the fluvial context are typically associated with areas of sediment deposition (Kotze *et al.*, 2008). Wetland sedimentary fill can be broadly divided into clastic (minerogenically derived), dissolved (chemically derived), and peat (organically derived) (Mitsch and Gosselink, 2000; Ellery *et al.*, 2009). Southern African wetland geomorphology studies to date have focused predominantly on systems dominated by clastic sedimentation. Peat wetlands represent accumulation of *in situ* organic matter and organic remains, as opposed to an accumulation of *ex-situ* clastic sediment derived from elsewhere.

Grundling and Grobler (2005), in an overview of peatlands in southern Africa, report that most of the country’s peat wetlands occur on the east coast and interior of the country, with less than 1% estimated to occur in the Western Cape region. This makes the peat wetlands of the southern Cape relatively rare, and current knowledge does not explain the circumstances of their formation.

Peat formation takes place where organic matter production exceeds decomposition (Charman, 2002). It typically occurs in areas that are permanently or semi-permanently saturated with water (Fey, 2010). Organic sediment typically requires low energy settings in order to accumulate (Mitsch and Gosselink, 2000; Charman, 2002; Rydin and Jeglum, 2006). It also requires very limited clastic sediment input (Rydin and Jeglum, 2006; Ellery *et al.*, 2012). Prolonged flooding is inevitable in low-lying contexts where run-off is low and where rainfall is very high and greater than potential evapo-transpiration, but this does not apply in South Africa given its semi-arid climate and high average altitude following uplift events over the last twenty million years, such that most rivers in this landscape are in a state of incision. Furthermore, southern Cape rivers have very variable discharges, which is generally not conducive to peat formation.

The Cape Fold Mountains and streams arising from them are typically associated with erosion-resistant quartzite lithologies of the Cape Supergroup, with shale as subsidiary lithologies. The mountain streams are generally clear with black waters that are the result of humic acids present in the water column. The clastic sedimentary load in streams associated with these catchments is generally much lower than those contributing to trunk- or tributary-blocking interactions observed elsewhere in the country, because quartzite is typically extremely resistant to weathering and erosion. Dolerite is absent from the Cape Fold mountains because the rocks of the Cape Supergroup did not allow dolerite penetration due to their density and strength (McCarthy and Rubidge, 2005). Peat formation in these mountains is also unlikely to be due to subsidence associated with mass loss linked to deep weathering, because quartzite cannot undergo mineralogical simplification and mass loss during weathering. However, peat formation in these systems is not uncommon, and is often associated with the robust plant “palmiet” (*Prionium serratum).*

1.1.3 Biological factors and palmiet as factors influencing wetland form and dynamics

The role of biological factors in influencing wetland form and dynamics has not been extensively documented or studied in South Africa, and the precise role of palmiet in river and wetland systems has only been superficially examined (Sieben, 2012). Palmiet tends to dominate fluvial systems with quartzite catchments in the Western Cape through forming dense, monospecific, stands (Boucher and Withers, 2004; Sieben, 2012). It is a robust shrub with semi-woody stems and it produces a large root mass and deep rooting system able to grow through recently deposited sandy sediments, stabilizing them (Munro *et al.*, 2001; Roux, 2003; Boucher and Withers, 2004). The "ecosystem engineering" role of plants has been described for papyrus in the Okavango Delta (Ellery *et al.*, 2000), and for sedges and small shrubs by Watters *et al.* (2007) in the southern USA. More recently, it has been suggested that palmiet is an ecosystem engineer with peat-forming properties (Sieben, 2012).

An interesting feature of many palmiet peatlands in the Western Cape is the high degree of gully erosion present within them, a situation that is true for the Goukou Wetland, greatly increasing the flood risk to nearby and downstream landowners. Although gullies are widely attributed to anthropogenic factors (Haigh *et al.,* 2002; Rebelo, 2012; Nsor and Gambiza, 2013), a study by Ngetar (2012) suggests that wetlands in South Africa may naturally experience valley-widening through repeated cutting and filling processes. Although Ngetar (2012) did not work in a wetland with organic sediment, it is possible that repeated cutting and filling may contribute to valley-widening in the case of Western Cape peatlands.

This study adds to our understanding of the geomorphological processes contributing to peat wetland formation in southern Africa and examines the following key questions:

1. Does the Goukou Wetland have a simple logarithmic longitudinal profile, what factors act as base level controls, and how do these relate to the distribution of peat?
2. What role is played by interactions between tributary and trunk stream deposits?
3. What factors affect valley width, how does depth to bedrock vary with variation in valley width and how do these relate to the longitudinal profile?
4. Is palmiet capable of influencing wetland structure and dynamics and therefore an important geomorphic agent?

1.2 Aim and objectives

This study aims to investigate the geomorphic origin and evolution of deep peat-filled valley bottom wetlands dominated by *Prionium serratum*, using the Goukou Wetland in the southern Cape as a case study. In order to achieve this, the following objectives were examined:

- Determine the relationship between geological lithologies and sea level as possible base level controls, and their relationship with wetland longitudinal slope, cross-sectional characteristics and downstream termination of the peat wetland.
- Examine variation in wetland stratigraphy longitudinally, with a particular emphasis on confluences of trunk and tributary valleys, and in relation to the bedrock surface.
- Examine the distribution and morphology of incised wetland areas (gullies) in relation to variation in wetland longitudinal slope, cross-sectional morphology, geological characteristics and human activities.
- Consider the role of palmiet as a geomorphic agent.
- Develop a conceptual model that describes the role of geomorphological, geological, biological and climatic (natural) and human (anthropogenic) factors on wetland formation and dynamics, specifically for this peat-filled valley bottom wetland dominated by palmiet.

2. CONCEPTUAL FRAMEWORK

2.1 Geomorphological drivers of wetland form and evolution

2.1.1 Wetland formation in the South African climatic and geomorphic context

Within South Africa, there is a rainfall gradient from a sub-tropical moist climate in the east to a semi-arid environment in the west (Mucina and Rutherford, 2006; Schulze, 2012). Overall, South Africa's mean annual rainfall is just over half the global average, with potential evapo-transpiration generally greater than rainfall due to high average daily temperatures (Ellery *et al.*, 2009; Schulze, 2012). It can therefore be anticipated that comparatively few wetlands in South Africa are driven by precipitation alone. Instead, the majority occur in close association with, or are driven by, fluvial processes (Ellery *et al.*, 2009), or have groundwater replenishment as an additional source of water, as described in other semi-arid regions of the world (Knighton, 1998; Tooth and McCarthy, 2007).

The southern Africa plateau is anomalous. Compared to areas of similar geology, such as Western Australia, northern Canada, northern Asia and eastern South America, which lie only a few hundred metres above sea level, the southern African sub-continent lies more than 1 000 m above sea level (McCarthy *et al.*, 2007). Despite its higher mean altitude, southern Africa has not undergone mountain-building processes through rejuvenation in the same manner as northern continents. Instead of plate collision as in regions experiencing mountain-building, other continents have moved away from Africa, allowing an extended period of some 150 million years of weathering and erosion on the southern African sub-continent (Ellery *et al.*, 2009). Glaciation has not been significant in shaping our landscape over the last 200 million years (Ellery *et al.*, 2009), which means that deep depressions which characterise many wetlands in the northern hemisphere, including peat-forming wetlands, are absent. The combination of these factors has led to a remarkably well integrated fluvial network and an absence of lakes (Ellery *et al.*, 2009).

Together with climate, these are factors that make the southern African subcontinent different from others in terms of their likelihood of having wetlands.

2.1.2 Wetlands and fluvial systems

Rivers function as integrated systems that adjust gradient and channel geometry (width and depth) to accommodate the volume of water available, and to transport the available sediment (Knighton, 1998; Ellery *et al.* 2009). Rivers adjust through erosion that reduces longitudinal slope, or through deposition that increases longitudinal slope (Knighton, 1998; Ellery and Rowntree, 2010). The fully developed longitudinal profile of a river is typically logarithmic, which means it is steep in the headwaters where streams are small, and becomes increasingly flat toward the sea, as overall discharge increases and the capacity of the trunk to erode and transport sediment increases (Knighton, 1998).

The presence and retention of water in the landscape is a key defining feature of a wetland, where water is held long enough to saturate soils to sufficient depth to influence the plants that grow there, and for characteristics indicative of flooded soil to develop. These typically include mottles or gleying, which are evidence of reduced conditions following significantly long periods of saturation (Mitsch and Gosselink, 2000; USACOE, 2006). While the seasonal, annual and inter-annual amount of water available to a wetland can be linked to climate variation, and the water may reach the wetland via rainfall, stream flow, overland flow, hillslope soil interflow or via geological fractures or contact zones, there are several possible important influences on water residence time within a wetland that relate to geomorphic factors.

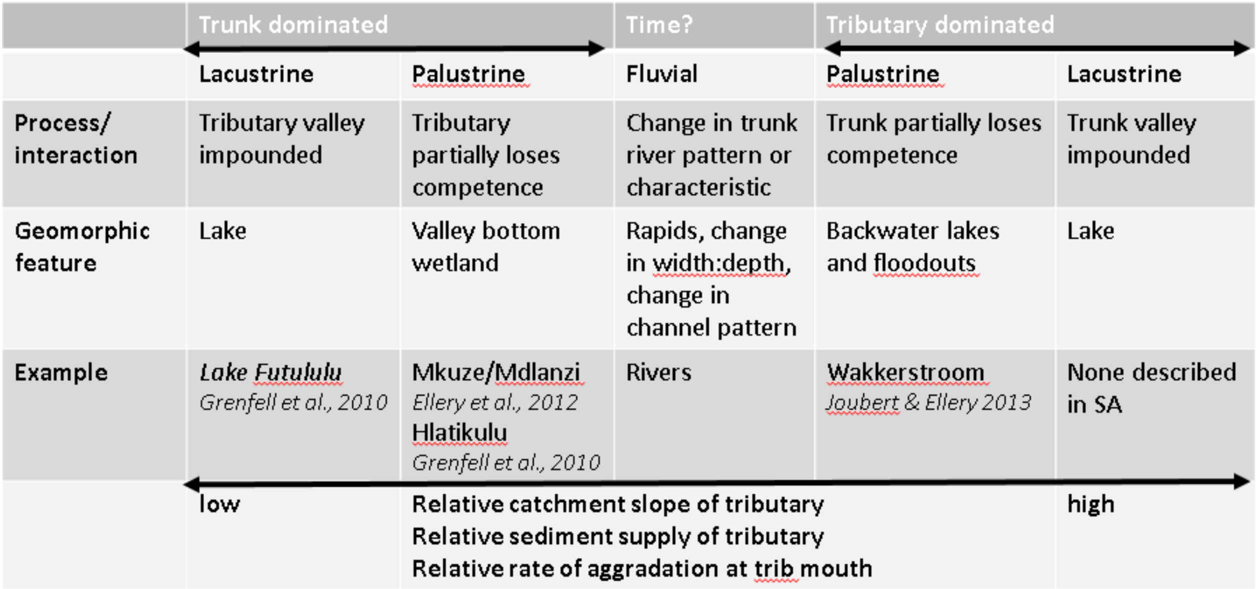
2.1.3 Local base level and accommodation space

In a fluvial context, the concept and term “accommodation space” has been used by several authors (Ellery *et al.*, 2009; Grenfell *et al.*, 2010; Edwards, 2009) to describe a reach where river erosion processes are temporarily halted, allowing waters to slow sufficiently to accumulate sediment along a watercourse. Cessation of incision is associated with the lowest level to which the river can erode its bed, which is known as the base level (Knighton, 1998). The ocean is regarded as the ultimate base level for rivers, as it is the lowest point on the river longitudinal profile (Leopold and Bull, 1979). As a stream erodes its bed such that the elevation of the bed approaches sea level, stream gradient approaches zero, velocity declines, and the ability to erode sediment is similarly reduced (Leopold and Bull, 1979). This applies not only where a river flows into the ocean, but also into a lake, or in some cases where a small stream enters another river (Leopold and Bull, 1979). These features act as local base levels along the course of the river. The presence of multiple local base levels along a watercourse will be reflected on the river longitudinal profile as relatively flat sections interrupted by "steps" associated with substantial narrowing of the valley (Grenfell *et al*., 2010).

Knighton (1998) and Schumm (2005) have identified a number of factors that may influence local base level in rivers, such as bedrock outcrops, interactions of the trunk stream with tributary streams, active local tectonic activity and valley morphology. Recent research has offered evidence that these controls over river form and behavior have also shaped wetland formation and evolution in southern Africa (McCarthy and Hancox, 2000; Tooth *et al*., 2004; Ellery *et al*., 2009; Grenfell *et al*., 2010; Joubert and Ellery, 2013). Many floodplain wetlands have been found to be located upstream of resistant rock barriers that cross river courses and form stable local base levels (Tooth *et al*., 2004). The excess stream energy upstream of dolerite dykes or sills, which is unable to cut vertically through the erosion-resistant rock, has been found to laterally plane the upstream valley of more easily eroded bedrock (typically Karoo lithologies of shale and sandstone), producing broad valleys with a shallow longitudinal slope and the accommodation space to support floodplain wetlands such as in the Klip River floodplain in the eastern Free State (Tooth *et al*., 2004). Sinchembe and Ellery (2010) describe a similar set of processes for the Fairview Spring wetland near Grahamstown, where a stream flowing across shale has been planed due to a resistant quartzite lithology of the Cape Supergroup at the toe of the wetland.

In addition to geologic controls, Tooth and McCarthy (2007) also refer to geomorphological origins of local base controls, such as the presence of laterally impinging alluvial fans, colluvium and glacial outwash, that extend into the trunk stream and form a local base level. This has been further described in the South African context in Hlatikulu Vlei by Grenfell *et al*. (2010) where floodplain sedimentation along a mainstem (trunk) stream obstructs a tributary stream, elevating the tributary base level. In turn, the slope of the tributary upstream of the trunk stream flattens, increasing water residence time and contributing to peat formation. It has been found that not only do trunk streams set the local base level for tributaries, but that tributary streams may themselves set a local base level for the trunk stream. Tributary streams in the middle reaches of Wakkerstroom Vlei have been found to block the trunk stream through sediment deposition in the form of large alluvial fans (Joubert and Ellery, 2013). The alluvial fans cause the slope of the trunk stream to be lowered in an upstream direction, causing the middle reaches of the wetland to experience diffuse flows, thus creating accommodation space for peat formation in the wetland (Joubert and Ellery, 2013).

The range of possible interactions between trunk and tributary streams was summarised by Grenfell *et al.* (2010) along a continuum attributed to variations in sediment deposition patterns and resultant features (Figure 2.1).



	Trunk dominated		Time?	Tributary dominated	
	Lacustrine	Palustrine	Fluvial	Palustrine	Lacustrine
Process/ interaction	Tributary valley impounded	Tributary partially loses competence	Change in trunk river pattern or characteristic	Trunk partially loses competence	Trunk valley impounded
Geomorphic feature	Lake	Valley bottom wetland	Rapids, change in width:depth, change in channel pattern	Backwater lakes and floodouts	Lake
Example	*Lake Futululu* *Grenfell et al., 2010*	Mkuze/Mdlanzi *Ellery et al., 2012* Hlatikulu *Grenfell et al., 2010*	Rivers	Wakkerstroom *Joubert & Ellery 2013*	None described in SA
	low	Relative catchment slope of tributary Relative sediment supply of tributary Relative rate of aggradation at trib mouth			high

Figure 2.1. A conceptual continuum of trunk-tributary relationships and the geomorphic implications of varying catchment slope and sediment supply (after Grenfell *et al.*, 2010).

Where tributary slope is low, tributary sediment supply is low and rate of aggradation at the mouth of the tributary is low, the trunk will control wetland formation on the tributary. The greater the dominance of the trunk and the lower the tributary slope and sediment supply, the greater the chance of lake formation on the tributary. Where tributary slope is high, tributary sediment supply is high and rate of aggradation at the mouth of the tributary is high, the tributary will control wetland formation on the trunk.

2.1.4 Wetlands and geomorphic thresholds

Wetlands within the fluvial context have been described as zones of deposition characterised by net accumulation of sediment (Kotze *et al.*, 2008). Through its control on erosion and deposition within river systems, local base level creates a particular hydrogeomorphic setting that is conducive to sediment accumulation and the development of wetlands (Ellery *et al.*, 2009). In addition to base level control, variation in stream discharge drives sediment accumulation and distribution, resulting in a variety of wetland forms and processes. Within fluvial systems in South Africa, these have been classified as floodplain wetlands, channelled valley bottom wetlands and unchannelled valley bottom wetlands (Ellery *et al.*, 2009; Ollis *et al.*, 2013).

Garden (2008), examining sediment response within floodplains as opposed to valley bottom wetlands, found that floodplain wetlands are usually generated where stream discharges and capacity to transport sediment are comparatively high, and the system is able to adjust internally to variations in discharge and sediment supply. In contrast, valley bottom wetlands are generally characterised by subsurface and diffuse surface flow with low unit stream powers and limited capacity to transport sediment, leading to aggradation (Grenfell *et al.*, 2008). Where the sediment load exceeds the ability of the stream to transport sediment (low discharge in relation to sediment supply), deposition occurs, and if discharge and gradient are sufficiently low, and sediment supply is such that this low gradient is maintained, the valley bottom wetland is most likely to be unchannelled, or with short, discontinuous channels that re-distribute water and sediment relatively evenly across the wetland. Where the ability of the stream to transport sediment is greater than its sediment load (high discharge), erosion can be expected to occur in response to higher discharges and low rates of sediment input (Ellery *et al.*, 2009). It follows that where sediment supply to a wetland is abundant it is unlikely to erode, while wetlands which are sediment starved are more vulnerable to incision (Ellery *et al.*, 2009).

Garden (2008), Grenfell *et al.* (2008) and Ellery *et al.* (2009) found that wetland size is broadly related to wetland longitudinal slope. Larger wetlands with bigger catchments are typically low gradient floodplains, while smaller, steeper wetlands are characteristically valley bottom wetlands (Garden, 2008). Valley bottom wetlands above a certain threshold slope were erosional with erosion gullies present (Figure 2.2). This led to the prediction of a slope threshold such that if the longitudinal slope is higher than the threshold slope for the size of the wetland, a wetland is vulnerable to erosion.

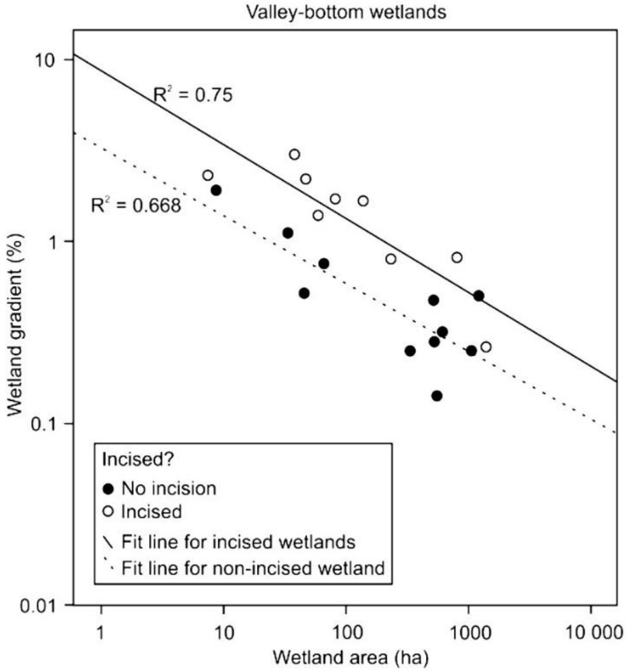


Figure 2.2. Erosion gullies in valley bottom wetlands above a certain threshold slope (Garden, 2008).

2.1.5 Ecosystem engineering

A further influence on stream and wetland morphology and local base level is bio-geomorphic, where "ecosystem engineering" as a result of biological activity has been documented. Ecosystem engineers have been defined by Jones *et al.* (1994; p373) as "organisms that directly or indirectly modulate the availability of resources to other species, by causing physical state changes in biotic or abiotic materials. In so doing they modify, maintain and create habitats". A well-described example is beavers changing fast flowing streams to still water habitats in the northern USA (Mitsch and Gosselink, 2000). In the Okavango Delta in Botswana, direct modification of fluvial structure and function is also attributed to biota present in the wetland (Ellery *et al.*, 2003*)*. In this case the plant *Cyperus papyrus* regulates water loss from the channel and initiates localised aggradation through deposition of bedload sediment. Encroachment of papyrus from the adjacent wetland into the channel controls channel width (Ellery *et al.*, 1995), and aggradation of the channel banks as papyrus grows as a semi-floating mass of entangled rhizomes controls channel depth (Ellery *et al.*, 2003), such that fluvial form and processes are fundamentally shaped by this plant.

In the southern Cape, it has been proposed by Seiben (2012) that palmiet plays a dominant role in initiating sediment trapping and peat formation in the wetlands. Palmiet has several characteristics that make it well suited to trapping sediment and altering the flow regime and characteristics of the river channel. The family Prioniaceae contains a single species, *Prionium serratum*, which was previously a member of the Juncaceae. The family is endemic to South Africa and limited in its distribution to the South Western Cape, Eastern Cape and southern KwaZulu-Natal (Munro *et al.*, 2001). Palmiet is a perennial shrub growing to 3 m tall. Roux (2003) and Munro *et al.* (2001) with an aerial, woody rhizome, up to 8 cm in diameter, which starts out sub-erect, and is later decumbent, often branched, with adventitious roots at nodes and covered with fibrous remains of old leaf bases. Boucher and Withers (2004) noted that what appear to be stems are actually the branching, aerial rhizomes. Roux (2003) reports that the roots are stout, to approximately 5 mm in diameter, and contain extensive aerenchyma (allowing submerged parts of the plant to receive oxygen from non-submerged parts of the plant above water, allowing the plant to remain submerged for long periods). Boucher and Withers (2004) noted that during fire, the thick "stems" of palmiet are not killed and they recover rapidly, with side shoots developing prolifically after the plants are burnt. They observed that the remains of old leaves drape down and enclose the stems and appear to protect the plants from damage during floods when the plants are "subject to boulders moving downstream and colliding against them". Finally, they also noted that dense stands are often a clonal system of inter-connected stems originating from only a few parent plants through vegetative reproduction.

Palmiet is said to "form thickets across rivers" and "dense, monospecific stands, usually in the beds of streams and rivers" (Munro *et al.*, 2001; p 3). The clumps of rhizomes trap soil and detritus, thereby "building up river beds, ameliorating flooding events, and filtering water" (Munro *et al.*, 2001; p 3).

The dense growth of robust palmiet stems and its very dense root mass, provide formidable frictional resistance to flood flows, dissipating their energy and trapping any sediment. In this respect the plant has been likened to an "ecosystem engineer", where "the occurrence and proliferation of palmiet in foothill streams eventually plugs the river, turning the river into a wide valley bottom wetland" (Seiben, 2012; p 8). In this sense, palmiet is viewed as a problem plant by farmers, in that it is thought to block waterways and lead to inundation of arable land and infrastructure. Many landowners therefore remove palmiet from peatlands in order to reduce flooding of arable land and infrastructure.

2.2 Factors that affect peat formation

2.2.1 Organic sediment

Organic sediment, which passively accumulates *in situ*, can form in response to the accommodation space created through geomorphic processes associated with streams and tributaries and occasionally by local subsidence (Edwards, 2009; Grenfell *et al.*, 2010; Ellery *et al.*, 2012; Joubert and Ellery, 2013). While clastic sediment can create topographic relief and produce long-standing features that affect gradient, water flow and residence time, peat tends to passively accumulate in shallow basins to the mean elevation of minimal flooding (Ellery *et al.*, 2009, 2012).

Wetlands incorporate an extremely wide range of hydrological regimes, from temporarily to permanently saturated. This is typically reflected in the morphology of mineral wetland soils that may be subjected to varying periods of inundation such that mottling reflects seasonal water level fluctuation between saturated (anaerobic) and unsaturated (aerobic) conditions, while grey colours reflect permanent saturation. The term "gleyed" is used to describe grey permanently flooded soils. The presence of organic soils reflects permanently- to semi-permanently saturated conditions. Mineral soils (sand, silt, loam or clay) can thus be distinguished in this way from organic soils, which are typically very dark to black in colour. Thus, organic and peat wetlands are set apart from other wetlands, as they represent accumulation from *in situ* plant matter and organic remains, as opposed to an accumulation of clastic sediment derived from elsewhere. According to the soil classification system used in South Africa (Soil Classification Working Group, 1991), soil with an average organic carbon content of at least 10% throughout a vertical distance of 20 cm is defined as organic and referred to as the Champagne Soil Form. Peat is commonly considered to be a sub-set of organic soil, where peat is defined as "a sedentarily (*in-situ*) accumulated material comprising of at least 30% (dry mass) of dead organic matter" (Joosten and Clark, 2002; p 24). A peatland has been defined as "an area with or without vegetation with a naturally accumulated peat layer that has a minimum thickness of 30 cm" (Joosten and Clark, 2002; p 33).

2.2.2 Factors contributing to peat formation

Peat formation is said to require low energy hydrological conditions in a setting that is free of clastic sediment or has very limited clastic sediment supply (Ellery *et al.*, 2009). Rydin and Jeglum (2006) similarly found that bogs had developed from lacustrine, riverine, and soligenous (groundwater or spring-fed) systems in locations removed from the influence of flooding or surface flow. Rydin and Jeglum (2006) also report that frequently flooded wetlands that receive dissolved or particulate materials, clay or silt, are often found to contain little peat, whereas other parts of floodplains, where the floodwaters may not carry as much particulate matter, can develop true peats. However, organic and clastic sediment content is typically present in varying amounts, as reflected in the Western Cape region of South Africa that has many wetlands with black soils where the organic content is as low as 2 to 15 % (Grundling, 2011; Mills *et al.*, 2012).

The positive overall water balance conducive to peat formation has several consequences, including high plant productivity, which contributes to carbon accumulation, and the development of anaerobic conditions, which slows decomposition. Belyea and Clymo (2001) report decomposition rates of 1 000 times slower under permanent saturation, with variable rates of decomposition according to the degree of oxygenation in the water. As is to be expected, faster rates of decomposition are observed in the catotelm (oxygenated areas of peat close to the surface) and slower rates in the acrotelm (oxygen reduced areas;Belyea and Clymo, 2001).

Several secondary factors may also influence peat formation. Temperature, under conditions where it is adequate for plant growth but low enough so that evaporation is limited and a water-logged substrate is maintained, and where decomposition rates are low (Charman, 2002), will enhance peat formation. Low temperatures contribute to reducing the activity of decomposing micro-organisms (Fey, 2010). Relatively impermeable underlying geology ensures that water is retained in place and it will influence the nutrient status of the groundwater (Charman, 2002). Typically, acidic conditions are conducive to peat formation, although this has been found to be variable. Kettle peatlands provide an unusual alternative example to an underlying impermeable surface, namely the "self-sealing properties of peat by which precipitation of humus colloids from the peat seals off the mineral soil at the interface of mire and basin. This raises the drainage level and thus the water level in the basin, so that peat growth and humus precipitation occur at progressively higher levels" (Gaudig *et al.,* 2006; p 1).

The most obvious conditions under which a positive water balance will prevail are areas of high rainfall and low temperature. This explains most peatland occurrence and explains the presence of the largest area of peatlands at high latitudes of North America, Canada, Europe, Russia, South America and New Zealand. Peatlands are, however, very extensive in South-East Asia, where temperatures are high and organic matter would be expected to break down quickly. However, very high rainfall prevails in these regions and very high plant productivity offsets rapid decomposition stimulated by the presence of high temperatures.

Peatlands occur in a multitude of landscape settings but predominantly those with a low gradient and/or basin-shaped topography, where current velocity is low. On floodplains within backwater channel and oxbow lake situations, water is similarly retained. Many peatlands occur in lake settings (Rydin and Jeglum, 2006). Peatlands are not common on slopes (water drains away), but exceptions have been described in parts of the world where precipitation is high and constant enough such that peat-forming vegetation and peatland growth does occur on a slope. These areas often have high groundwater input or an impermeable underlying surface. Examples include the blanket bogs of the United Kingdom (Yeloff *et al.,* 2006).

Peat would be least expected in semi-arid regions. A positive water balance is unexpected in South Africa, where the average rainfall is often less than potential evapo-transpiration. Nevertheless, eleven peatland ecoregions have been described in South Africa (Marneweck *et al.*, 2001) and they support peatlands as varied as interdune tropical swamp forests on the east coast, percolation mires in the interior (on the southern African plateau) and palmiet peatlands in the Cape Fold Mountains. The largest peatland in the country, in KwaZulu-Natal, is reportedly the Mkuze swamp, which, together with Mbazwana swamp forest, forms the largest peatland complex in South Africa (approximately 8 800 ha in extent) (Grundling and Grobler, 2005).

An internal factor to peatlands and peat formation is the plants which contribute to the peat-forming process. Sphagnum moss is the most commonly described peat-forming plant in northern peatlands. Sphagnum has ecosystem engineering capabilities in that it can alter the chemistry of its environment (it is proposed that sphagnum can increase the acidity of its environment through the release of organic acids which, in turn, retard bacterial action and therefore decomposition rates). In this way, sphagnum is able to promote peat accumulation despite low primary productivity rates (Van Breemen, 1995; Mitsch and Gosselink, 2000). Sphagnum has also been reported to hold water up to 15 to 20 times its dry weight (Mitsch and Gosselink, 2000*)* due to its growth habit and morphology. In this way, sphagnum is adapted to control and sustain water-logging rather than simply responding to it. A New Zealand study has described the properties of the restio, *Empodisma minus*, which produces a "dense mass of upward growing fine roots and root hairs at the bog surface", and forms the bulk of the peat (Clarkson *et al.,* 2004; p 146). The cluster roots have similar water-holding capabilities to sphagnum, while the plants have further adaptations to conserve water, allowing them to grow in areas of high seasonal deficits where bogs would not normally be expected to develop (Clarkson *et al.,* 2004).

Plants differ in productivity and decay rates, with higher decomposition rates reported in plant material with higher nitrogen content (Mitsch and Gosselink, 2000). Papyrus (*Cyperus papyrus)* has been shown to exhibit high rates of productivity and low nutrient concentrations, and the combination of these processes contributes to the accumulation of organic matter (Ellery and McCarthy, 1998; Ellery *et al.*, 2003).

2.3 Geology and climate – the southern Cape context

Despite being internally dynamic, wetlands are relatively stable ecosystems, and as such may provide long term records of environmental change. However, wetlands and landscapes are subject to change occurring over multiple spatial scales and time-frames (Knighton, 1998; Ellery *et al.*, 2009; Joubert and Ellery, 2013). These changes and associated ecosystem processes range from climatic and hydrological variability within a year or between years, to processes that operate over time scales of decades to centuries (such as through climate variability), to geological timeframes where weathering, erosion and tectonic processes shape the landscape. This inherited history has a great influence on current wetland morphology and dynamics (Edwards, 2009; Joubert and Ellery, 2013).

Approximately 450 million years ago, when Africa was part of the supercontinent of Gondwanaland, stretching, thinning and rifting of the earth's crust occurred along what is now the southern Cape coast as Antarctica drifted southwards relative to the current Cape coastline forming a shallow sea (the Agulhas Sea). Sandstones and mudstones were deposited by rivers flowing into the rifted basin in shallow coastal edges and deeper waters respectively (McCarthy and Rubidge, 2005). Over millions of years these cemented into sedimentary rock collectively known as the Cape Supergroup (Table 2.1). Roughly 300 million years ago, the Cape Supergroup rocks were folded and compressed as Antarctica and the African continent collided and a subduction zone developed (Compton, 2004; McCarthy and Rubidge, 2005; Ellery and Rowntree, 2010). The Cape Fold Belt was thus formed, including the east-west-trending Langeberg Mountain range that runs parallel to the southern Cape coast and forms part of the study area.

Table 2.1: Geological context (Theron and Johnson, 1991; Johnson *et al.*, 1999.; McCarthy and Rubidge, 2005: Johnson *et al.*, 2006; Malan and Viljoen, 2008).

Million Years Before Present	PERIOD	DEPOSITIONAL SETTING		LITHOLOGY	AGE
400	DEVONIAN	CAPE SUPERGROUP	Rivers deliver *coarse sandy material* to the Agulhas basin, shallow, marine environment	**Table Mountain Group** Erosion-resistant sandstone	**450 MYA:** Africa lies over South Pole, rifting forms the Agulhas basin. **400-300 MYA:** Plant life amphibians move onto land
			Deepest section of basin receives *fine sediments*, deep water environment	**Bokkeveld Group** Fine-grained mudstone, more easily eroded	
			As basin fills in, rivers continue to deliver *coarse sandy material* over the Table Mountain Group. Shallow, marine environment	**Witteberg Group** Erosion-resistant quartzitic sandstone	
362	CARBON-IFEROUS	Time of extensive wetlands			**320-270** Great Ice Age
286	PERMIAN	Time of compression and formation of subduction zone, sedimentary rocks (CAPE SUPERGROUP) buckle and fracture			**Cape Fold Mountains**, incl. **Langeberg Range**
251	TRIASSIC				
208	JURASSIC	Gondwanaland begins to break up, **faulting along base of Langeberg**			**Half-graben basins formed**
144	CRETA-CEOUS	UITENHAGE GROUP	Large, fast-flowing rivers deposit coarse gravel and sand where rivers enter basins formed by half grabens associated with continental drift	**Enon Formation** Coarse pebble-rich conglomerate	**125 MYA:** Origin of Angiosperms, Proteaceae **60-120 MYA: Warm and wet**, tropical climate, cyclone-induced rainfal, steep gradient energetic rivers, high rates of fluvial erosion
			Finer material is transported further from the point of entry into rifted basin, estuarine environments	**Kirkwood Formation**	

Around 190 million years ago, the continents of Gondwanaland began moving apart, causing tearing and faulting in the southern Cape. Faulting along the base of the Langeberg mountains as described by Marker and Holmes (2010) and Malan and Viljoen (2008), created a series of half-graben basins (Figure 2.3), which initiated a second important period of sedimentary rock formation as the rifted basins began to fill with sediment approximately 120 million years ago.

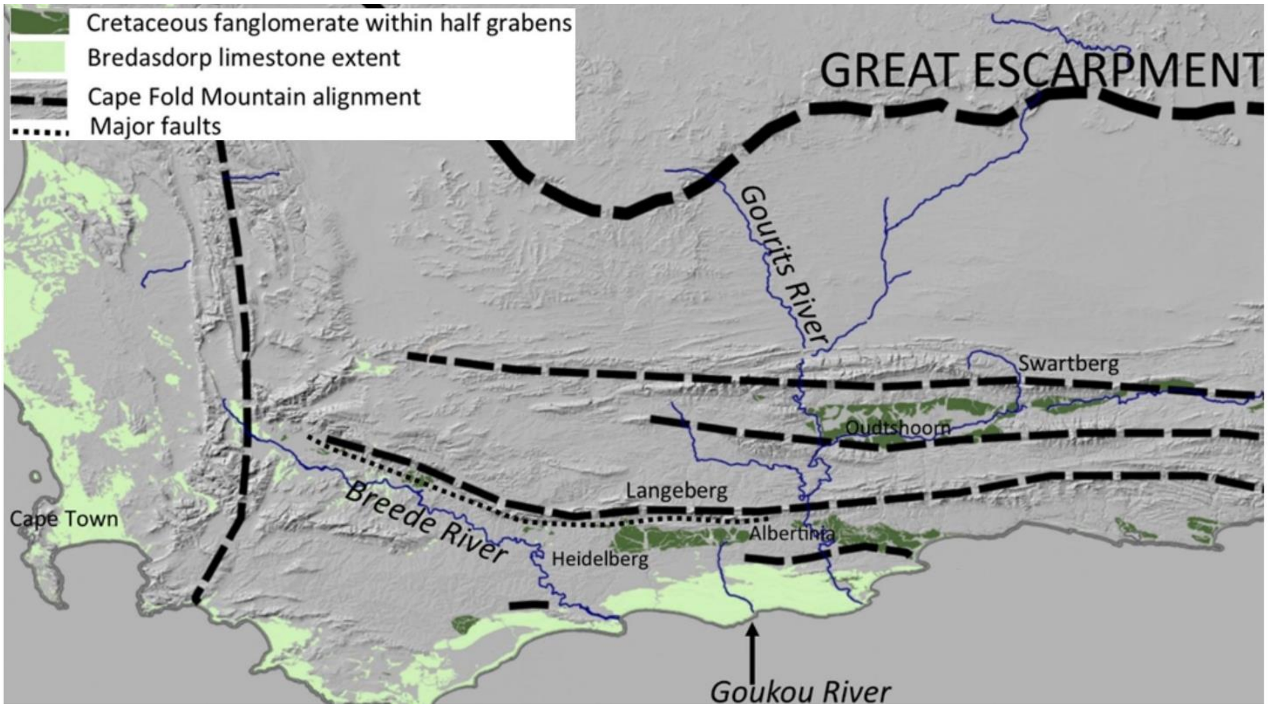


Figure 2.3. Regional topography and geological context of the study, and half graben locations in the southern Cape (after Marker and Holmes, 2010).

During the Cretaceous, the climate was warm and wet (McCarthy and Rubidge, 2005), and steep gradient, energetic rivers, with high rates of erosion, delivered sediment and developed large alluvial fans extending into the half-graben basins (Malan and Viljoen, 2008). A large river flowed within the basin, perpendicular to the direction of the current day Goukou river, flowing eastwards towards Mossel Bay (Malan and Viljoen, 2008), with a braided floodplain filling the valley and large alluvial fans along the sides of the basin. Spanning millions of years the alluvial fans consolidated into the red-coloured Enon Conglomerates which lie along the steep slopes of the former basin. The mudstone and sandstones of the floodplain, originally derived from steep Cape Supergroup slopes, were deposited and consolidated to form the Kirkwood Formation (Table 2.1). These two formations make up the Uitenhage Group.

In the moist and warm climate of the Cretaceous, thick, highly leached tropical soils developed across the landscape (Schloms *et al.*, 1983; McCarthy and Rubidge, 2005; Ellery and Rowntree, 2010). One end product of the prolonged weathering of these soils over tens of millions of years are areas of cemented silcrete and ferricrete which cap the saprolite that developed on the African

Surface (Schloms *et al.*, 1983), today known as the Grahamstown Formation (Table 2.2). Extensive erosion of this surface occurred prior to about 60 million years ago to form what is termed the African Erosion Surface (McCarthy and Rubidge, 2005; Marker and Holmes, 2010). This erosion cycle ended during a global shift to lower temperatures and arid conditions about 64 million years ago (McCarthy and Rubidge, 2005), but before that produced an extensive plain between the coast and the mountains (Marker and Holmes, 2010) today known as the coastal platform. Together with the Cape Fold mountains, and extending from the base of the mountains to the coastline, this is a distinctive feature of the southern Cape landscape and the study area.

Table 2.2: Chronology and processes associated with erosion surfaces (synthesised from the literature as referenced below).

PERIOD	CHRONOLOGY, PROCESSES AND ASSOCIATED LITHOLOGY	EROSION SURFACE
Paleocene **Eocene** **Oligocene**	**African cycle of erosion** (King, 1963), giving rise to the AES. **Before 65 MYA** Conditions favoured deep weathering of soils over tens of millions of years and the formation of 5-10m laterised soils with silcrete and ferricrete capped Cape Supergroup lithologies (Schloms *et al.* 1983; Marker and Holmes, 2010; Rowntree and Ellery, 2010). Silcrete (**Grahamstown Formation**) occurred in a humid tropical or subtropical environment with minimal local relief (Summerfield, 1991). **Coastal platform** planed to an elevation close to the then sea level during the mid-Cenozoic **By 60 MYA:** Rivers lose gradient and erosional power	AES
Miocene	**20 MYA** Uplift event, lifting the southern Cape 200 m. Rivers once again became erosional, present-day evidence in terraces and high sediment loads. Erosion planed the land surface giving rise to the PA I erosion surface.	PA I
Pliocene	**5 MYA** 2nd uplift event, lifting the southern Cape a further 200 m. (Marker and Holmes, 2010; McCarthy and Rubidge , 2005). Bredasdorp Group aeolianites of the Wankoe Formation were deposited on the PA I surface (Malan and Viljoen, 2008). **Bredasdorp group** limestone belt (250-270 masl) was related to sea level changes (Marker and Holmes, 2010) Erosion planed the land surface (and continues to do so) giving rise to PA II.	PA II

*AES (African Erosion Surface); PA I (Post Africa I); PA II (Post Africa II)

Erosion of the southern Cape Coastal Platform was initiated once again approximately 20 million years ago (Table 2.2) when southern Africa experienced a period of uplift attributed to injection of heat from the Earth's mantle into the crust, which caused the southern African continental crust to rise (McCarthy and Rubidge, 2005; Ellery and Rowntree, 2010). During the uplift event, the southern Cape coastal region was raised approximately 200 m (Marker and Holmes, 2005, 2010). The raised elevation led to widespread erosion. The erosion surface created between 20 million and 5 million years ago is known as the Post Africa I Erosion Surface (Ellery and Rowntree, 2010). A second uplift event 5 million years ago (Table 2.2) lifted the southern Cape coast by another 200 m, and was similarly accompanied by stream incision and erosion of the land surface (McCarthy and Rubidge, 2005; Marker and Holmes, 2010). The Post African

Erosion cycles (Table 2.2) were responsible for eroding the relatively easily weathered Uitenhage Group and Bokkeveld shales into rolling hills, developing coastal river gorges 100 to 300 meters deep, and for removing much of the deeply weathered older African Surface (or Grahamstown Formation), leaving small areas of silcrete and ferricrete outcrops on hilltops and slopes (Figure 2.4A; Lewis, 2008; Marker and Holmes, 2005, 2010).

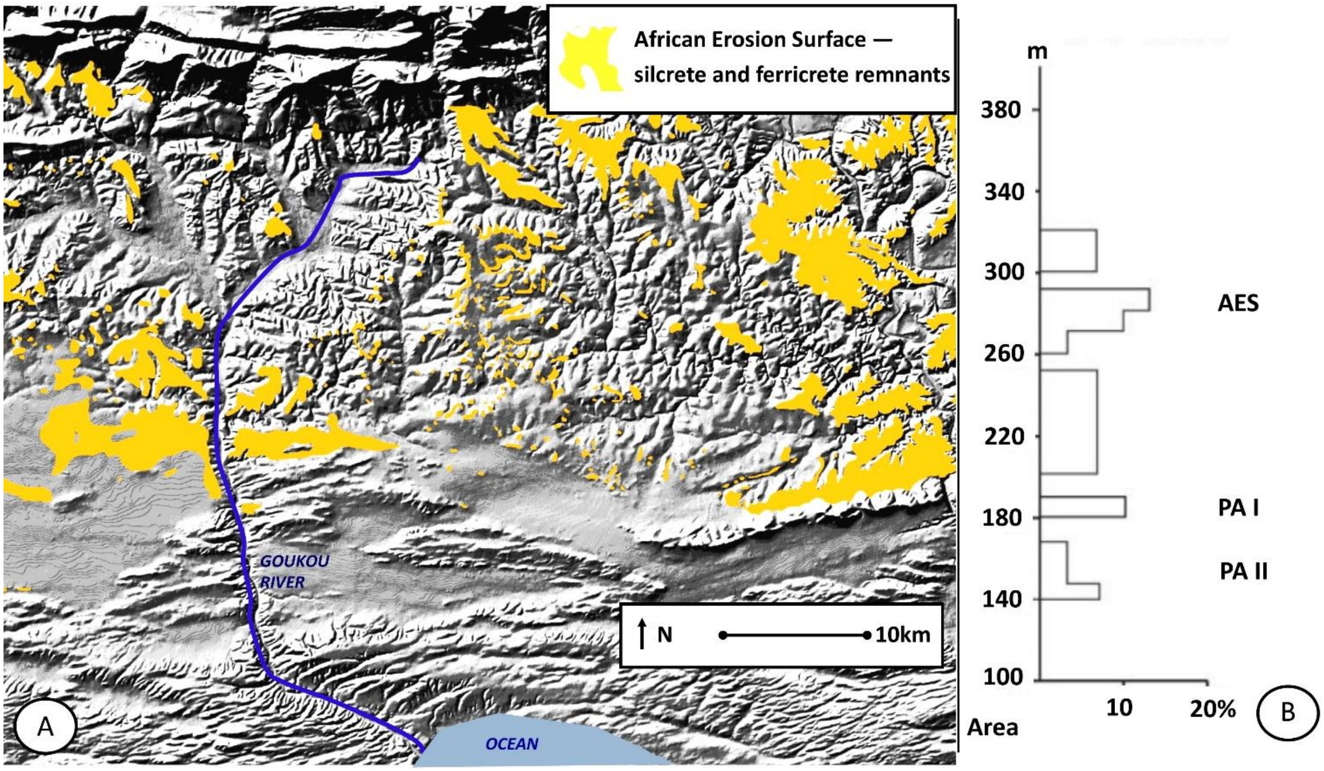


Figure 2.4. African Erosion Surface remnants (sourced from the 1:250 000 geological cover) overlain on a digital elevation model to illustrate relief and the highly dissected landscape of the study area (4A), and regional altitude range and associated locations of erosion surfaces (4B, reproduced from Marker and Holmes, 2010).

The African Erosion Surface (Table 2.2) developed across multiple lithologies to similar altitudes (Marker and Holmes, 2010). In the study area, it lies between 250-350 m above sea level (Figure 2.4B; Marker and McFarlane, 1997).

Along with the consequences of base level changes caused by rejuvenation associated with uplift (the most recent being 5 million years ago), the Goukou catchment landscape has since been shaped by sea level fluctuations, which seem to have been key events in the recent (last 100 000 years) geomorphic evolution of the landscape and the rivers and wetlands embedded within it (McCarthy and Rubidge, 2005; Marker and Holmes, 2010).

The southern hemisphere climatic record over the last 750 000 years has been deduced from oxygen and deuterium isotope records in ice cores such as the Vostok and Dome-C ice cores from Antarctica (Burenhult, 2003; Ellery *et al.*, 2009; Figure 2.5). Over this time southern Africa has undergone five climatic cycles, where warm, interglacial periods occurred approximately every 100 000 years, but generally lasted only a few thousand years at a time (McCarthy, 2009). As indicated by the dust concentration in the ice, which is thought to indicate rainfall in the southern continents, during glacial periods southern Africa became extremely arid (McCarthy and Rubidge, 2005; Figure 2.5).

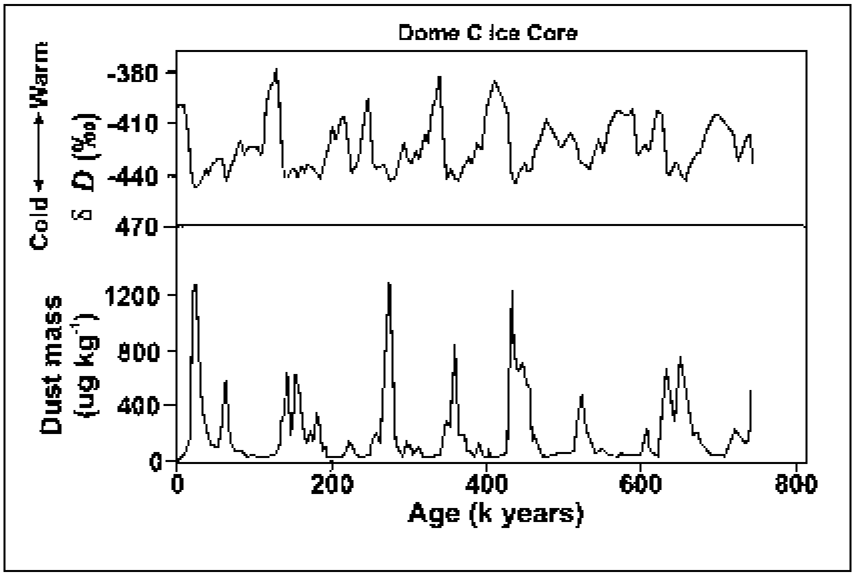


Figure 2.5. Record of climate change over ~ 750 000 years, Dome C Ice Core (Burenhult, 2003; Ellery *et al.*, 2009).

Continental ice sheets were recently most extensive about 20 000 years ago and sea level at this time dropped about 120 metres below current levels (Burenhult, 2003; Henshilwood, 1995; Figure 2.6). Ever since the arid/semi-arid, cold and harsh conditions and low sea level of 20 000 years ago, sea level, temperature and rainfall have been rising (Lewis, 2008; Ellery *et al.*, 2009). A temperature record of the past 30 000 years for the southern Cape has been obtained through combining data on the isotopic composition of a deep cave stalagmite with that of a confined groundwater aquifer in the same region. The analysis suggests multiple fluctuations over the past 5 000 years, with generally lower temperatures (1–2°C) around 4 500 and 3 000 years ago (Talma and Vogel, 1992). The fluctuations recorded suggest "quasi-cyclical oscillations in rainfall, with periods of about 1 500, 600, 80 and 18 years" (Ellery *et al.*, 2009; p 17). A steady rise in sea levels occurred over this time, with a likely series of minor regressions until about 3 500 years ago, when current sea levels were established (Henshilwood, 1995; Figure 2.6; Table 2.3).

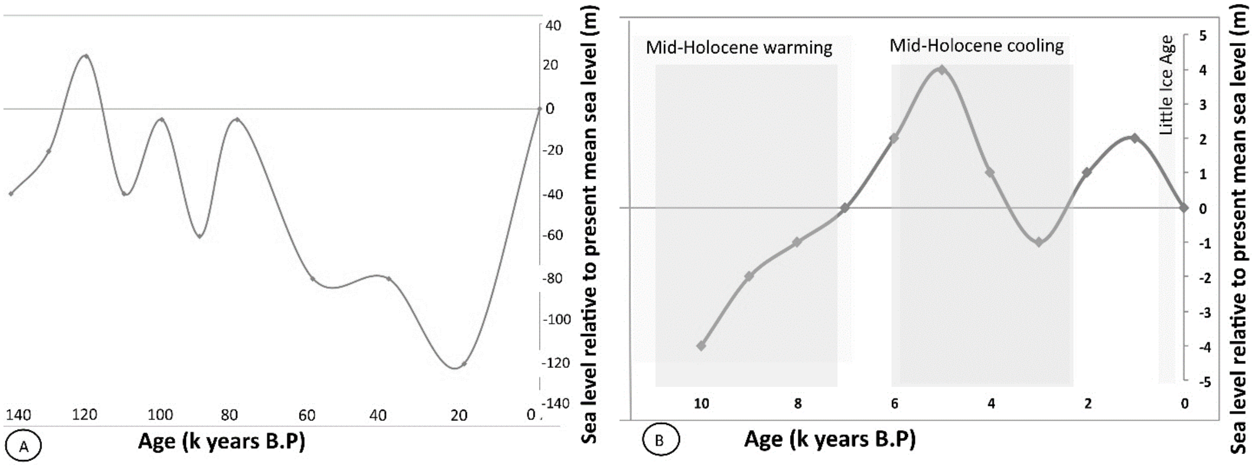


Figure 2.6. Record of sea level change over the last 120 000 (6a) and 10 000 (6b) years (Ramsay, 1995; Compton, 2004).

Further evidence of the past southern Cape climate is available from several recent paleo-environmental studies of the winter to summer rainfall zone. Carr *et al.* (2006; p 261), investigating lunette dune accretion on the Agulhas Plain reported accretion between 12 000–13 000 years ago, suggesting drier conditions, and up to four episodes of accretion during the last 2 800 years, including at 700 and 450 years ago, "which might reflect brief episodes of drought or drier conditions within an otherwise wetter period".

Table 2.3: Summary of sea level and climate fluctuations (synthesised from the literature as referenced below).

SEA LEVEL AND CLIMATE FLUCTUATIONS OF RELEVANCE TO THE SOUTHERN CAPE
Since 500 000 BP Five temperature and sea level highs have occurred around 425 000 BP, 325 000 BP, 230 000 BP, 120 000 BP (**+ 20m)** and 7 000 BP (Labeyrie *et al.,* 2002; Ellery *et a*l, 2009). Sea levels **below -120m** have similarly occurred multiple times at approximately 345 000 BP, 140 000 BP and 20 000 BP (Labeyrie *et al.,* 2002). Temperatures follow glacial-interglacial 100 000 year cycles, with each interglacial lasting about10 000 yrs.
Since 20 000 BP (Pleistocene and Last Glacial Maximum) sea level has been rising from a low of -120m and temperature has also been rising overall (Henshilwood, 1995; Talma and Vogel, 1999; Ellery *et al*., 2009)
Since 11 000 BP (Holocene) (after Ramsay, 1995)
6,000 BP Sea level similar to present day
4 480 BP Sea level rose with a high of +3.5m
3 880 BP Sea level similar to present day
3 000 BP Sea level dropped -2m
1 610 BP Sea level rose +1.5m
900 BP Sea level similar to present day

2.4 Conclusion

The Goukou catchment landscape has been shaped by multiple uplift events and sea level fluctuations over time scales of tens to hundreds of thousands of years. Over the last 20 000 years, temperature has been warming, and sea level has risen from -120 m to its current level and has fluctuated between 3.5 m above and 2 m below present for the last 6 000 years. Rainfall has similarly followed quasi-cyclical oscillations within an overall wetter trend in recent times.

Despite the overall high elevation, steep and incising landscape, arid climate and high PET in southern Africa, geomorphic factors have been shown to be capable of setting local base levels and prolonging water residence time within river systems, leading to wetland formation. These geomorphic controls include impoundment of tributary streams by the trunk, or the encroachment of tributary sediment deposition into a trunk, impounding the upstream region. The interactions of trunk and tributary streams are influenced by slope, sediment supply and the ability of the stream to transport the available sediment. Where water is retained for long periods within the resulting landscape, sustained anoxic conditions leads to peat accumulation. These conditions are typically prevalent where there are low energy flow conditions, low clastic sediment input, low temperature, areas of underlying impermeable geology, and higher plant productivity than decomposition.

Geomorphic slope thresholds, above which wetlands are vulnerable to erosion, have been described for clastic sediment-dominated valley bottom wetlands in southern Africa, but research is limited on this topic for peat wetlands.

In addition to fluvial geomorphic controls, certain plants may play a bio-geomorphic role in controlling wetland formation. For example, plants may be morphologically adapted to sustain or prolong saturation, have increased productivity or able to physically colonise and influence the dynamics of a system.

3. STUDY AREA

3.1 Location, topography and geology

The Goukou Wetland is approximately a 700 ha, unchannelled valley bottom, peat wetland system located in the Western Cape province of South Africa (Figure 3.1). The wetland is near the town of Riversdale, approximately 300 km east of the city of Cape Town and 90 km west of Mossel Bay.

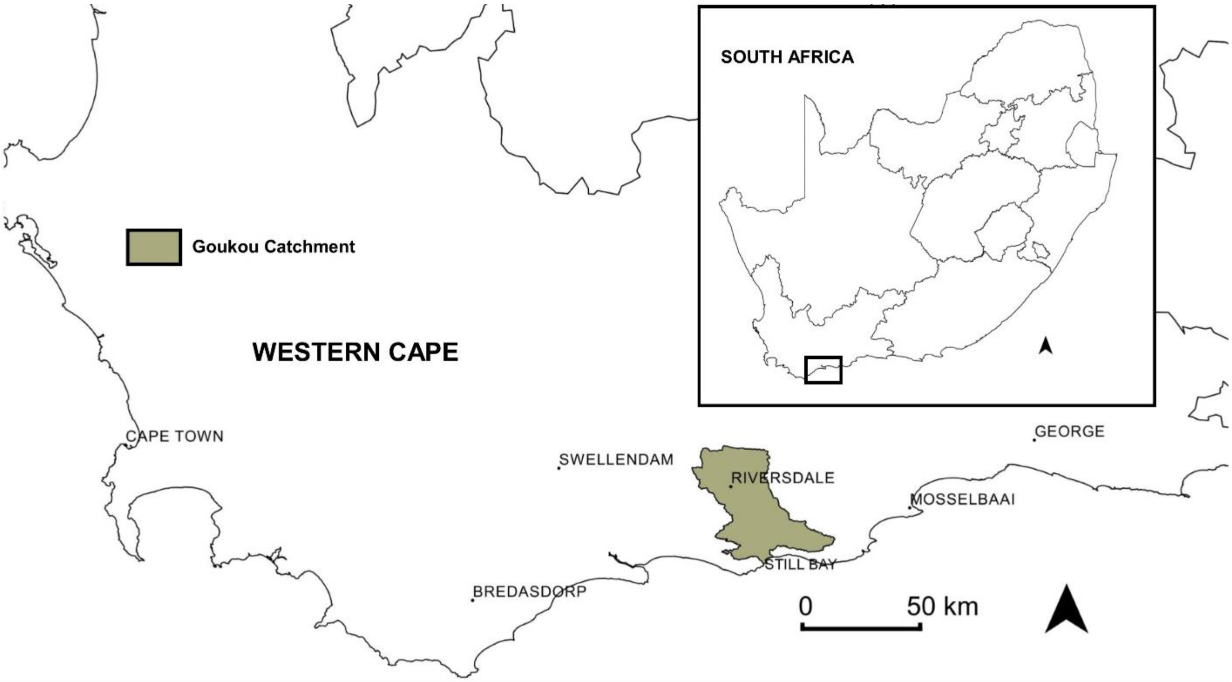


Figure 3.1. Vicinity map showing Goukou river catchment.

The Goukou Wetland lies in the gently rolling hills of the upper Goukou River catchment at the foot of the east-west oriented Langeberg mountain range (Figure 3.2). Streams rising at elevations between 1 000 and 1 400 m above sea level (masl) feed an approximately five km long mountain stream flowing to the head of the wetland. Just upstream of the wetland, the stream drops down a sandstone cliff and flows through a narrow valley before losing confinement and flowing as diffuse flow across the wetland. The head of the Goukou Wetland lies at 235 masl, and the lower reaches of the peat wetland, approximately 16 km downstream, lie at 95 masl. Two major tributaries, with similar properties to the upper Goukou River, also arise in the Langeberg mountains. These are the Kruis River, which joins the Goukou Wetland within the lower third of the current peat extent, and the Vet River, which joins the Goukou River on the outskirts of Riversdale, downstream of the current peat extent. Downstream of the confluence with the Vet River, the Goukou flows within a narrow, steep-sided valley in a relatively straight, southerly direction for a further 44 km, entering the Indian Ocean at the town of Still Bay. Overall, the Goukou River can be described as a relatively short (approximately 65 km), coastal river.

Figure 3.2. Close up of the upper Goukou catchment and wetland extent as seen from Google Earth imagery.

The headwater streams draining into the Goukou Wetland arise in a mountainous area dominated by Table Mountain rocks of the Cape Supergroup. The Goukou Wetland is located on an incised plain extending from the foothills of the Langeberg Mountains to the sea. The area is described by Mucina and Rutherford (2006) as undulating hills and tablelands, steeply dissected by rivers.

The Goukou Wetland is embedded within Uitenhage and Bokkeveld lithologies, with an outcrop of Witteberg Group quartzites evident downstream of the confluence with the Vet River (Figure 3.3).

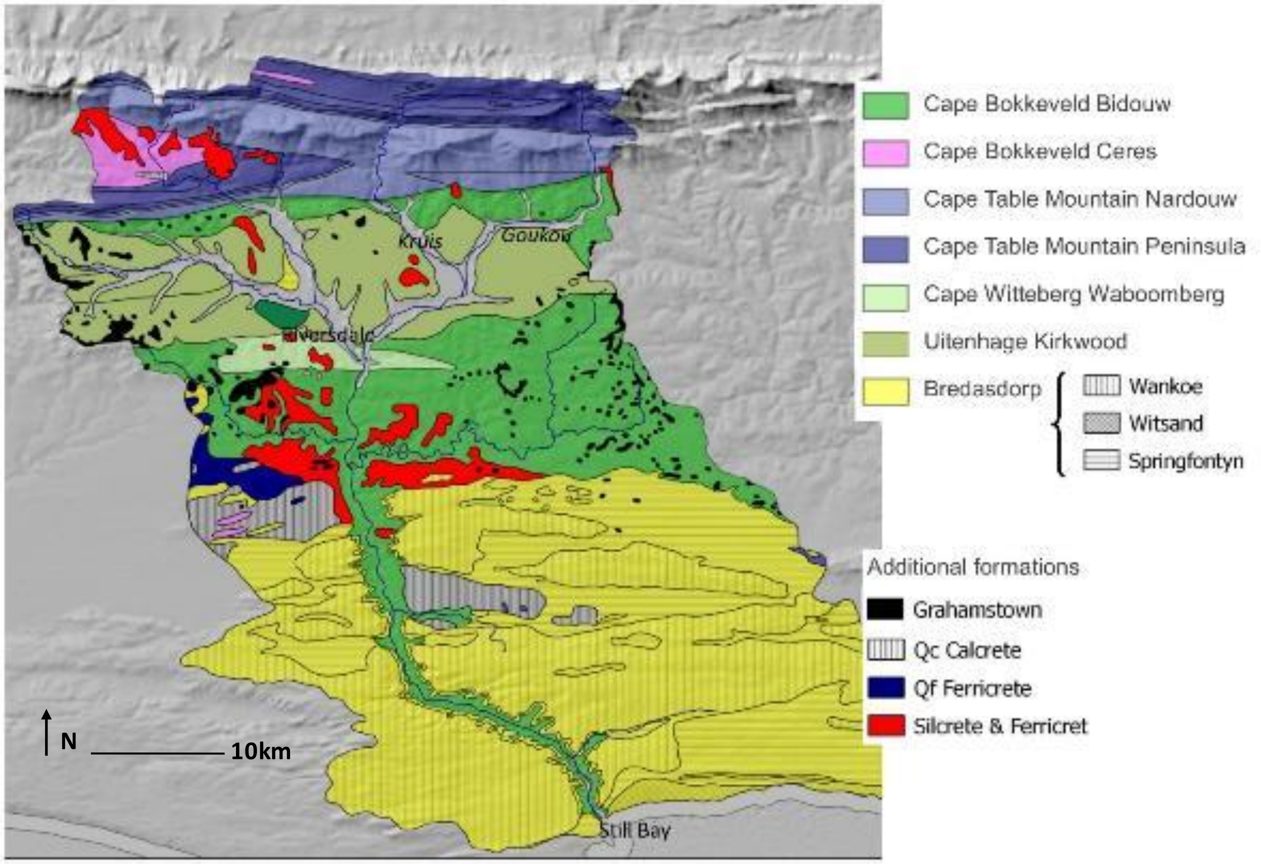


Figure 3.3. Dominant geology of the Goukou catchment (source: 1:250 000 geological layer).

3.2 Vegetation and local climate

The Goukou Wetland falls within the Fynbos Biome, known for its high endemism and species diversity (Cowling *et al.*, 1992). The headwater streams feeding the Goukou Wetland arise within South Langeberg Sandstone Fynbos, which has the status of Least Threatened, and which is further split into Fynbos Montane Ericaceous and Fynbos Montane Mesic Proteiod Habitat Groups (Mucina and Rutherford, 2006; Vlok and de Villiers, 2007). Wetland seeps originating within the Ericaceous Fynbos at these higher altitudes have short vegetation, mostly dominated by members of the Ericaceae and Restionaceae (Vlok and de Villiers, 2007). Where the headwater streams flow through narrow, south-facing gorges protected from fire, small pockets of Afromontane forest persist.

Mossel Bay Shale Renosterveld (Endangered) and Eastern Ruens Shale Renosterveld (Critically Endangered) (Mucina and Rutherford, 2006) vegetation covers the hill slopes flanking the Goukou Wetland. Vlok and de Villiers (2007) have refined these into more finely divided vegetation groupings in the study area, namely Valsrivier Thicket Renosterveld and Riversdal Thicket Renosterveld. Renosterveld is a shrub-dominated vegetation type found on rich, shale soils. In the study area it is characterised by short bunch grasses (Mucina and Rutherford, 2006). The threatened status of the vegetation indicates the degree of transformation of natural vegetation through agricultural land use in this vegetation type, mostly due to the rich clay soils on which it grows. The lower section of the river flows through limestone hills within Southern Cape Valley Thicket vegetation.

Despite being embedded within shale geology, which often gives rise to brackish systems (Vlok and de Villiers, 2007), the wetlands and rivers remain fresh due to the high rainfall on the mountains, and the contribution of groundwater from the adjacent highly fractured sandstone geology (Vlok and de Villiers, 2007). The Goukou River can be described as a southern Cape acid river, brown in colour and with low pH (Davies and Day, 1998). These systems are known for low productivity, high endemism and organisms specially adapted for life in clean, sediment free waters (Davies and Day, 1998).

The plant species present in the wetland reflect those with a preference for fresh over brackish water. The wetland is dominated by restios (such as *Callopsis paniculata)* and palmiet (*Prionium serratum)*, with a rich diversity of sedges, geophytes, sphagnum moss, other fynbos herbaceous species and some woody species interspersed (Vlok and de Villiers, 2007; Seiben and Zelany, 2010; Seiben, 2012). Fire is a key factor of these wetland systems, as shown by the presence of reseeder shrub species *Psoralea filifolia* (a regional endemic), *Psoralea aphylla* and *Cyclopia maculata* (honeybush “vleitee”) within the upper Goukou Wetland (Vlok and de Villiers, 2007). Fire is necessary for the seeds of these plants to germinate.

The wetland falls in the transition between the Western Cape winter rainfall zone and the year-round rainfall of the coastal zone. The climatic pattern tends towards bimodal, with spring and autumn generally the wettest times, although rain can occur at any time of the year (Mucina and Rutherford 2006). The area has a relatively low summer rainfall but can occasionally receive large amounts of summer rain, especially when cut-off low pressure systems form or the significant east-west trending mountain range acts as a rain trap for orographic rain, with thunderstorms, flash floods and large floods occurring periodically (Henshilwood, 1995). Annual rainfall across the catchment ranges from 1 000 mm in the Langeberg Mountains, to 400 mm in the mid-catchment and 600 mm at the coast in Still Bay (Mucina and Rutherford, 2006).

Average daily temperatures range from 27.6°C in January to 6.1°C in July, with frost occurring on an average of three days per year (Mucina and Rutherford, 2006). Snow occurs annually at the highest altitudes. Quaternary catchments H90A and H90C, where the Goukou Wetland is located, have an estimated median annual runoff of 110 and 55 m^3, a mean annual precipitation (MAP) of 517 and 490 mm, potential evapo-transpiration (PET) of 1780 and 1884 mm, and a MAP to PET ratio of 0.29 and 0.26 respectively (Table 3.1).

Table 3.1: Summary of climatic characteristics of the Goukou catchment (Schulze, 1997; DWA quaternary catchments GIS cover, 2000).

	MAP[1]	PET[2]	MAR[3]	MAP/PET ratio
H90A	517.0	1780.7	111.0	0.290
H90B	648.2	1728.2	131.9	0.375
H90C	490.8	1884.7	55.6	0.260
H90D	454.4	1849.2	25.7	0.246
H90E	385.9	1729.4	49.6	0.223

Maximum flow reported over the period of 1969 to 2010 from the Department of Water Affairs gauging weir located mid-way between the confluence of the Kruis and Goukou and the Vet and

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[1] MAP = mean annual precipitation
[2] PET = potential evapotranspiration
[3] MAR = mean annual runoff

Goukou Rivers (within quaternary H90A), was 389.6 cubic metres per second (cumecs). In contrast to this, median flow reported by the Department of Water Affairs during the same period was 0.2 cumecs and the 90^{th} percentile was 2.4 cumecs. Carter and Brownlie (1990) reported average yearly flow of 106.42 million cubic metres, and years of higher flows than this recurring on average every three years.

3.3 Socio-economic characteristics and history of land use

The Riversdale and coastal plain region has an extremely long record of human habitation, possibly extending as far back as 250 000 years (Fisher *et al.*, 2010) in the vicinity of Blombos cave along the coast near Still Bay. There is evidence of more "recent" implements and artwork since 30 000 years ago, recorded within Blombos Cave, and fish traps in the ocean near the river mouth, and rock art in the Langeberg mountains in the headwaters of the Goukou catchment. The rock paintings depict elephant and hippopotamus, among other wild animals (unpublished descriptions, Julius Gorden Africana Centre, Riversdale). Elephant, Cape buffalo, hippopotamus and eland were present in the Riversdale District in the 17th and 18th Centuries (Le Vaillant, 1790 *in* Henshilwood, 1995). By the latter part of the 19th Century, most of the larger mammals, particularly predators, had been eradicated and most of the land on the Riversdale Plain had been granted for settlement by farmers (Henshilwood, 1995).

The wetlands of the area have likely had some manipulation of the natural fire regime (more frequent than usual local fires set on purpose to improve grazing) and moderate grazing by livestock for a very long time. The area was inhabited over the last 2 000 years by several Khoi-Khoi clans, who roamed the area extending from Grabouw to the Gouritz River (Henshilwood, 1995 as well as unpublished descriptions, Julius Gorden Africana Centre, Riversdale). They were nomadic and constantly moved to keep their cattle and sheep in grazing, living in *matjieshuise* (walls and roof made from reed mats) which could be easily put up and taken down as they moved. There is a report as early as 1689, of several clans camped between the Vet and Goukou rivers through the January dry season.

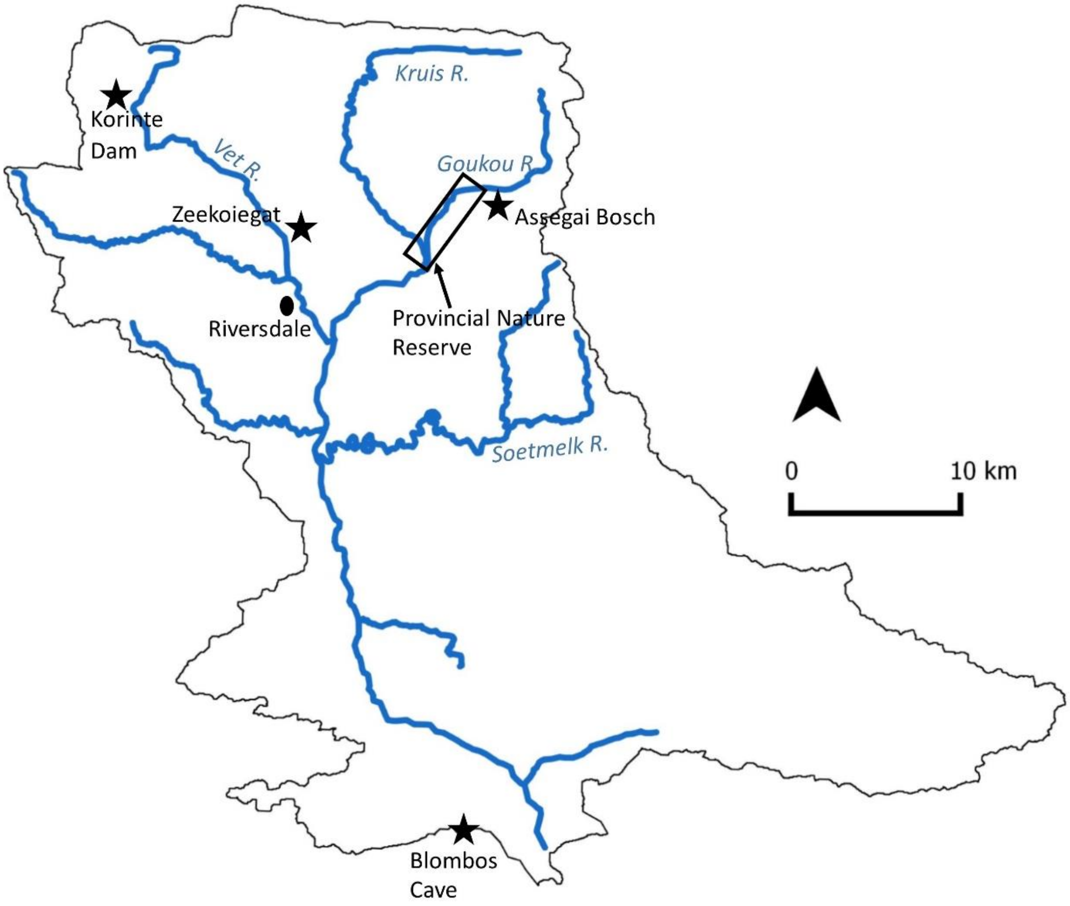


Figure 3.4. Goukou catchment vicinity map with historic locations.

Since the early 1700s, wetlands of the area are expected to have been subject to more intense modification from agricultural practises. In the early eighteenth century at least 5 stock posts were leased out in the Riversdale area, including the farms Assegai Bosch (middle mainstem of Goukou River) in 1728 and Zeekoiegat (Vet River) in 1746 (unpublished descriptions, Julius Gorden Africana Centre, Riversdale; Figure 3.4). Zeekoiegat was known to be an important wheat farm. Tobacco, a wine cellar and 200 milking cows were also noted in the early records. In 1808, a visitor to Zeekoiegat described oranges, lemons, figs, peaches and other fruit trees, also referring to an extensive irrigation system. One can assume that much land was cleared for cultivation, and the first ditches and water diversions were put in place during this period. During this time forests of yellowwood, assegai, wild pear, stinkwood and ironwood in the area were likely heavily impacted. Green (in unpublished descriptions, Julius Gorden Africana Centre, Riversdale) states that all yellowwood indigenous to the area was used up by the 1840s for beams, ceilings, floors and furniture. The last blue buck in the area was shot nearby in Soetmelk Valley (a tributary to the Goukou River; Figure 3.4) and by 1800 all blue buck were thought to have disappeared. The first dam for the town (the Korinte Dam) was built on the Vet River in 1859. This remains the only instream dam in the catchment. Dam capacity is 9.46 million cubic metres and the water is used for irrigation and household use in Riversdale. The catchment for the dam is 8.8% of the upper Vet River catchment and 4.1% of the entire catchment (Carter and Brownlie, 1990).

Today, the economy of the region relies on agriculture. During the recent past, cultivation within wetlands was predominantly for vegetable crops (Filmater, personal communication). Since the 1940s, use of the land changed from predominantly vegetable farming (including areas of cultivated peat soils), to predominantly dairy farming. Current land use in the catchment is a combination of irrigated pasture, cultivation for fodder crops, and dairy cattle and horse farming.

A small section of the Goukou Wetland (80 ha) is protected within a Provincial Nature Reserve in an area that was previously State Forest land.

4. METHODS

4.1 Desk top analyses

Orthophotographs at a 1:10 000 scale and 1:50 000 scale relief GIS layers (20 m elevation interval), both obtained from the Surveyor General of South Africa, were used to plot longitudinal slope and across-valley profiles. The wetland boundary and catchment was mapped and digitised on Arcview GIS (WGS84 and UTM 34 South Projection) using available (5 and 20 m) contours and SPOT imagery together with DWAF aerial ortho-rectified photography. Geological maps at a 1:250 000 scale were reviewed for any mapped major lithological and structural geological characteristics in the area.

Flow data collected by the Department of Water Affairs at flow gauge H90-102130 were analysed.

Historical aerial photography (dated between 1942 and 1996), obtained from the Surveyor General of South Africa, was used to map changes in geomorphological characteristics and land use activities for the period of the photographic record since 1942 for the Goukou main stem and its tributaries. Any evidence of human activities and changes in geomorphic character such as river pattern change or erosional features within wetland were digitised. Catchment land cover was also analysed based on data prepared for the C.A.P.E. fine-scale planning project by Mark Thompson (Thompson, 2007).

4.2 Field work

To examine down valley variation in stratigraphy and morphology, fifteen transects were undertaken at locations shown in Figure 4.1. Transects are numbered in the order that they were undertaken in the field. Transects T1 to T6, and T8 are located within wetland. Transects T7, and T9 to T15 examine changes in valley width and valley floor, and were located at accessible locations representing changes in valley morphology. Measurements made at each transect varied as described in the following sections.

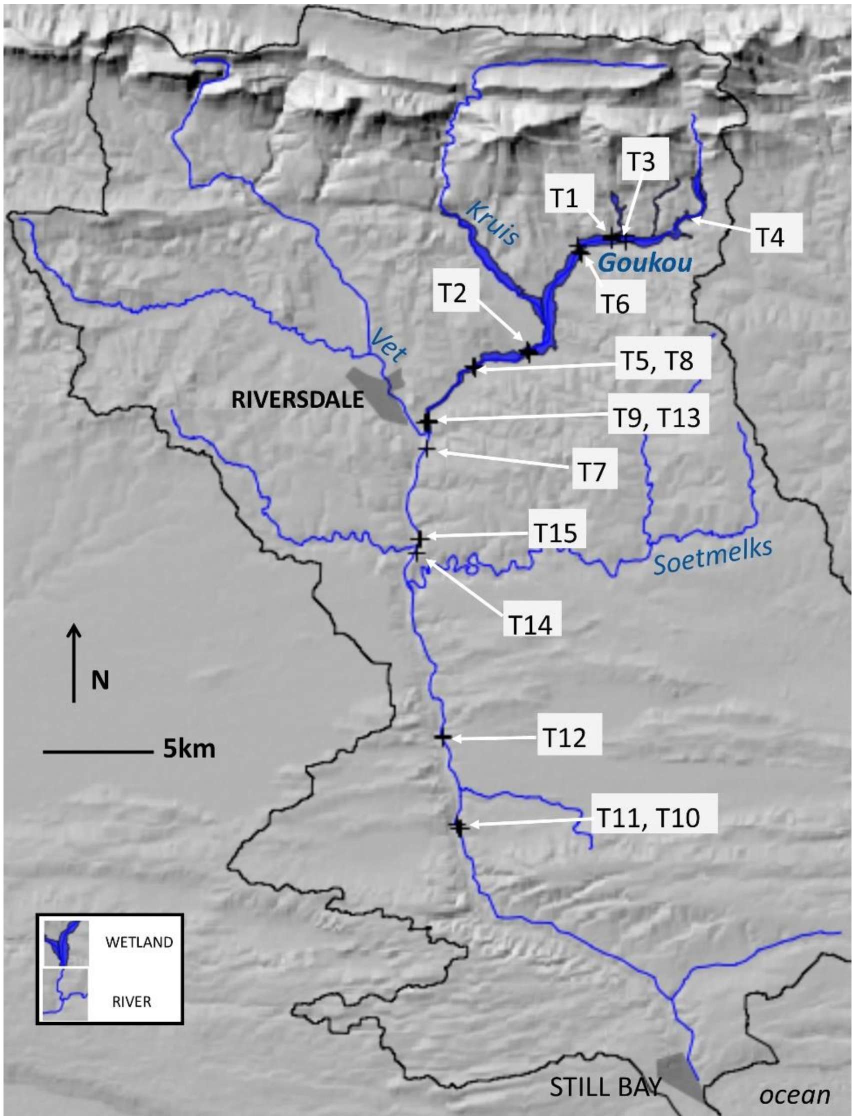


Figure 4.1. Location of transects and surveyed cross-sections.

4.1.1 Sediment sampling

Six transects (T4, T3, T1, T6, T2, T5) were undertaken across the width of the wetland. Between one and three cores (more cores were taken where variation was anticipated) per transect were undertaken with a gouge corer or soil auger. Sediment samples were logged qualitatively in the field during the extraction of each core, allocating an approximate U.S.D.A. soil texture description (loam, clay or sand; U.S.D.A., 1975) and noting changes in texture and colour. The presence of peat was identified in the field by visual observation of fibrous material and by squeezing the material in the hand to determine the behaviour of the soil between the fingers and noting the colour of water released (Table 4.1). Peat humification was examined and classified in the field according to the Van Post humification scale (in Rydin and Jeglum, 2006; Table 4.1).

Table 4.1: The Van Post system of humification (*in* Rydin and Jeglum, 2006).

H1	Undecomposed: plant structures unaltered; yields only clear, colourless water when squeezed
H2	Mostly undecomposed: plant structures distinct; yields yellow-brown water, still almost clear
H3	Very weakly decomposed: plant structures distinct; yields somewhat turbid brown water, no peat substance passes between the fingers. Residue is not mushy/pasty.
H4	Weakly decomposed: plant structures distinct; yields muddy, dark, and turbid water, no peat substance passes between the fingers and no distinct ridges after squeezing. Residue slightly mushy/pasty.
H5	Plant structures clearly evident; yields turbid water and some peat substance. Slightly pulpy.
H6	Plant structures evident; up to 1/3 of peat substance passes between the fingers. Residue is very pulpy.
H7	Plant structures barely recognisable; about ½ of peat substance
H8	Plant structures very unclear; about 2/3 of peat substance
H9	Plant structures almost no longer recognisable; almost all the peat substance
H10	Plant structures no longer recognisable; all of the peat substance; no residue

Sediment samples, representative of the variation encountered down the core, were placed in plastic bags, sealed, labeled and transported back to the laboratory for analysis. In at least one (central) core per transect, the depth of the water table relative to the land surface was recorded using a tape measure, and electrical conductivity and pH of surface and/or sub-surface water were measured. For the remainder of the transect, the depth of peat and clastic sediment fill to bedrock was determined with a gouge corer or soil auger. The location of each core was recorded using a hand held GPS (to 3 m accuracy).

4.1.2 Cross-sectional surveys

Eight cross-sectional surveys (T8, T9, T10, T15, T14, T12, T11, T13) were undertaken using a dumpy level and staff. Cross-sections T8 and T9 were within the peat wetland, the remaining cross-sections were undertaken downstream of the peat wetland, in order to investigation valley morphology down the full length of the valley to the ocean. Sedimentary cores and depth to bedrock were surveyed into each transect so that the subsurface characteristics of the wetland or floodplain could be related to the surface characteristics. The relative elevations and distances of the survey points and the depths to the water table and bedrock were plotted using MS Excel to show wetland cross-sectional and longitudinal morphology, slope and depth of the water table, and the morphology of, and depth to, the bedrock surface.

4.2 Laboratory analyses

4.2.1 Soil preparation

Sediments collected in the field from each core were transferred to a labeled paper bags and oven dried at a temperature of 90° C for 48 hours.

4.2.2 Organic matter content: Loss-on-ignition (LOI) method

Clean, empty porcelain crucibles were each weighed to four decimal places. Approximately 10 g of dry soil per core sample section was placed in each crucible and the combined weight was recorded. The crucibles of soil were then transferred to a muffle furnace, which gradually reached a temperature of 450° C. After 12 hours the furnace was turned off. The samples were left to cool for an hour in the furnace, placed in a glass desiccator to prevent absorption of moisture during the cooling phase. Once cool, the crucibles and ash were re-weighed. The organic matter content of the sample was represented by the loss of mass and calculated as a percentage of the original mass.

4.2.3 Particle size analysis

Sediments collected from each core were analysed in the laboratory for organic content and particle size distribution (percent gravel, sand and clay/silt). Sediment samples taken in the field varied in amount, but all weighed more than 50 g. Dried sediment samples were crushed using a pestle and a mortar, then shaken consecutively through a graded set of six sieves of various sizes (2 mm to 63 µm;

Table 4.2) for fifteen minutes, after which the retained fraction in each sieve was weighed. The clay and silt fraction (less than 63 µm) were reported together. Where gravel or coarser sediment was present, angularity or roundness was recorded.

Table 4.2: Table of particle size and common terminology (Gee and Bauder, 1986).

Size range	**Description**
Greater than 2 mm	pebble /gravel
1–2 mm	very coarse sand
0.5–1 mm	coarse sand
0.25–0.5 mm	medium sand
125–250 µm	fine sand
62.5–125 µm	very fine sand
Less than 62.5 µm	silt and clay

5. RESULTS

5.1 Catchment and tributary characteristics

The catchment of the Goukou River, comprising Department of Water Affairs quaternary catchments H90A, H90B, H90C, H90D and H90E, is approximately 1 600 km^2 or 160 000 ha. The largest sub-catchment, H90B, is the Vet River, at 27 368 ha. The Goukou Wetland, to the northeast, falls within catchment H90A, together with multiple tributaries (Table 5.1). The relative characteristics and stream order of the largest tributaries flowing to the upper Goukou River are summarised in Table 5.1 and illustrated in Figure 5.1. The Goukou Wetland upstream of its confluence with the Vet River is almost 700 ha in extent with a catchment of about 23 250 ha, such that it occupies about 3 % of its catchment. The peatland on the Kruis River occupies 2.5 % of its catchment, the Veldmans 1.7 % of its catchment, the Tierkloof 1.3 % of its catchment and the Groot 4.2 % of its catchment.

Table 5.1: Comparative characteristics of the Goukou and tributary peat wetlands.

Wetland	Catchment (ha)	Size (ha)	Length (km)	Slope (%)	Average width (m)	Quat.
Vet	27 368	unknown	unknown	unknown	unknown	H90B
Goukou	23 247	668	15	0.81	445	H90A
Kruis	8 548	214	5	0.80	428	
Veldmans	2 107	35	2	1.90	175	
Tierkloof	1 639	22	1.5	3.00	146	
Groot	402	17	1.5	3.00	113	

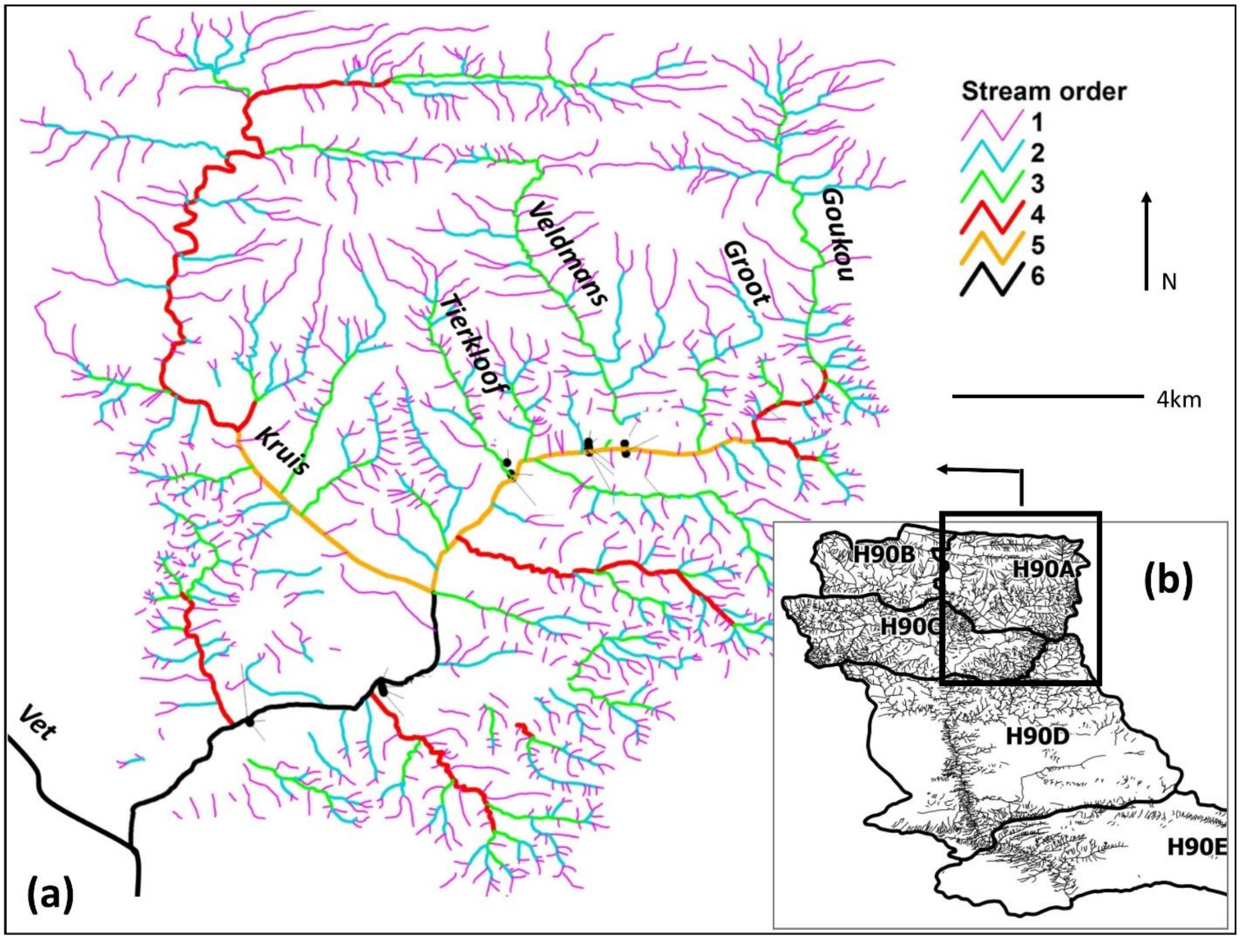


Figure 5.1. The upper Goukou sub-catchments and stream order (a) in the context of the entire catchment of the Goukou (b). Tributaries supporting peat-forming wetlands are labelled by name in (a), as are DWA quaternary catchments (b).

Several mountain streams rise between 1 000 and 1 400 masl to flow an average of five kilometres before entering the head of the Goukou Wetland as a third order stream. Most peat-bearing tributaries to the Goukou are similarly headed by third order streams, with the exception of the Kruis River, which is the largest tributary of the sub-catchment and has a fourth order stream at the head of the wetland (Figure 5.1). The Vet River (inset, Figure 5.1b) is the largest tributary and enters the Goukou as a sixth order stream. At least four relatively large (fourth order) non-peat-bearing tributaries also flow into the Goukou upstream of the Vet River confluence (Figure 5.1), all of which arise (and are fully contained) within shale geology, entering the Goukou from the left bank.

The Kruis Wetland is severely degraded in places, but extensive peat wetland remains, covering an area of approximately 214 ha, with an estimated slope of 0.8%, which is similar to that of the Goukou Wetland. The next largest is Veldmans Wetland, with an area of approximately 35 ha and a 1.9% slope, followed by the Tierkloof Wetland, with an historical extent of approximately 22 ha and a slope of 3 percent. The smallest wetland is the Groot Wetland, with an area of approximately 17 ha and a slope of 3 percent.

The Vet River joins the Goukou River about one third of the way down the length of the overall Goukou catchment, and below this confluence, the density and length of streams are significantly less (inset, Figure 5.1b). Approximately 1 832 km (60 %) of the total river network (calculated on total river length) occurs in the upper half of the Goukou catchment (above Soetmelks tributary), with 757 km (40%) occurring downstream of this.

5.2 Longitudinal characteristics of the Goukou valley

The stream flowing into the head of the Goukou Wetland does so at an average slope of 2.6% and enters the wetland at an elevation of 235 masl, while the lower reaches of the wetland, approximately 16 km downstream, lie at 95 masl (Figure 5.2), giving the wetland an overall slope of 0.87 percent (Figure 5.3).

Within this overall wetland extent several sections with a gradually flattening overall slope are overwhelmingly evident, although there are reaches of localised steepening. Slope discontinuities appear to be located immediately downstream of points where larger right bank tributary streams enter the Goukou (Figure 5.2). Two exceptions are noteworthy: the first at an elevation of 185 masl which appears to be associated with narrowing of the valley, and the second is just upstream of the confluence of the Goukou with the Palmiet River at 100 masl.

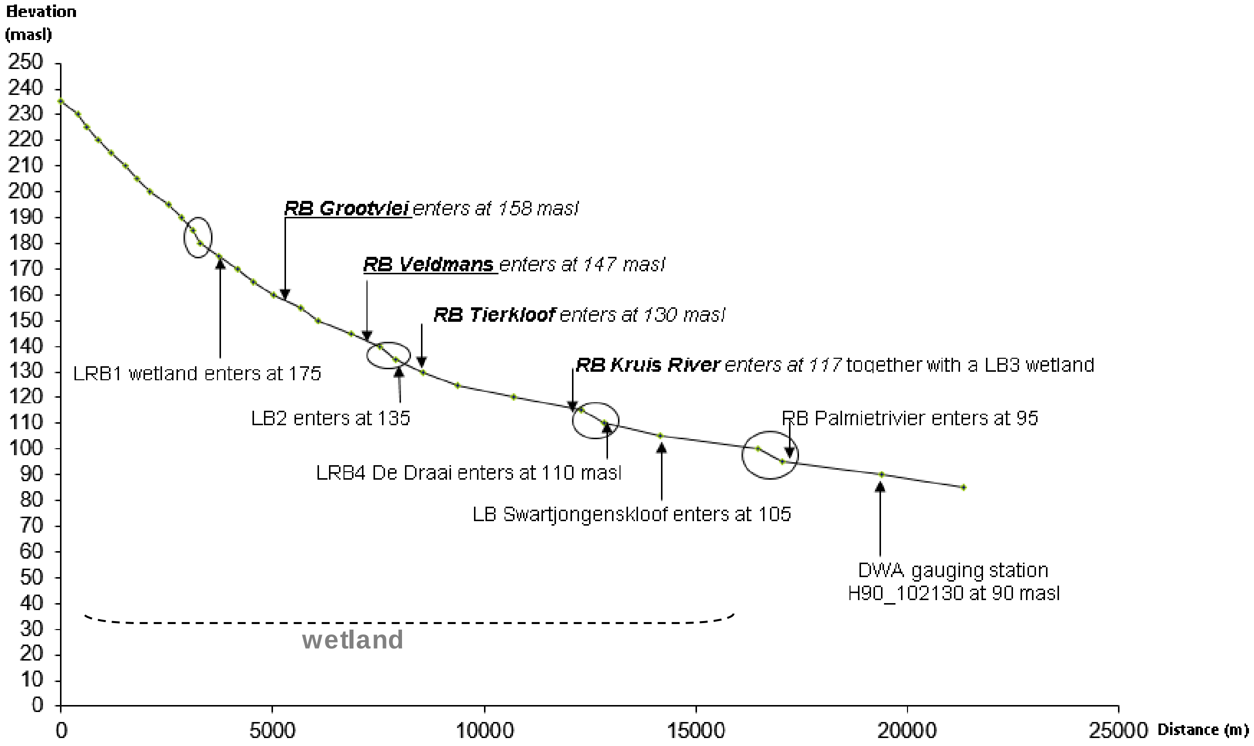


Figure 5.2. Longitudinal profile of upper Goukou River and current wetland extent. The four right bank (RB) tributary streams with their source in quartzitic lithologies and which support peat-bearing wetland are in bold.

Examination of the longitudinal profile of the entire length of Goukou River from the 235 m contour to the sea shows the co-incidence of right bank tributary valleys with steepened sections (Figure 5.3a, b) and the lack of co-incidence of major changes in longitudinal slope with underlying lithologies (Figure 5.3a, c). At a distance of about 33 km from the upper part of the wetland (elevation of 50 m amsl), the valley steepens markedly without any large stream entering the wetland or a change in the underlying geology associated with the stream.

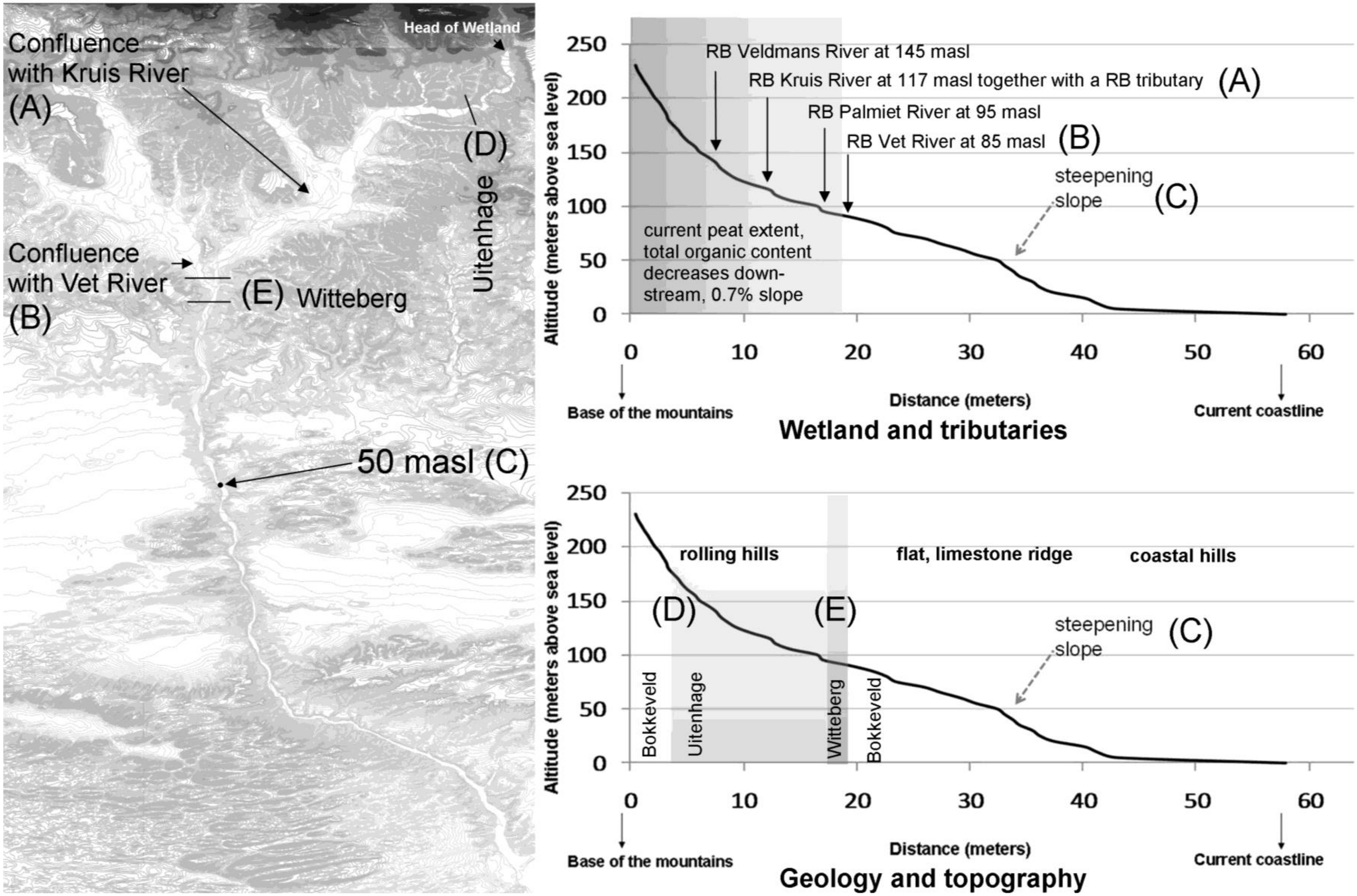


Figure 5.3. Longitudinal profile and associated characteristics of the Goukou River, from the head of the Goukou Wetland.

5.3 Cross-sectional characteristics of the Goukou valley

A mountain stream flows into the head of the Goukou Wetland within a narrow valley that rapidly loses confinement at an altitude of 235 masl, changing to diffuse flow once it enters the wetland (A; Figure 5.5). From the head of the wetland, the valley widens considerably and the slopes of the valley onto the floor become progressively shallower as far downstream as Section D. In the upper section of the Goukou Wetland, illustrated by sections A to D, the wetland occupies most of the valley floor, and there is no obvious river channel until approximately 12 km downstream, below the confluence of the Goukou with the Kruis River. This channel appears to be the result of a historical drainage ditch. Field observations suggest that at times of high flow, water is naturally distributed through the upper 12 km of wetland through a series of short, discontinuous channel sections.

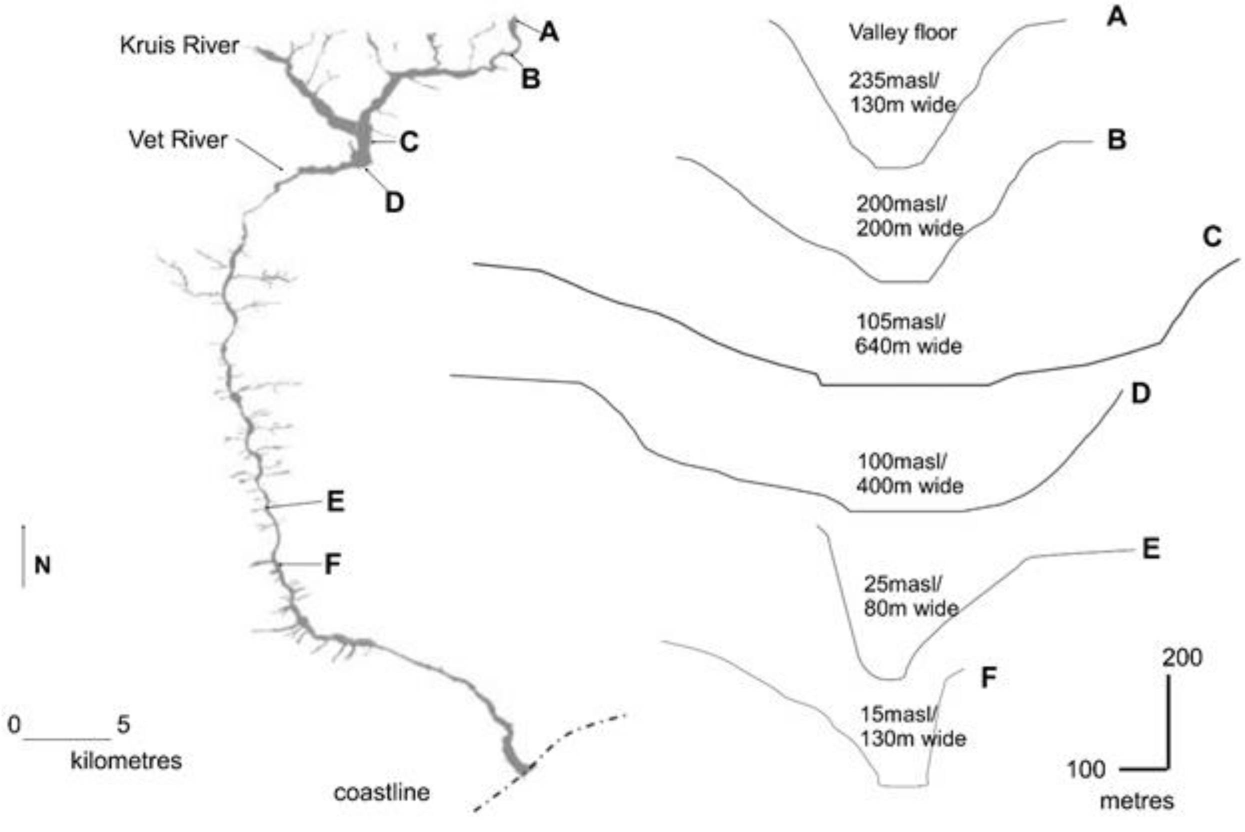


Figure 5.4. Cross-sectional characteristics of the Goukou valley from 235 masl to the ocean.

At the head of the wetland, the valley floor is 100 m wide (point A in Figure 5.4) but soon widens to 400 m. At about 1.5 km downstream of the head of the wetland, where the wetland changes to an east-to-west orientation, the valley narrows again to 100 m, and varies between 100 and 200 m wide for the next 3 km downstream. At 4.5 km downstream, the valley widens to almost 500 m.

Downstream of the confluence with Veldmans Wetland (5.5 km downstream), the valley floor continues to be almost fully occupied by unchannelled wetland with an average width of 400 m, and it then widens to more than 600 m approximately 14 km downstream of the head of the wetland, at an elevation of 105 masl (Section C in Figure 5.4). This widest section occurs from the confluence with the Kruis River and continues for approximately 1.2 km downstream. The wider sections of the wetland correspond with the lower longitudinal gradients reported in the previous section.

From the confluence of the Goukou and Vet Rivers to the river mouth, the valley narrows for much of the remaining downstream length. The valley floor mostly varies between 100 and 200 m wide, occasionally widening to between 300 and 400 m. The river flow direction changes from east to west to a generally north to south direction after the confluence with the Vet River. Section E and Section F in Figure 5.4 are representative of this relatively uniformly narrow section, from the Vet River to just upstream of the river mouth.

5.4 Peatland cross-sectional and longitudinal valley fill characteristics

5.4.1 The upper and mid Goukou valley

Cores from the upper part of the wetland had the highest and most consistent organic content with depth (Figure 5.5). The organic content of the core furthest upstream and centrally located across the width of the wetland was consistently high at 50% from a depth of about 1.5 m to a depth of 6.0 m (T4C1). In the next site downstream (T3C2), organic content of the sediments increased from 20% near the surface to 80% approximately 3 m below the surface, below which it remained at this level to a depth of 7.5 m below the surface, dropping to 20% to 7.8 m.

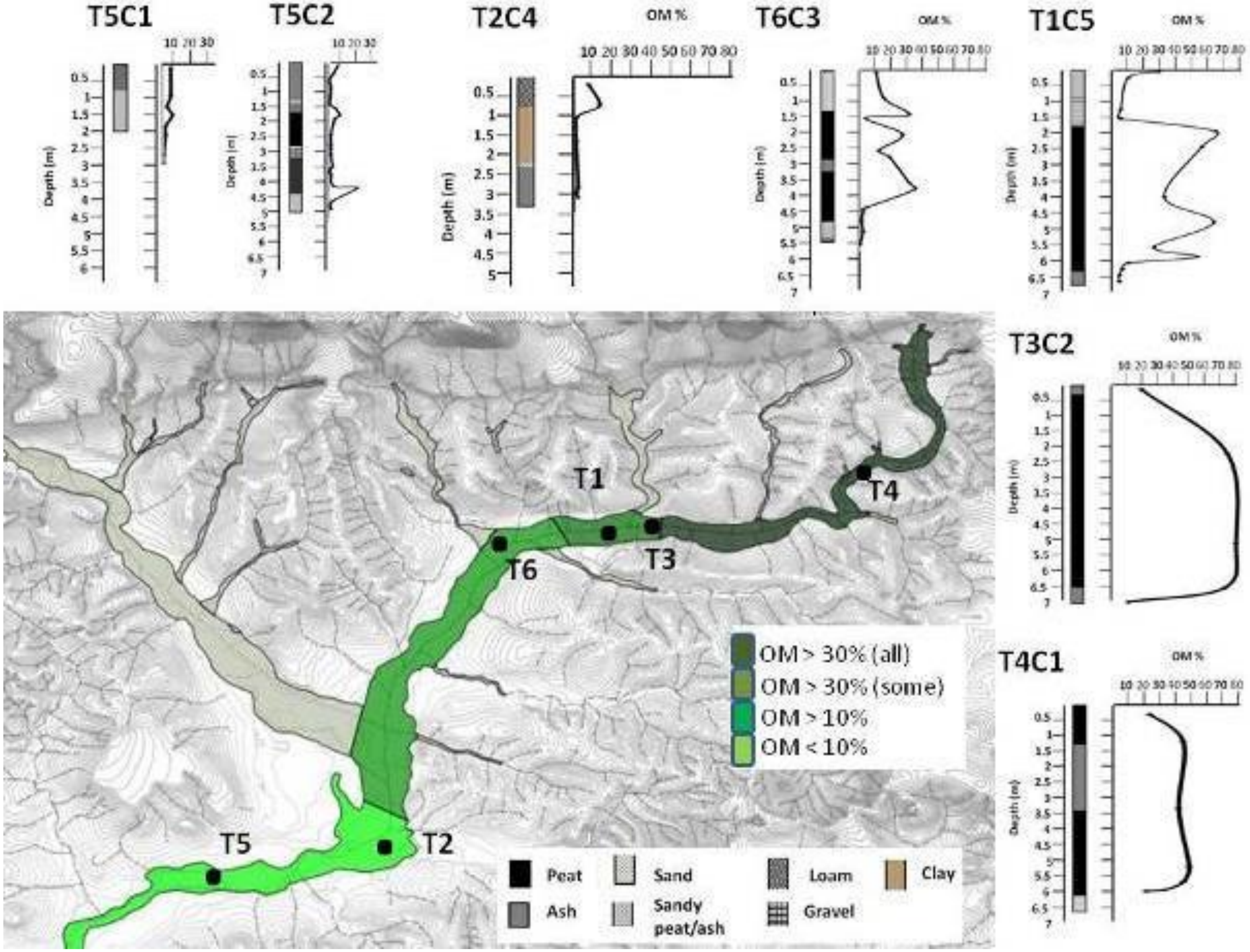


Figure 5.5. Location of transects, with associated core depth and percent organic matter.

In Transect 1 and Transect 6, organic content was highly variable, being interspersed with high sand content (Figure 5.5). Transect 1 was downstream of the confluence with Grootvlei tributary. Organic content was around 10% in the upper core, increasing to 70% from 1.8 m below the surface, below which it fluctuated between 70% and 30% until 6 m below the surface. At 6m it dropped to between 10 and 5% for the lowermost 1 m of the core. Transect 6 was downstream of the confluence with the Tierkloof tributary. Organic content was around 10% to a depth of 1.2 m, where it reached 40%. For the next 3 m it fluctuated between 30 and 10%, and then dropped significantly at 4 m below the surface to 5%, and remained at about 2% for the last 1.5 m of the core.

In Transect 2 and Transect 5, organic content dropped significantly (Figure 5.5). Transect 2 revealed 8-15% organic content in the upper 1 m of the core, but for the remaining 2.5 m of the core it was never above 2%. Transect 5 was below 5% in the upper core, and from 1.2 m it remained below 2% organic content throughout the core.

Figure 5.5 illustrates that overall organic content declined in a downstream direction. The area of highest organic content is the uppermost section of the basin, at the base of the mountain, before any tributaries of significant size enter the wetland. This includes cores from Transect 4 and Transect 3, which is immediately upstream of the confluence with Veldmansvlei tributary. In the section where major tributaries flow from the Langeberg mountains, organic content in the Goukou Wetland fluctuated but remained above 10%, reaching 70% at times. Some distance downstream of the confluence with the Kruis tributary, organic content dropped to mostly below 10%.

Figures 5.6 and 5.7 illustrate the full complement of cores investigated, highlighting wetland width, sediment stratigraphy and depth to bedrock. The width of the wetland in areas that were cored varied between 250 and 550 m and (with the exception of Transect 2) the bedrock maintained a relatively constant elevation across the wetland.

As described above, the stratigraphy of the core taken in the uppermost section of the wetland, in Transect 4, was predominantly moderate to highly decomposed organic material, with the remaining sediment comprising predominantly medium sand at the base of the core. Depth to the valley floor was 6.6 m. Similarly, moderately to highly decomposed organic sediment dominated all three cores in Transect 3, and the depth to the valley floor ranged between 5.5 and 7 m. The valley floor across Transect 1 varied between 5.7 m and 6.5 m, and cores varied from highly organic to sandy organic sediments, with sections of fine clay-like sediment assumed to be ash. The valley floor across Transect 6 ranged between 3.3 m and 5.4 m, and cores varied between highly organic to sand-rich organic sediments, with sections of fine clay-like sediment again assumed to be ash.

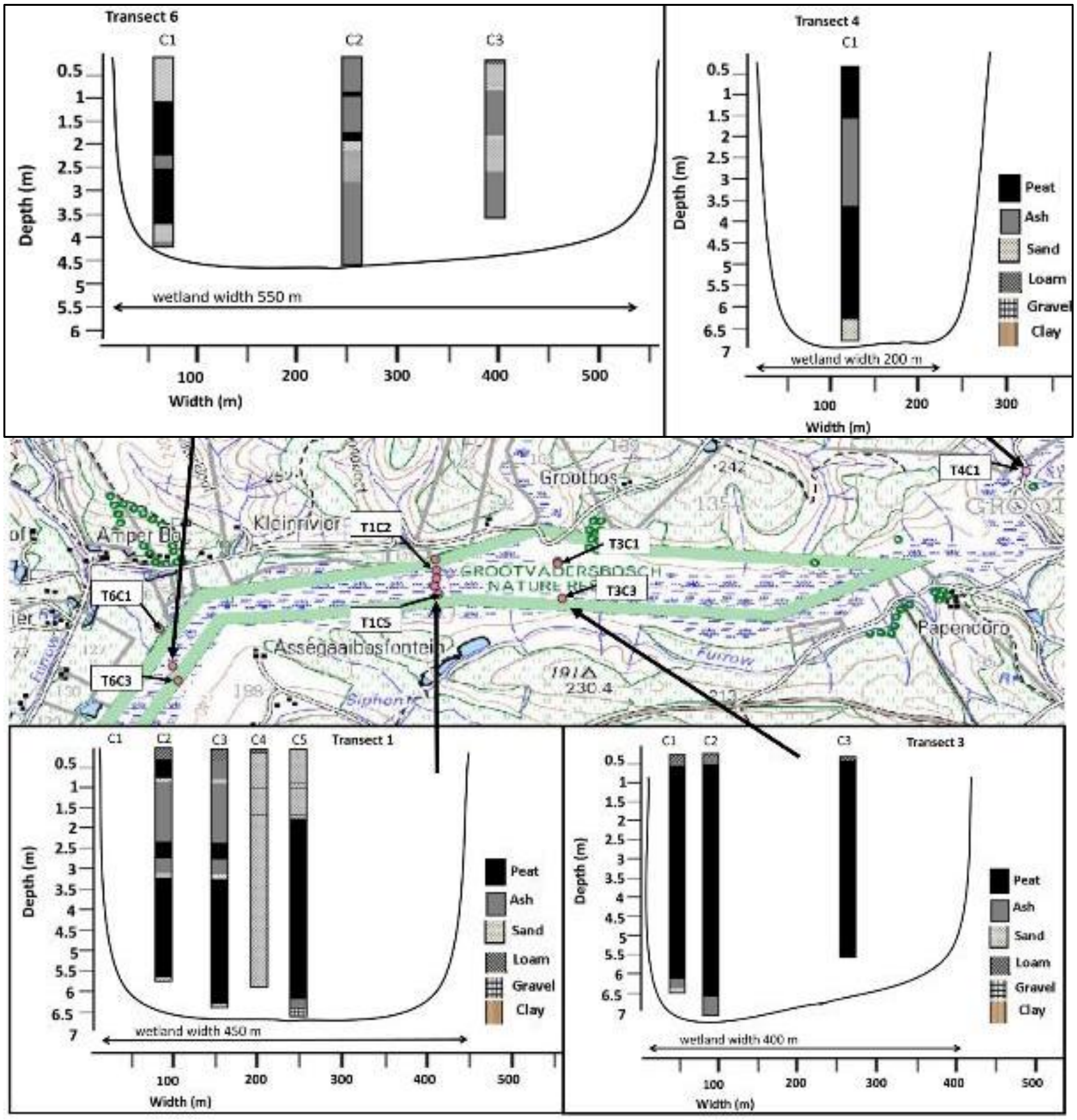


Figure 5.6. Transects 1, 3, 4 and 6, showing core depth, sediment variation across wetland width.

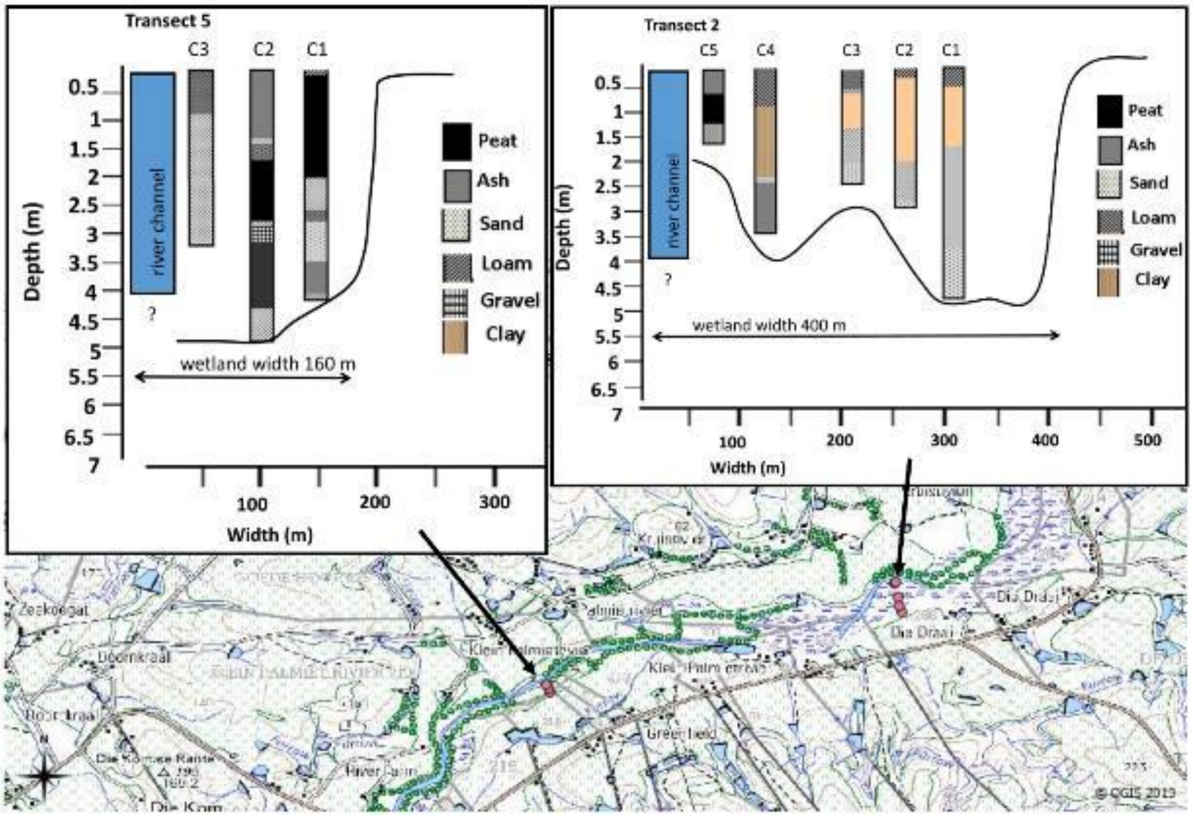


Figure 5.7. Transects 2 and 5, showing core depth, sediment variation across wetland width.

Overall, transect cores revealed a decrease in peat thickness in a downstream direction, from 6.6 to 7 m in Transects 3 and 4, to 5.4 m in Transect 6. Transects 2 and 5 (Figure 5.7) ranged between 3 and 5 m in depth. Organic sediment was present to a limited extent in the cores of Transects 2 and 5. Gleyed and yellow clays were the predominant sediments noted in the cores of Transect 2, while a great variation was evident in the cores of Transect 5, including loam and clays, and even a lens of pebbles was noted. However, the cores were predominantly sandy.

5.4.2 The lower Goukou valley

Peat is largely absent in the lower Goukou, and the overall valley width narrows, averaging about 200 m (Figure 5.8).

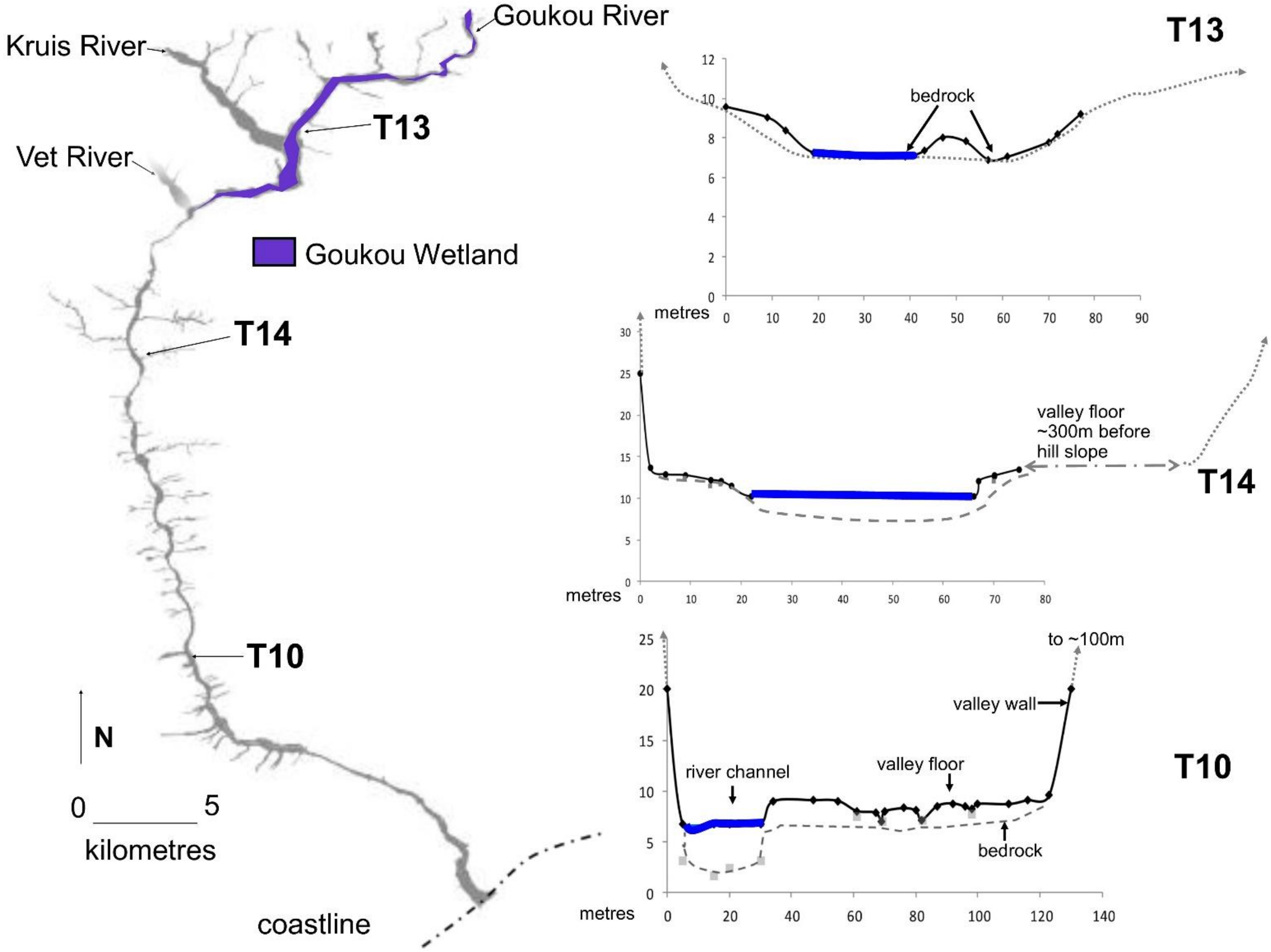


Figure 5.8. Location of surveyed cross-sections in the lower Goukou catchment.

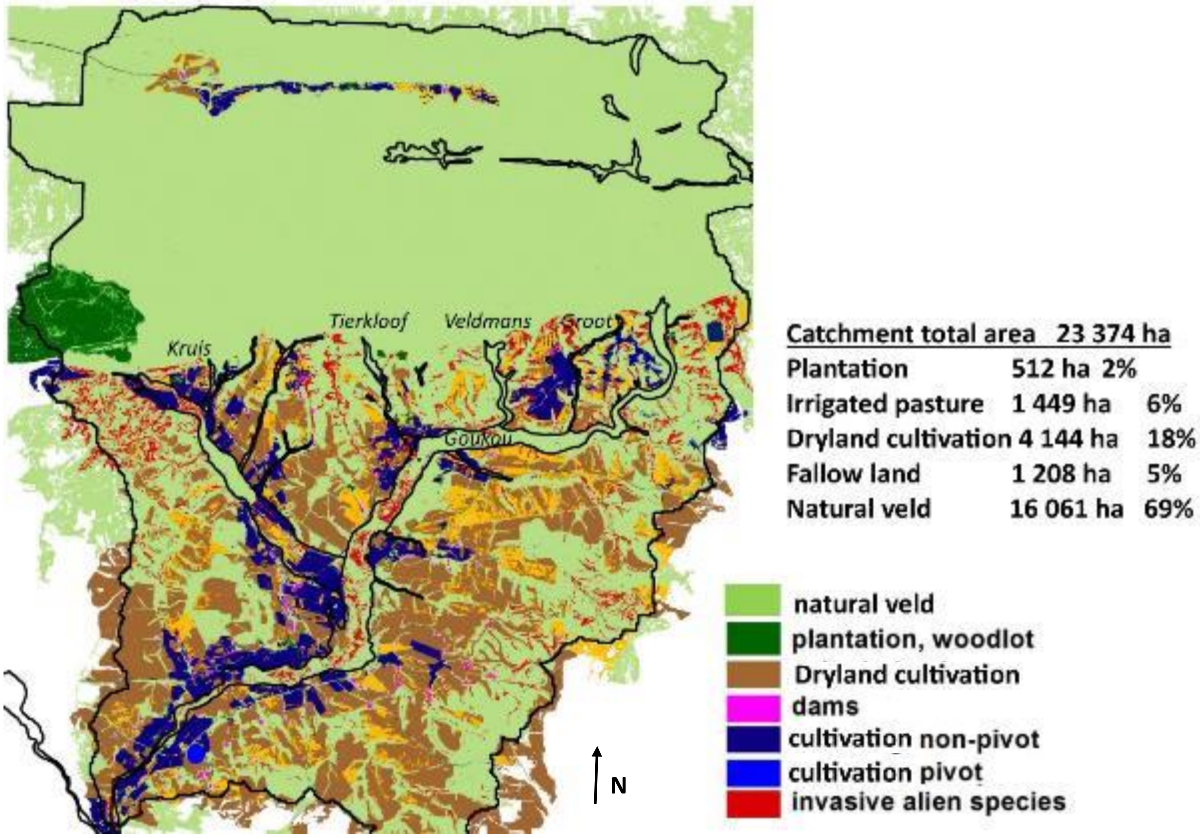
The surveyed transects of the lower Goukou valley showed that despite irregularities in the topography of the land surface that were generally associated with fluvial features, often in association with palmiet, with the exception of T10 the elevation of bedrock was generally relatively flat across tens of meters (Figure 5.8). In areas adjacent to the stream, the bedrock was elevated on a floodplain terrace. These measurements were supported by observations along the course of the stream (Plate 5.1), where relatively extensive areas of bedrock were remarkably flat across tens of meters adjacent to the flowing stream of very shallow depth.

Plate 5.1. Photos of bedrock showing evidence of planing to a common elevation across the width of the river bed. The upper photograph was taken near Transect 9, at 90 masl, the middle photograph was at 85 masl, just downstream of Transect 10, and the bottom photograph corresponded with Transect 14, at 70 masl.

5.5 Natural and human-related impacts

5.5.1 Land use

Currently, approximately 1 450 ha (6%) of land is under irrigation in the upper Goukou catchment and a further 6 552 ha (23%) of the catchment is under dryland cultivation or currently lying fallow (Figure 5.9). Natural veld is concentrated in the steep, high-lying areas of the catchment.



Catchment total area	23 374 ha	
Plantation	512 ha	2%
Irrigated pasture	1 449 ha	6%
Dryland cultivation	4 144 ha	18%
Fallow land	1 208 ha	5%
Natural veld	16 061 ha	69%

Figure 5.9. Land cover results for the upper Goukou catchment prepared from the 2007 (Thompson, 2007) dataset.

Examination of historical photos from 1942 to 1991 showed the Goukou upstream of the Kruis River tributary to be relatively stable and unchanging. With the exception of Tierkloof, where extensive sediment deposition was evident at the base of the tributary that extended well into the Goukou Wetland, the remaining peat-bearing tributaries also appeared stable (Plate 5.2a).

Cultivation within the upper section of the Goukou Wetland is limited but had already taken place by 1942, the date of the earliest historical imagery. The extent of cultivation is depicted in Plate 5.2b, based on interpretation of the 1942 imagery.

Road-crossings at the base of Tierkloof and Veldmansvlei tributaries, and crossing the upper Goukou near the farm Papendorp (Plate 5.2b) were already in place prior to 1942. An irrigation canal (Plate 5.2c) also originated at this road crossing, with a ditch to capture water for the canal originally dug into the Goukou Wetland above the road crossing, parallel to and close to the left bank of the wetland. Invasive alien trees first appeared in the historical imagery in the 1970s and were well established on every tributary to the Goukou Wetland by 1991 (Plate 5.2c). Plate 5.2d shows that by 2009 erosion was evident in the headwaters of every peat-bearing tributary. Erosion appears to have been to bedrock based on the light colour present in the gullies, a feature confirmed by recent observations in the study area. *Pteridium aquilinum*, which favours disturbed areas, indicates drying out of peat adjacent to erosion gullies. The peat depth was found to be between six and eight metres in these upper tributaries, and field observations reveal that the water table has dropped to the same extent.

Wetland cultivation was most notable at the confluence of the Tierkloof and Kruis Rivers with the Goukou Wetland (Plate 5.3). Both areas were mostly cultivated prior to 1942, as cultivation was already evident in the historical imagery dated at this time, but additional cultivation and manipulation of the areas took place in the 1990s. Since the 1990s, a well-defined channel is evident extending well into the Goukou Wetland in both of these regions (Plate 5.3).

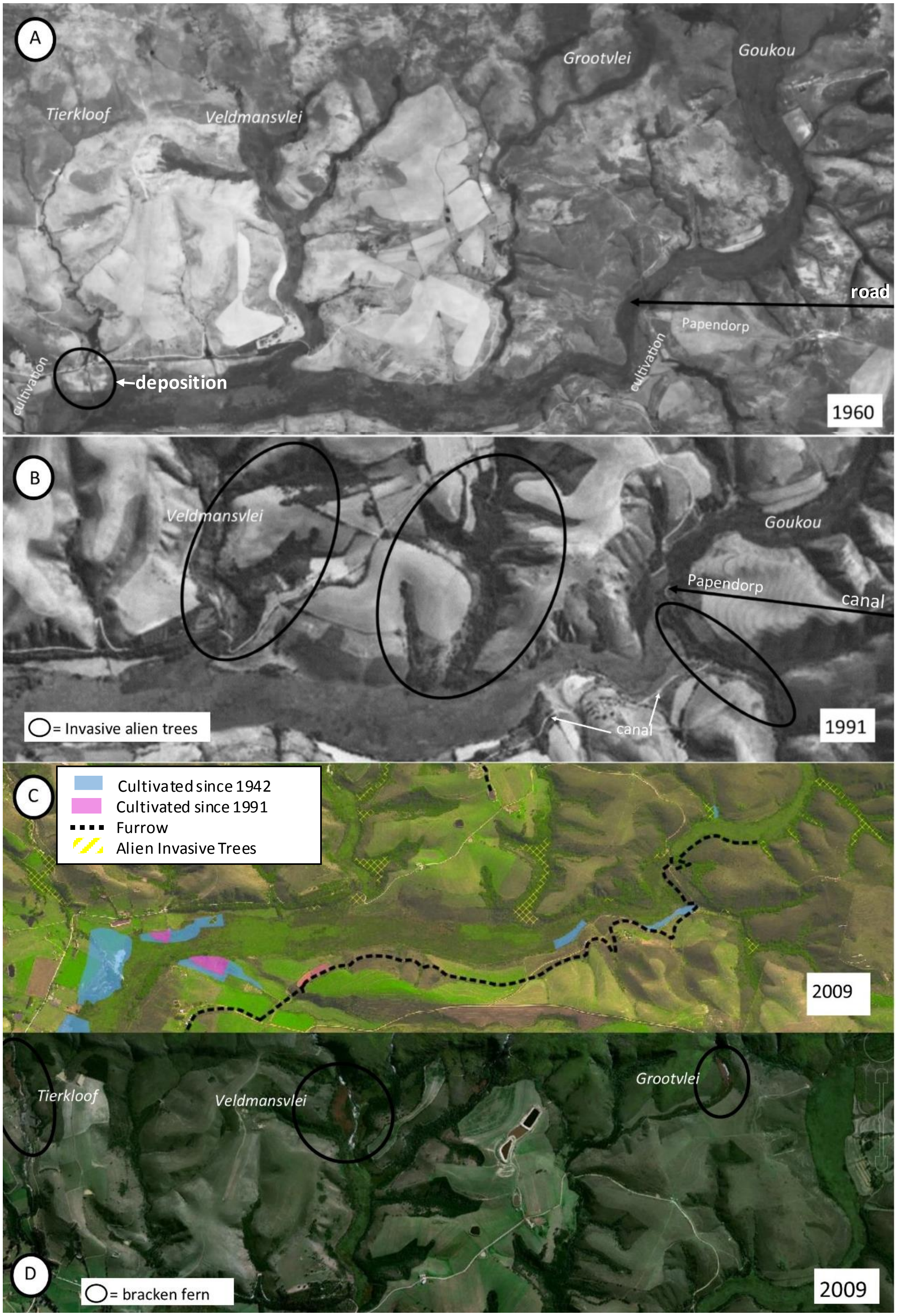


Plate 5.2. Imagery depicting the upper Goukou Wetland between 1960 and 2009.

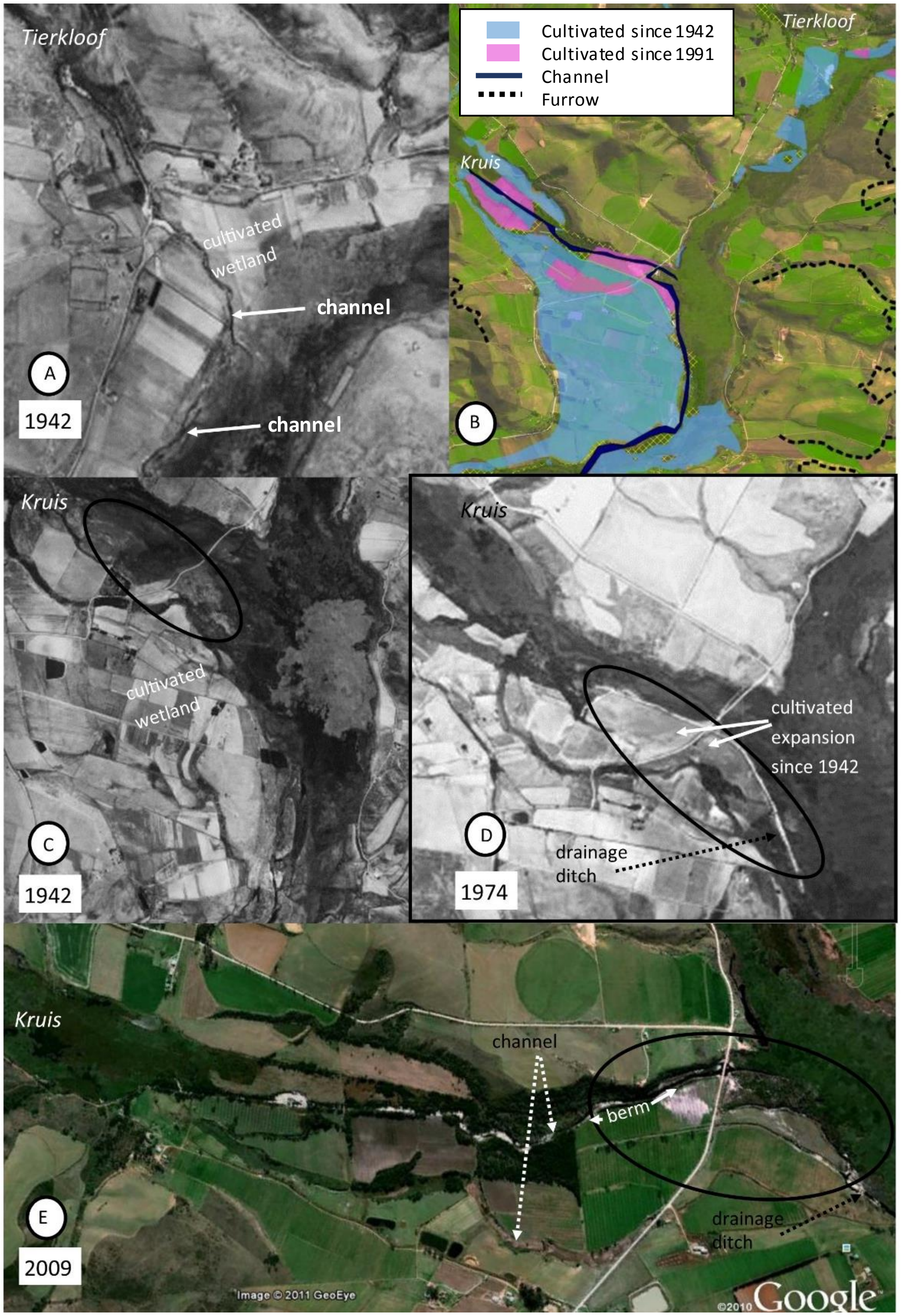


Plate 5.3. Imagery depicting Tierkloof and Kruis confluence between 1942 and 2009. Arrows indicate clearly defined stream channels. Oval shapes indicate narrowing of wetland and expansion in cultivation between 1974 and 2009, at the confluence of the Kruis and Goukou.

Tierkloof is a small, steep wetland, while the Kruis is one of the largest tributaries to the Goukou. Among the most extensive areas of cultivated wetland in the catchment occurs in the Kruis. Plate 5.3b-e focuses on the lowermost Kruis in the region of its confluence with the Goukou Wetland. As mentioned, most cultivation took place prior to 1942 (Plate 5.3b), but since then the cultivation footprint has continued to expand (Plate 5.3c-e). In the 1970s, a deep and extensive ditch was excavated both upstream and downstream of the road crossing. By 2009, almost the entire confluence upstream of the road crossing was cultivated or under permanent pasture and the main river flow was confined to a narrow, bermed channel.

The lower section of the of the Goukou Wetland, between the confluence of the Kruis River and the Vet River has also been extensively cultivated since before 1942 (Figure 5.10). By 1991, the cultivation had further encroached within wetland and the wetland adjacent to the entrenched channel increasingly invaded by invasive alien trees (alien invasive trees begin to be evident by the late 1970s in the historical imagery).

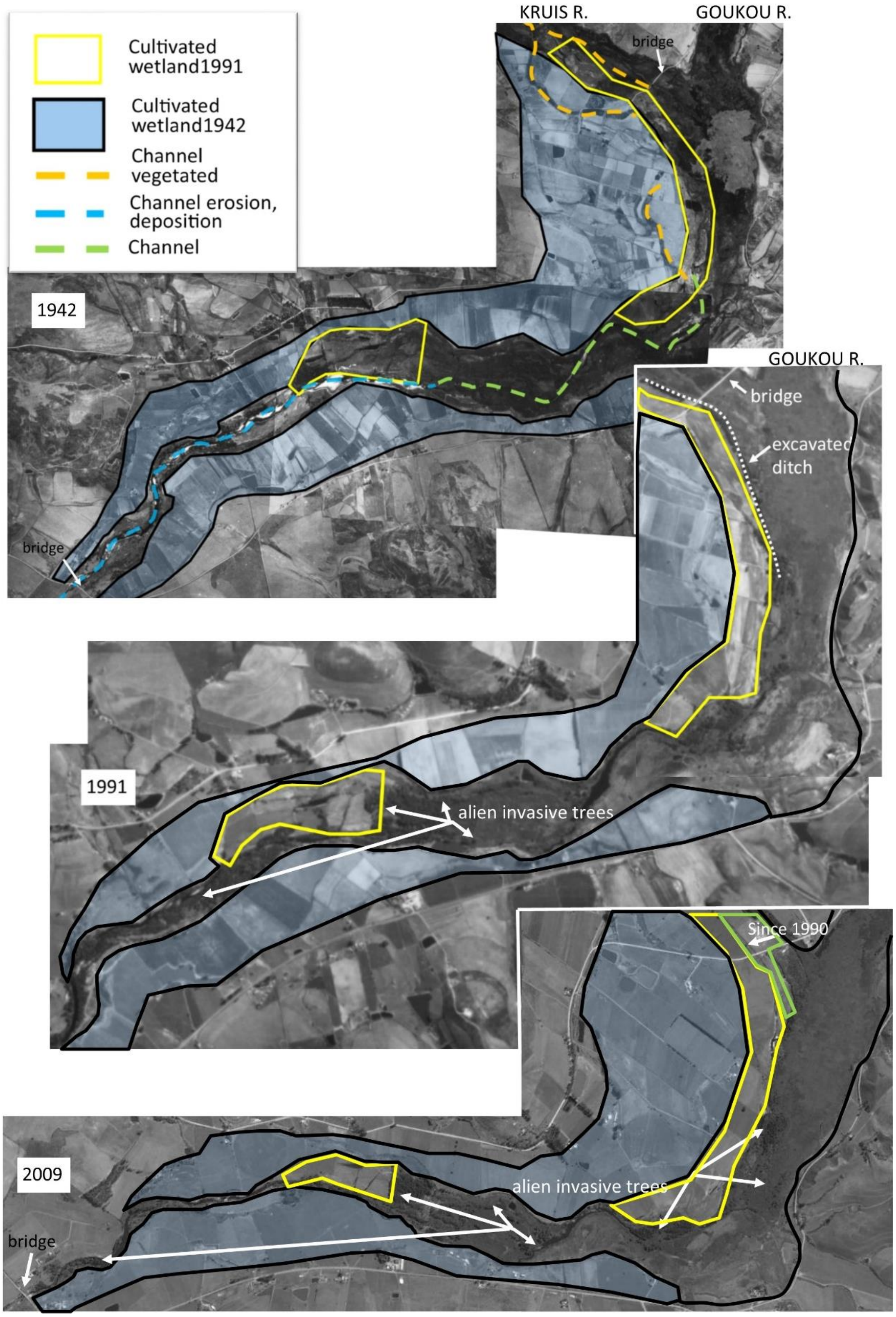


Figure 5.10. Cultivation and channel development within the Goukou Wetland since 1942.

In summary, erosion gullies are currently present in every peat-bearing tributary to the Goukou, and, with the exception of Veldmansvlei and the Goukou itself, all have developed stream channels along the entire length of the wetland (Figure 5.11). Although the prevalence of erosion gullies is striking, there are zones of aggradation where sediment produced by erosion is being deposited. This is typically where tributaries enter trunk streams. Where sedimentation is present at the confluence with the Goukou, channels have developed along the Goukou.

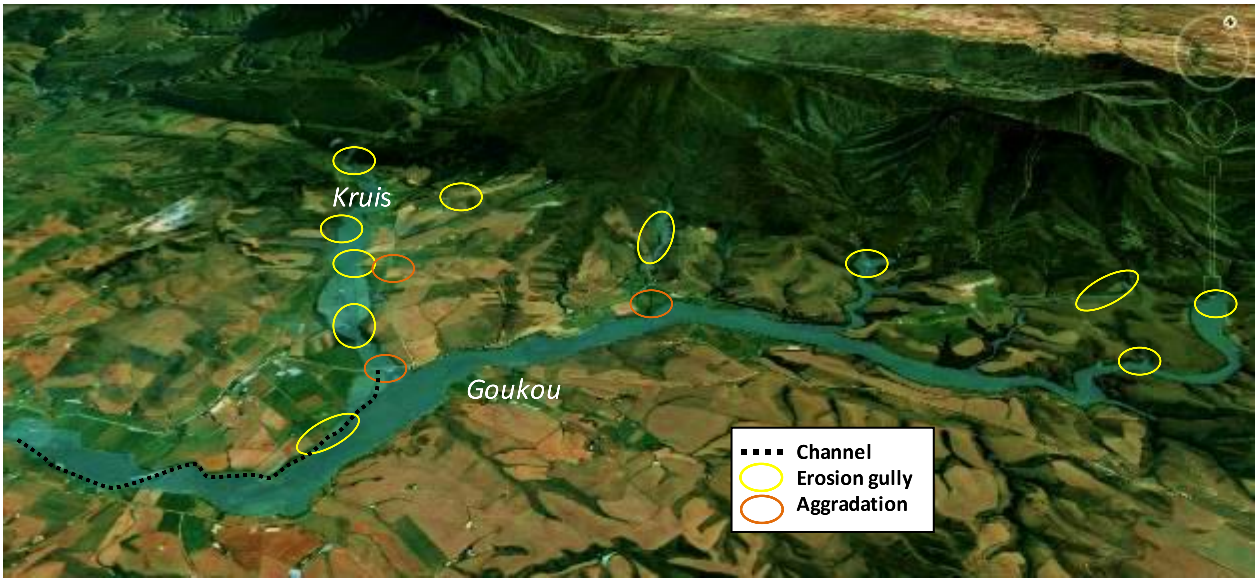


Figure 5.11. Overview of Goukou Wetland and tributaries. Yellow circles indicate observed erosion gully locations. The orange circles indicate areas of observed aggradation.

Where systems appear in a relatively unimpacted state, erosion gullies appear to have formed at the head of the wetlands (Goukou, Veldmansvlei and Grootvlei; Figures 5.9-5.11). These gullies appear in imagery between 2004 and 2008. Human impacts associated with road crossings, irrigation canal expansion and cultivation / vegetation clearing (Figures 5.9-5.11) appear to have contributed to erosion in the mid- or lower systems (Grootvlei, Tierkloof, Kruis and Vet River systems). These gullies were mostly in place prior to 1942.

Figure 5.12. Head of the Kruis Wetland (left) in1942, with eroding channel already established. Head of Veldmansvlei Wetland, Google image dated November 2005 (right). White arrows indicate flow direction.

Figure 5.13. Erosion at the head of Veldmansvlei looking downstream. Dense stands of black wattle flank the wetland and sections of the gully. Bracken fern appears as the red-brown vegetation, and its dominance indicates drying of the wetland and its associated peat. Erosion is to bedrock in this instance.

5.5.2 Flow

Maximum flow reported over the period of 1969 to 2010 at the Department of Water Affairs gauging weir, located downstream of the confluence of the Kruis and Goukou Rivers, is 389.6 cubic metres per second (cumecs). Analysis of the data indicates a high flow of 433 cumecs in 1981 (Figure 5.14). Median flow reported by the Department of Water Affairs over this period was 0.2 cumecs and the 90th percentile was 2.4 cumecs. Very high flows, therefore, are relatively uncommon. Years where flows exceeded 350 cumecs include January 1981, July 1986, October 1991, November 1996, May 2003, December 2004, November 2007, June 2011. Figure 5.14 illustrates that large flows appear to be becoming increasingly frequent within the known record, however, this is too short a period to infer long term patterns. Furthermore, anecdotal reports of weirs located on the Goukou River and other rivers in the study area suggest that at times flows are suspected to exceed the ability of the available instruments to record them and thus go unrecorded.

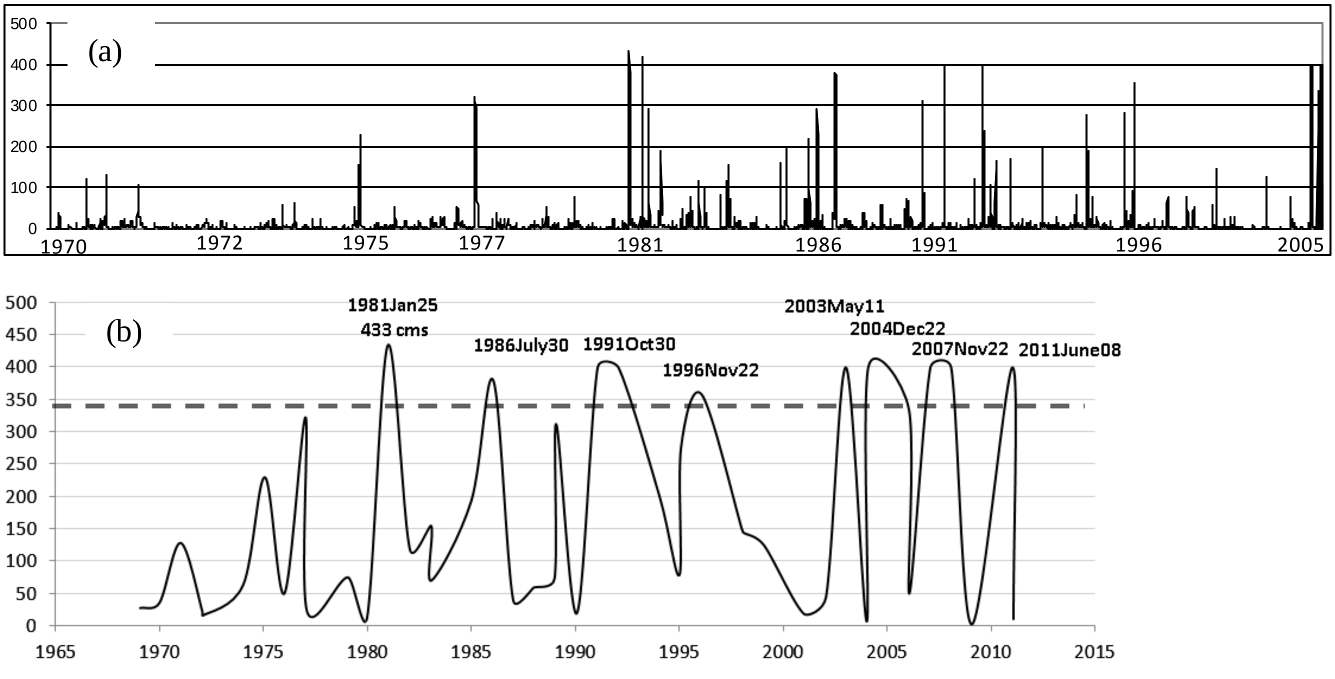


Figure 5.14. Goukou river daily flows 1969-2004 (a) and average annual flows 1969-2011with peaks above 350 cumecs identified (b) (Department of Water Affairs station H90A_102130).

6. DISCUSSION

6.1 The Goukou as a graded stream

Overall, the longitudinal profile of the uppermost 33 km of the Goukou River exhibits a logarithmic slope, becoming gradually shallower from the foot of the Langeberg Mountains. This reflects that over this stretch it is a graded stream that acts as a unified, integrated fluvial system. There are no obvious longitudinal changes in slope, associated with a mapped or observed change in lithology of parent material of differing resistance to weathering or erosion, over this stretch. However, there is marked steepening of the longitudinal profile from about 33 to 42 km from the foot of the Langeberg Mountains. Once again, this change in slope is not associated with a change in lithology. Downstream of this steepened section, the stream slopes gently towards the ocean.

The steepened section of the Goukou River occurs at approximately 50 masl, approximately 25 km upstream of the river mouth. Bokkeveld shale extends upstream and downstream of the step within the river valley, and the surrounding hills are Bredasdorp cover sands and limestone. It is tempting to attribute the steepening of the Goukou River over this reach to erosion associated with the most recent uplift event (McCarthy and Rubidge, 2005) given that streams respond to a lowering of the base level by incision and the establishment of grade (Morisawa, 1968). However, the Post Africa erosion surfaces are much higher than 50 m amsl. The African Erosion Surface is approximately 280 m amsl, and Post Africa I at an elevation of approximately 200 m amsl.

It is also tempting to attribute the steepening of the grade of the Goukou River with a change in the width of the valley in the steepened reach, particularly a steepening associated with reduced stream confinement (Ellery and Rowntree, 2010). However, valley cross sections do not reveal a systematic change in valley width over the steepened reach.

Much of the study area can be considered semi-arid, which is defined to be between 300 and 600 mm annual rainfall (FAO, 1987). There is a radical decrease in mean annual rainfall in the study area from the mountains (approximately 1 000 mm annual rainfall) to the coast (approximately 400 mm)(Mucina and Rutherford, 2006). While river discharge commonly increases downstream as tributaries progressively contribute flows to the main river, Summerfield (1991) notes that this is sometimes not the case in arid regions, where a river may experience water loss through evaporation and transpiration by riparian plants, leading to a downstream decrease in discharge. Streams in the mountains thus have relatively low discharges despite the high rainfall, due to their small catchment sizes on steep slopes (Figure 6.1a). Instead of overall discharge increasing in a downstream direction as tributaries join the trunk stream, there is an overall diminished stream flow downstream in the Goukou reflecting the decreased rainfall in the mid and lower catchment (Figure 6.1b).

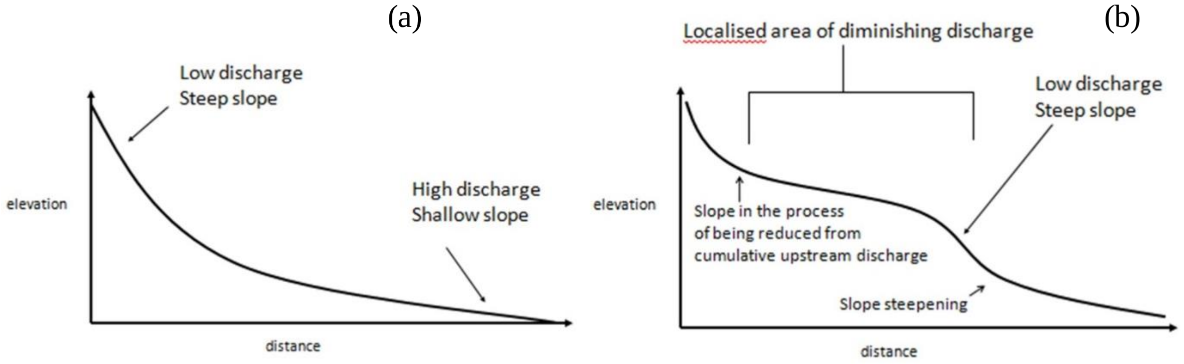


Figure 6.1. Localised change in slope in response to diminishing discharge.

The decline in stream discharge downstream is supported by stream density in the Goukou River catchment, as more than 60% (1 832 km) of total stream length falls in the upper catchment, whereas in the lower catchment it totals 757 km (Figure 6.2). Remarkably, much of the fluvial network in the lower catchment is poorly integrated with the Goukou River such that tributaries in this area are typically short. Given this, and the fact that the boundary of the dense and sparse stream network occurs at an elevation of about 50 m amsl on the Goukou River, it is suggested that the reduced discharge in the lower Goukou accounts for the observed steepening of this stream section. It is therefore argued that the Goukou is a graded stream over its entire length.

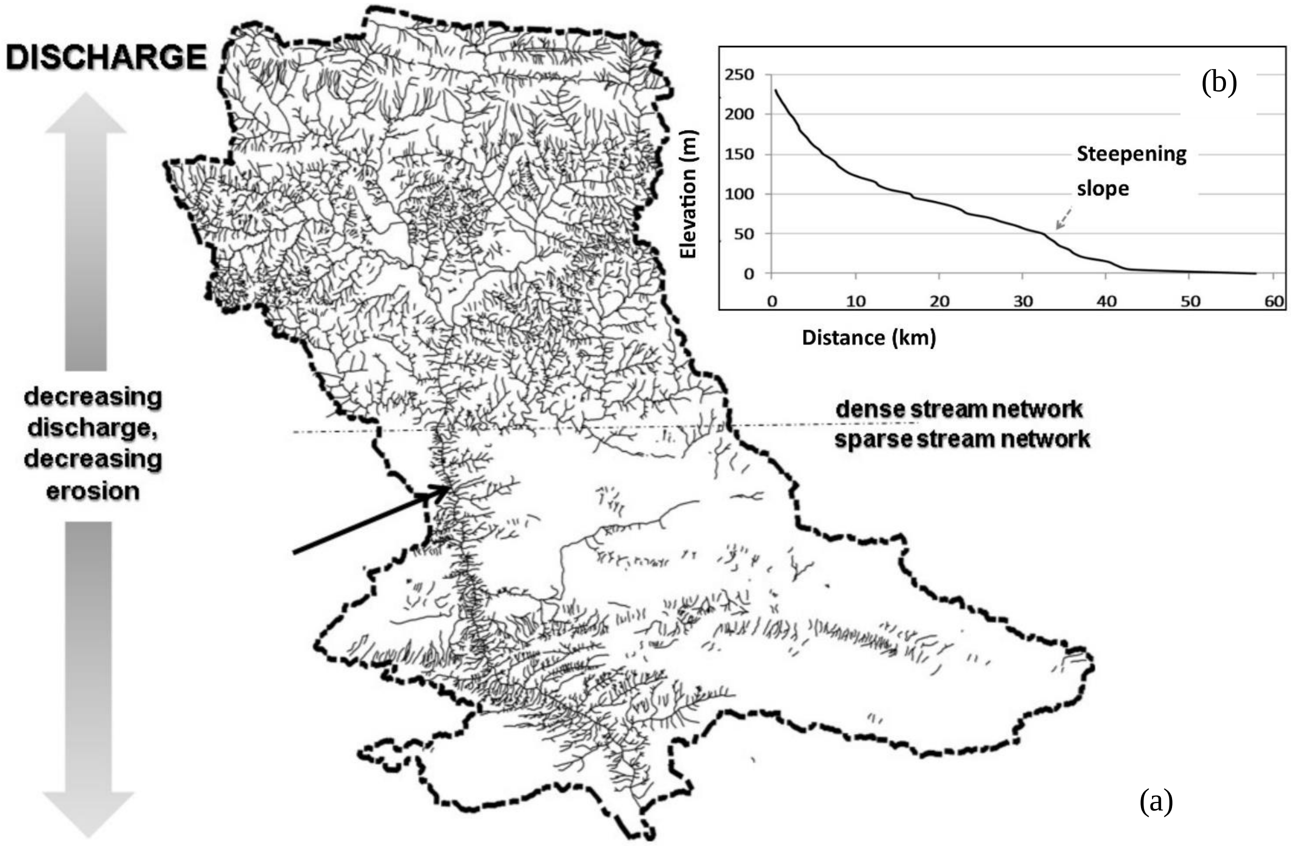


Figure 6.2. Goukou catchment stream network (a) with inset showing location of slope steepening on the Goukou River longitudinal gradient (b).

6.2 The anomaly of peat in the Goukou

Current conceptual models of peat formation do not explain the occurrence of peat in the Goukou. Ellery *et al.* (2012) make the case that peat formation in southern African wetlands, where rainfall is unlikely to drive peat formation, requires two key factors to be present, namely, an elevated base level, along with limited clastic sediment input. This is illustrated in the case of the Mkuze Floodplain on the coastal plain of northern KwaZulu-Natal, where blockage of tributary valleys by the trunk stream elevates the local base level and results in prolonged flooding of the tributary valleys. Given the low velocities and lack of fine sediment in the tributary catchments, there is very limited clastic sediment input to these valleys, and peat formation is therefore inevitable (Ellery *et al.*, 2012). This is also the case for peat accumulation in Lake Futululu, a tributary to the Umfolozi Floodplain on the coastal plain of northern

KwaZulu-Natal (Grenfell *et al.*, 2010). In the case of Wakkerstroom Vlei in the foothills of the Drakensberg foothills in KwaZulu-Natal, it is the blockage of the trunk valley by tributary streams that gives rise to the accommodation space necessary for peat formation along the trunk valley (Joubert and Ellery, 2013).

A further explanation for the occurrence of peat in wetlands in southern Africa has been attributed to sagging due to mass and volume loss associated with deep weathering of volcanic rock (Edwards and Ellery, in prep.). Peat has formed within the accommodation space thus created and permanently flooded conditions occur in the resulting basin.

However, in the case of the Goukou Wetland, while there is limited clastic sediment input due to the extremely resistant nature of quartzite in parts of the catchment that provide most of the water supply, there is neither evidence of an elevated base level at the toe of the wetland, nor of an association between bedrock that may weather deeply and the distribution of the peatland.

The absence of any association between lithological factors or trunk-tributary relationships in the case of the Goukou leads one to hypothesise that the distribution of the Goukou Wetland is associated with the plant *Prionium serratum* (palmiet), and that it is sufficiently robust to create a local base level and water ponding. An elevated base level leads to a stable (not fluctuating) water table and a situation where organic matter accumulation exceeds decomposition, likely assisted by resistance to decomposition of the woody and fibrous tissues of the palmiet plant.

The distribution of the peat-filled basin of the Goukou Wetland is related to the zone of the stream which is semi-permanently flooded and where palmiet is able to grow most prolifically and peat can accumulate. Downstream of the wetland, due to declining discharge downstream (and increasing distance from potential groundwater-discharge prone geology), flooding is not sufficiently permanent to enable peat to form. The combination of permanent flooding associated with declining discharge downstream, the growth of the robust plant palmiet, and the absence of large quantities of clastic sediment input from those catchments that contribute most to flow in the Goukou River, explains the distribution of the Goukou wetland fully, and constitutes the simplest explanation for this peat wetland and its deposits.

6.3 The role of palmiet in peat formation

The plant palmiet (*Prionium serratum*) is dominant in much of the Goukou Wetland, and has several characteristics that make it well suited to trapping clastic sediment and altering the hydrological regime of the valley. As such, it may be considered an ecosystem engineer, through its contribution to physically transforming the habitat. Palmiet is a robust, perennial shrub to 3 m tall with strong rhizomatous roots that can bind sediments and withstand heavy flows (Figure 6.3). Seiben (2012) found palmiet to have a significantly deeper rooting depth than other wetland plant species growing nearby and a more extensive root/shoot ratio.

Figure 6.3. View of a typical stand of palmiet showing its robust growth form and dense growth habit in monospecific stands.

The role of vegetation in controlling channel form and focusing the deposition of sediment to in-channel areas has been described in the literature (Ellery *et al.*, 1990; Ellery *et al.*, 1995; Rogers, 1995; Mitsch and Gosselink, 2000). In an experiment using wooden dowels to simulate in-stream willow saplings, Bennet *et al.* (2010) demonstrated a significant reduction in flow velocities immediately upstream. In Western Cape rivers, Holmes *et al.* (2005) found that dense invasive woody trees within flooded areas increased flow resistance, dampened turbulence and aided in sediment deposition. They found that the trees "have a damming effect on flow, leading to a widening of the watercourse and the conversion of well-defined rivers into diffuse systems of shallow channels" (Holmes *et al.* 2005; p 557).

Palmiet has been observed to line river channels and, in places, encroach across them from both banks in inter-fingering patches. It has also been observed stabilising sediment islands within river channels (Munro *et al.,* 2001; Boucher and Withers, 2004; Seiben, 2012; personal observation). Overall average flows for the Goukou River are reportedly low at around 2.4 cumecs measured in the mid-Goukou downstream of the wetland. During sustained low flows, palmiet patches would be able to expand by vegetative propagation in deposited sediment. Facilitated by its clonal nature, the plant can extend well into river channel open water, narrowing channel width (Plate 6.1c), such that palmiet may densely fill a river channel (Plate 6.1d). In this way palmiet may control the form of a river channel, establishing across the entire valley in places where clastic sediment input is low, giving rise to diffuse flow conditions across the valley. Palmiet has been described as a peat-forming species (Sieben, 2012), and once it colonises a valley and promotes diffuse flow, peat accumulation may take place and gradually cause the water table across the valley to rise. Seiben (2012) reports more than 60% occurrence of palmiet in transects undertaken in the upper third of the Goukou wetland.

Plate 6.1. Palmiet pictured in several Cape rivers, encroaching across a channel in an inter-fingering manner in the Kruis River, a Goukou tributary (a) and the Riviersonderend (b), resisting high velocity flows and slowing waters, in the Olifants River (c), and growing in a dense mass across the full width of the channel, in the Olifants River (d).

The process of peat accumulation has been described as "highly nonlinear, characterised by thresholds and positive and negative feedbacks" (Larsen and Harvey, 2010; p 14), such that peat would not accumulate in deep water conditions which limited vegetation growth and organic matter accumulation, nor in shallow conditions where aeration of the substrate led to oxidation of organic matter. In this process, vegetation both affects and responds to water flows and water depth, where water depth primarily controls vegetation colonisation and vertical peat accretion rates, while gradient and in-stream vegetation community composition are the dominant controls on flow velocities through their effect on roughness (Larsen and Harvey, 2010). Palmiet has a reported tolerance for wide-ranging hydrological conditions, and a clonal robust growth form that affords it the potential to influence flow conditions in a stream, but this study suggests variations in sediment load, water depth and flow velocity limit its establishment and growth, and in particular, its association with peat accumulation. Further research into thresholds for these factors could offer insights into why the majority of Western Cape rivers have palmiet present, but few currently support peat.

The diffuse flow conditions established by palmiet promote permanent or near-permanent flooding of soils, leading to high plant productivity due to the abundant water supply, and to a low rate of organic matter decomposition because soils are starved of oxygen. Organic sediment accumulation across the Goukou valley allows a diverse range of further wetland plant species to establish. Shrubs, restios, bulbs, sedges, and other herbaceous species make up the dense community of plants present in the Goukou Wetland which may also contribute to peat formation. Seiben (2012) reports a high C/N ratio for several species present in his transects, with several showing a higher C/N ratio than palmiet.

Peat forms to the elevation of the prevailing water table, and peat in the Goukou has accumulated to depths greater than 7 m. This suggests that relatively stable conditions prevailed over a long period of time. Radiocarbon dating of a peat sample taken from 4 m deep on the Tierkloof tributary, in similar stratigraphy to the upper Goukou, revealed a date of 5 050 ±30 years before present (Bekker, in prep), suggesting a similar timeframe for the accumulation of peat in the upper Goukou.

Peat, and the occurrence of palmiet, appear to be more narrowly confined where non-sandy clastic sediment enters the valley from tributaries that drain non-quartzitic lithologies (all tributaries entering downstream of the Kruis River, including the Vet and its tributaries [Korente and Brak Rivers]), as revealed by sediment cores. Conditions conducive to peat formation appear to be most favourable in the upper reaches of the wetland where clastic sediment supply is low and sandy due to the prevalence of Cape Supergroup quartzite in the catchments. However, conditions that favour peat formation diminish in a downstream direction due to increased sediment input that is fine-grained (Figure 6.4). Sediment cores with low organic carbon had finer-grained sediments, while cores supporting high organic material correlated with sandy sediment. The sediment variation reflects the heterogeneous geology of the area and declining discharge downstream, with tributaries bearing finer-grained sediment burying and preventing any further peat accumulation.

The Goukou peat basin becomes progressively shallower in a downstream direction, which contrasts with wetland formation behind a local base level – such as in the case of tributary or trunk sedimentation blocking the trunk or tributary respectively – in which case the thickness of organic sediment decreases upstream.

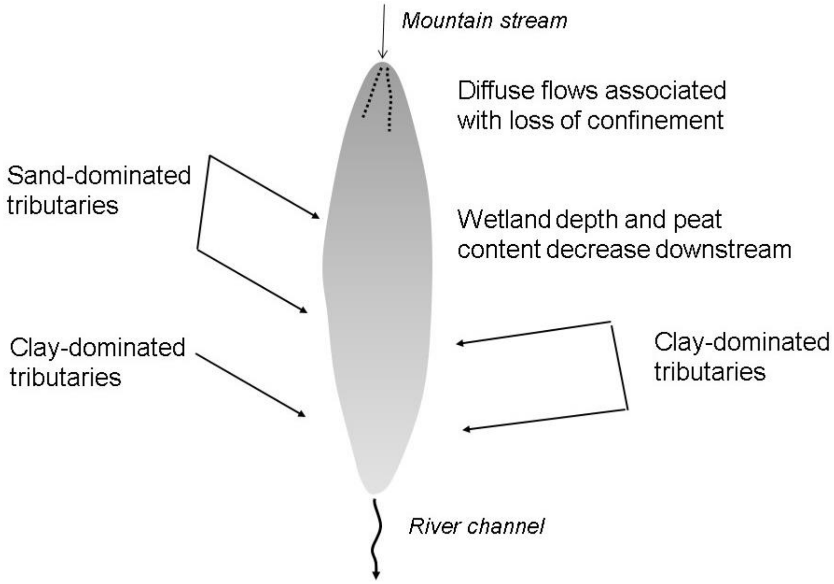


Figure 6.4. A schematic illustration of the contribution of clastic sediment to the Goukou Wetland based on sediment cores and the parent material of catchments that supply water to the wetland.

Organic carbon content also decreases fairly systematically in a downstream direction, which is likely due to increased clastic sediment input from tributaries that increasingly occur on catchments that are non-quartzitic.

The decrease in water availability as rainfall decreases in a downstream direction takes place over a very short distance and appears to correlate with the location of the peat wetland, within the influence of the high rainfall associated with the mountains. However, rainfall is highly variable. Thus, the folded and fractured nature of the Langeberg Mountains that are dominated by quartzites of the Cape Supergroup seems vital as a source of sustained water flow to the wetland, located as it is at the foot of these mountains. This water source appears sufficiently large and prolonged to create hydrological conditions that sustain peat formation, particularly in a flow-through riverine wetland setting with no closed outlet. This seems a key element of the hydrological regime of the Goukou Wetland that needs to be better understood.

6.4 Processes that contribute to valley widening

It is clear from this study that valley width initially increases in a downstream direction, becoming narrow again downstream of the confluence of the Vet and Goukou Rivers. If palmiet simply colonised the stream and formed peat vertically, the bedrock would maintain a V-shape across the width of the valley. However, a remarkable feature of the valley cross-section is the uniformity of elevation of “bedrock”, suggesting that peat associated with palmiet has not simply filled a V-shaped valley, but that bedrock has been planed to a uniform elevation across the entire width of the valley.

Valley widening in floodplains has been elegantly explained by the presence of a resistant lithology that acts as a local base level below which the river cannot cut (upstream of the base level), such that excess energy that might be used to cut vertically is used to plane the valley floor and widen it (Tooth *et al.,* 2004: Tooth and McCarthy, 2007). This has been described for several floodplain systems in South Africa, including the Blood River (Tooth *et al.*, 2014), the

Seekoeivlei in the eastern Free State (Tooth *et al.*, 2004; Tooth and McCarthy, 2007), the Stillerust Vlei (Grenfell *et al.*, 2008) and Hlatikulu Vlei (Joubert and Ellery, 2012), the latter two of which are in the Drakensberg foothills. However, the Goukou valley has no floodplain meander features and is best classified as an unchannelled valley-bottom wetland. Furthermore, peat has not been described in the floodplains that form through the processes described above, as these systems are dominated by clastic sediment.

The planed nature of the bedrock in the Goukou suggests that instead of continuous planing of the valley floor, it has been exposed to a series of cut and fill episodes that repeatedly cut to a similar elevation along the stream over a long period of time. Following cutting, the valley fills again with peat, presumably physically controlled by palmiet, which chokes the stream and again fills the valley with peat. It is hypothesised that this is the mechanism that produces a wide valley with a uniform depth to bedrock across the valley.

6.5 Factors that affect cutting and filling

During the last Ice Age, sea level was more than 120 m below its current level (Compton, 2004), and rivers extended across what is now an extensive shallow continental shelf stretching out to sea along the southern Cape coast. During this time, the lower reaches of the Goukou River and its tributaries would have incised in response to the lowered base level. This study suggests that incision in response to this lowering of the base level did not affect the upper reaches of the Goukou at all. The upper valley is shallower and wider than the steep-sided, deep and narrow lower valley. Since then, sea level has risen and, particularly within the last 8 000 years, fluctuated within 2 or 3 m above and below present day levels (Ramsay, 1995). It is unlikely that these changes in sea level had any significant effect on the structure of the Goukou Wetland. Two radiocarbon dates from the bottom of the gully wall in the Tierkloof tributary suggest it was stripped of peat to bedrock throughout most of the valley prior to 5 000 years ago. The first date at 5 050 ±30 BP (Bekker, in prep) likely represents the most recent cut and fill cycle, while a second date of 7 490 ±200 BP (Filmater, personal communication) could be a remnant of a separate cutting and filling episode not completely removed during the more recent cutting cycle, supporting the concept of multiple cutting and filling episodes.

Wet climate cycles or even large rainfall events can lead to increased discharge off the mountains into the upper wetland. As a result of the variable rainfall regime and relatively small but steep catchments, the catchment often experiences long periods of drought, interspersed with periods of heavy rainfall, often accompanied by flooding. Peak flows over the last 45 years have reached as high as 495 cumecs compared to an average flow of 2.4 cumecs. Such extreme events could trigger gully erosion in the upper reaches of the wetland, especially in the more vulnerable, steeply sloping wetlands. Although gullies may initiate anywhere along the wetland (evident in the land use mapping and historical photo interpretation in association with invasive alien vegetation, road crossings and the digging and expansion of irrigation canals), examination of tributary wetlands where there are minimal human impacts reveals gullies initiating mostly at the head of these wetlands.

According to available historical accounts between the late 1800s and 1930s, major floods were recorded as early as 1875. Since then, there has been a major flood approximately every decade, sometimes with multiple floods in a decade. Flooding seems to occur throughout the year as indicated by the reconstruction of flood events in the area (Table 6.1). Reports of floods late in the nineteenth century suggest that major floods occurred with a frequency of once every fifteen years but in the early 20th century they appear to have occurred with a frequency of once every 5 to 10 years. Presumably this difference is related to the availability of records and not an altered frequency.

Table 6.1: Reconstruction of the flood history of the area from various sources (compiled by the Weather Bureau *in* CAELUM, 1991).

Year	**Dates** (if available)	**Description**
1875	not reported	Widespread flooding occurred and at Heidelberg 45 homes were swept away by the Duivenhoks river. At the Swartberg Pass there is mention of the great floodwaters of 1875.
1885	14-16 May	From Thursday to Saturday heavy rain fell between Montagu and Meiringspoort. The Gouritz River was full of carcasses of dead cattle. On the 15th and 16th, 250mm of rain fell in George.
1902	11-12 February	Continuous rain caused considerable damage. Robertson streets were under

		a metre of water. At Heidelberg 250mm of rain was reported for two days.
1905	11-26 September	Widespread flooding took place after rivers in several districts overflowed. The areas worst affected by foods were in the vicinity of George and Hankey. More than 480mm was recorded during the month in George.
1906	14 December	Flooding occurred from Cape Town to Riversdale, with the worst flooding between Swellendam and Riversdale, with damage to roads and rail tracks. At Heidelberg, about 280mm of rain fell between 14:00 and 22:00 on 14 December.
1916	3-5 May	Heavy rains and flooding.
1921	14 February	Flooding in Laingsburg and other inland areas.
1922	11 January	Flooding in inland areas.
1925	June	“An exceptionally wet June".
1932	not reported	Severe flooding.

More recent flooding reconstructed from Department of Water Affairs flow records and anecdotal evidence suggests that flooding occurs with a frequency of once every 2 to 5 years (Table 6.2).

Table 6.2: Recent flood history.

Year	**Dates (where available)**	**Description**
1981	January	Flows exceed 350 cumecs mid Goukou River station H90_102130 (DWA, 2010)
1986	July	Flows exceed 350 cumecs mid Goukou River station H90_102130 (DWA, 2010)
1991	October	Flows exceed 350 cumecs mid Goukou River station H90_102130 (DWA, 2010)
1996	November	Flows exceed 350 cumecs mid Goukou River station H90_102130 (DWA, 2010)
2003	May	Flows exceed 350 cumecs mid Goukou River station H90_102130 (DWA, 2010)
2004	December	Cut-off low, resulted in heavy flooding affecting towns as far apart as Robertson and Plettenberg Bay and reaching as far north as Merweville in the Karoo. (Price, 2010)
2006	23 August	Severe flood, damaging several houses and the newly rebuilt Heidelberg sewerage plant. Rainfall for August in Vermaaklikheid was 234mm compared to an August average of 40mm over the previous five years. Some 70mm fell on 23 August alone (Price, 2010)
2007	November	Flows exceed 350 cumecs mid Goukou River station H90_102130 (DWA, 2010)
2011	June	Flows exceed 350 cumecs mid Goukou River station H90_102130 (DWA, 2010)

Sediment cores reveal episodes of sand deposition interspersed with times of peat accumulation, suggesting a dynamic flow history, since peat formation requires very low energy conditions while the introduction, movement and deposition of sand indicates high flows. It is likely that peat development on tributaries, driven by palmiet, takes place independently of peat formation on the trunk, although once erosion takes place in a tributary, it will likely affect the trunk. The Kruis and Vet Rivers illustrate this well, given that these systems now comprise well-developed river channels that flow into the Goukou and deposit large quantities of sediment at and downstream of their confluences, therefore limiting peat development. Brierly and Fryirs (1999) suggest that cut and fill incision episodes coinciding across tributaries are climate driven, while those that take place at different times between wetlands are usually related to intrinsic thresholds such as "valley slope, local large rainstorm events, or local changes of vegetation (caused by fires)" (Eriksson *et al.*, 2006; p 67).

6.6 Conceptual model

Palmiet establishes itself across V-shaped river channels during seasonal or long term cycles of reduced flows. Once it is fully established across a river channel it is able to slow flows and trap sediment, leading to permanently flooded, quiet waters that are low in sediment, conditions that are conducive to peat formation. However, during wet climate cycles, gullies are initiated and erosion cuts into the side of the valley, widening the valley, such that the valley floor is planed to a particular elevation (Figure 6.5). Over time, particularly where no large floods occur, the palmiet again colonises the eroded stream and peat forms across the valley floor. Once permanently saturated, the peat wetland may be stable for long periods of time. Renewed wet climate cycles, possibly in combination with drought or fire, again initiate erosion of the peat, leading to further valley widening. Over long term cycles of wet and dry climate, cut and fill repeatedly takes place to a common level, moving from valley side to valley side, developing the valley into a wide and flat-bottomed U-shape.

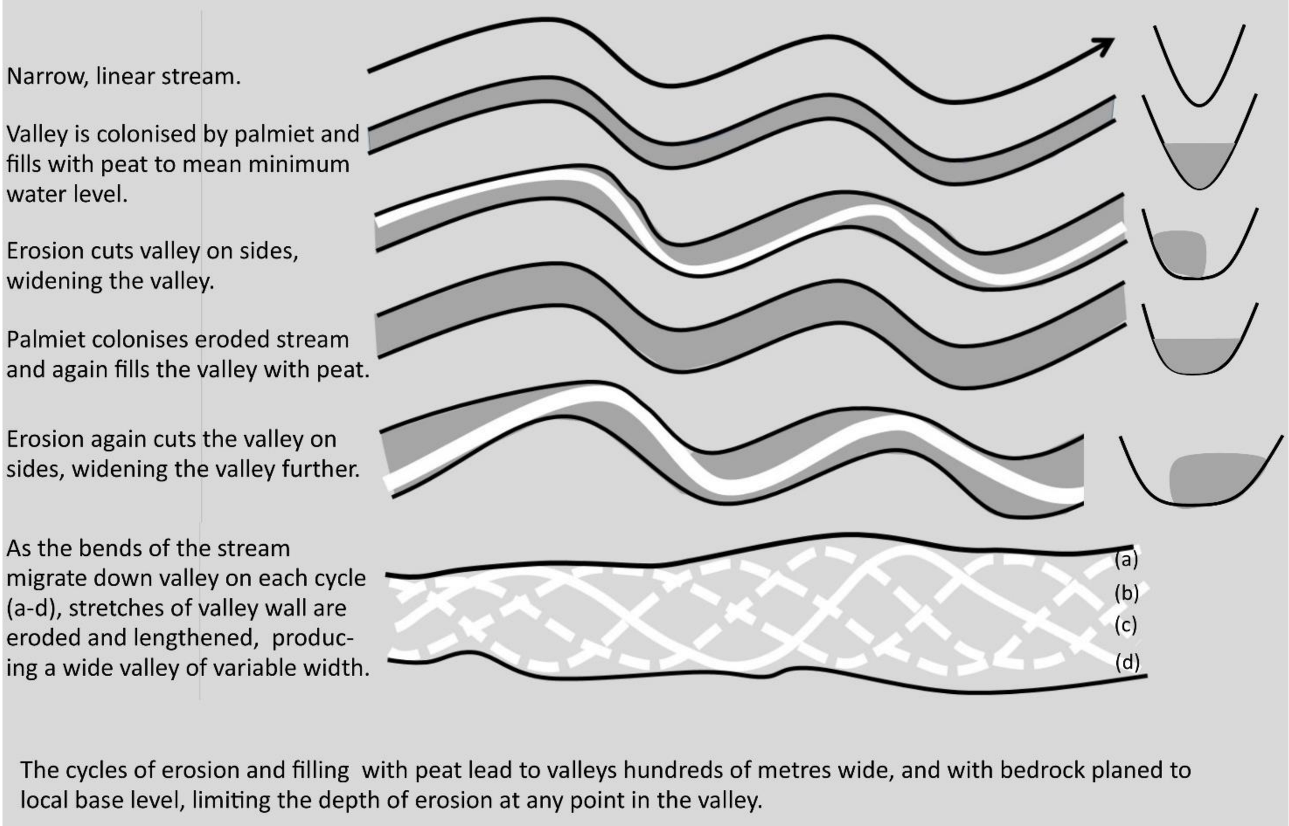


Figure 6.5. Conceptual model of peat wetland formation in wetlands dominated by palmiet.

Although the Goukou is not a meandering stream, as it does not have a conducive sediment regime nor setting, water naturally will not flow for very long in a straight line, responding to multiple local conditions of discharge, gradient and existing valley morphology. In this way, the stream cuts from side to side rather than keeping to one side of the valley. Multiple stream successions over multiple cut and fill cycles (a-d in Figure 6.5) gradually shift downstream, cutting the valley spurs so that ultimately the sinuosity of the original stream gives way to a long, linear valley of substantial width. It is expected that this will be reflected in the wetland peat deposits, but this requires more detailed dating and sediment description than was possible for this study.

6.7 Management implications

Peatland ecosystems provide a range of ecosystem services that benefit human well-being. In this case the provision of ecosystem services is dependent largely upon the presence of the robust plant palmiet, which fundamentally shapes valley form and function and promotes peat accumulation. Peat soils are able to expand and absorb water as water levels rise during a flood, and shrink again and release water gradually to the stream as water levels drop after a flood, improving flood attenuation and streamflow regulation services. Carbon sequestration through organic matter in peat deposits could mitigate climate change impacts of greenhouse gas emissions, while these wetlands also enhance water quality, trap sediment and limit erosion. In a natural, well-vegetated and semi-permanently saturated state, these wetlands may be stable over extremely long time periods. However, they become increasingly vulnerable once the palmiet is physically disturbed and roots destabilised, or the water table is lowered, either through drought, fire, or human-related disturbance, and may rapidly degrade, leading to catastrophic damage to property and infrastructure.

7. CONCLUSION

As with most floodplain and valley-bottom wetlands studied in South Africa, the Goukou Wetland formed under the climatic and tectonic conditions that have prevailed since the Pliocene, located within an incising drainage network below the African Erosion Surface. The Goukou River suggests that it is a graded stream along its entire course, with longitudinal slope determined by discharge alone.

The high rainfall in the folded Langeberg Mountains of quartzite lithologies of the Cape Supergroup plays a key role in facilitating the expansion and persistence of a large peat basin at the base of the mountains, contributing to permanent saturation and peat formation. Furthermore, it is clear that the sustained release of water from these fractured quartzite lithologies contributes enormously to the formation of the Goukou Wetland, which is a subject that requires further investigation. It is contended here that if the mountains were of lithologies other than fractured quartzite, it seems unlikely that the wetland would exist in its present form. For example, foothill wetlands in the Drakensberg Mountains are generally floodplains with little or no peat.

The formation of extensive peat deposits in the upper Goukou River appears to be controlled by the plant *Prionium serratum*. By growing across the full width of the valley floor, the plant is able to "take hold" of the river, trapping sediment and slowing flows such that it completely changes the environment from a fast flowing river to diffuse flow, initiating the formation of organic sediment to form a deep peat basin. The presence of palmiet throughout the system offers an explanation for the occurrence of diffuse valley-bottom wetland conditions, low unit stream powers, discontinuous streams, and peat formation. Multiple cycles of cutting and filling have laterally planed Uitenhage Formation sedimentary rocks to form a broad, peat-filled basin.

Palmiet has several characteristics which make it well suited to trapping sediment and altering the flow regime and characteristics of the river channel, yet only a small number of Cape rivers have developed deep peat basins such as that of the Goukou Wetland. This study has produced a general conceptual model for peat accumulation and dynamics in the Goukou Wetland which would benefit from future research. In particular, to further explore the ecology of palmiet, and to investigate its contribution to the plant material making up the peat. The dating of sediments would be invaluable in constructing a more detailed picture of trunk-tributary interactions and timing of cut and fill cycles. The concept of cutting and filling leading to valley widening in this particular context is newly described and contested and requires further study. This would require sufficient funding to be in place, as it would be costly and entail a very detailed sediment description and analysis of dates and ages of peat across the valley. It is hypothesised that sustained input of water from the folded and fractured Cape Supergroup quartzites of the Langeberg Mountains are vital for the development of the Goukou Wetland, which also needs further investigation.

LIST OF REFERENCES

Alistoun, J. (2013). *The origin of endorheic pans on the African Erosion Surface north of Grahamstown, South Africa*. Unpublished Masters Thesis submitted to Rhodes University, Grahamstown.

Bekker, D. (In prep). *The geomorphic origin, evolution and collapse of a peatland dominated by Prionium serratum – a case study of the Tierkloof Wetland, Western Cape*. Unpublished Masters Thesis submitted to Rhodes University, Grahamstown.

Bennett, S.J., Pirim, T. and Barkdoll, D. (2010). Using simulated emergent vegetation to alter stream flow direction within a straight experimental channel.

Beylea, L.R. and Clymo, R.S. (2001). Feedback control of the rate of peat formation. *Proceedings of the Royal Society of London: Biological Sciences*. 268:1315-1321.

Boucher, C. and Withers, M. (2004). The only one of its kind – the unique Cape river plant *Prionium serratum*. *Veld and Flora*. 90(1):26-28.

Brierley, G.A. and Fryirs, K. (1999). Trunk-tributary relations in a cut-and-fill landscape: A case study from Wolumla catchment, New South Wales. *Earth Surface Process and Landforms*. 28: 107-124.

Burenhult, G. (Ed). (2003). *People of the Past: The epic story of human origins and development*. Fog City Press, San Francisco, USA.

CAELUM - *A history of notable weather events in South Africa 1500-1990*. Published by the Weather Bureau, Department of Environmental Affairs, Pretoria. December 1991

Carr, A.S., Bateman, M.D., Roberts, D.L., Murray-Wallace, C.V., Jacobs, Z. and Holmes, P.J. (2010). The last interglacial sea-level highstand on the southern Cape coastline of South Africa. *Quaternary Research*. 73:351-362.

Carr, A.S., Thomas, D. and Bateman, M. (2006). Climatic and sea level controls on Late Quaternary eolian activity on the Agulhas Plain, South Africa. *Quaternary Research*. 65:252 – 263.

Carter, R.A. and Brownlie, S. (1990). Kafferkuils and Duiwenhoks. Estuaries of the Cape. Part II. Synopses of available information on individual systems. CSIR Research Report 433. Stellenbosch.

Charman, D. (2002). *Peatlands and Environmental Change*. Wiley and Sons, UK.

Chase, B. (2010). South African paleoenvironments during marine oxygen isotope stage 4: a context for the Howiesons Poort and Still Bay industries. *Journal of Archeological Science*. 37(6):1359-1366.

Clarkson, B.R., Schipper, L.A and Lehmann, A. (2004). Vegetation and peat characteristics in the development of lowland restiad peat bogs, North Island, New Zealand. *Wetlands*. 24(1):133-151.

Compton, J. (2004). *The Rocks and Mountains of South Africa*. Double Storey Books. Cape Town, South Africa.

Cowling, R.M., Holmes, P.M. and Rebelo, A.G. (1992). *The Ecology of Fynbos: Nutrients, Fire and Diversity*. Oxford University Press, Cape Town.

Davies, B.R. and Day, J. (1998). *Vanishing Waters*. University of Cape Town Press, Cape Town.

Department of Water Affairs. (2010). Flow dataset for Goukou River station H90_102130. Resource Quality Services Directorate, Pretoria.

Dollar, E. S. J. (1998). Palaeofluvial geomorphology in southern Africa: a review. *Progress in Physical Geography*. 22:325 - 349.

Edwards, R. (2009). *The origin and evolution of Dartmoor Vlei in the KwaZulu-Natal Midlands*. South Africa. Unpublished Masters Thesis submitted to University of KwaZulu-Natal, Durban.

Edwards, R. and Ellery, W.N. (In prep). *The origin and evolution of Dartmoor Vlei in the KwaZulu-Natal Midlands.*

Ellery, K., Ellery, W.N., Rogers, K.H. and Walker, B.H. (1990). Formation, colonization and fate of floating sudds in the Maunachira river system of the Okavango Delta, Botswana. *Aquatic Botany*. 38: 315-329.

Ellery, W.N., Ellery, K., McCarthy T.S, Cairncross, B. and Oelofse, R. (1989). A peat fire in the Okavango Delta, Botswana, and its importance as an ecosystem process. *African Journal of Aquatic Science.* 27:7-21.

Ellery, W.N., Ellery, K., Rogers, K. and McCarthy, T.S. (1995). The role of *Cyperus papyrus* L. in channel blockage and abandonment in the northeastern Okavango Delta, Botswana. *African Journal of Aquatic Science.* 33:25-49.

Ellery, W.N., Humphries, M., Barnes, K., Grenfell, M.C., Grenfell, S., Fischer, D., Kindness, A., and Hughes, G. (2012). Peat formation in the context of landscape evolution of the Mkuze Wetland on the coastal plain of Maputaland, South Africa. *Geomorphology*. 141-142:11-20.

Ellery W.N., Kotze, D.C., McCarthy, T.S., Tooth, S., Grenfell, M., Beckendahl, H., Quinn, N. and Ramsay, L. (2009). *The Origin and Evolution of Wetlands,* Water Research Commision Wetlands Research Programme: Wetland Rehabilition, South Africa.

Ellery, W.N. and McCarthy, T.S. 1998. Environmental change over two decades since dredging and excavation of the lower Boro River, Okavango Delta, Botswana. *Journal of Biogeography*. 25:361-378.

Ellery, W.N., McCarthy, T.S. and Dangerfield, J.M. (2000). Floristic diversity in the Okavango delta, Botswana as an endogenous product of biological activity. In: *Biodiversity in Wetlands: Assessment, Function and Conservation, vol. 1*. B. Gopal, W.J. Junk, and J.A. Davis (Eds.) Backhuys Publishers, Leiden.195–226.

Ellery, W.N., McCarthy, T.S. and Smith, N. (2003). Vegetation, hydrology and sedimentation patterns on the major distributary system of the Okavango Fan, Botswana. *Wetlands*. 23(2):357-375.

Ellery, W.N. and Rowntree, K. (2010). The Baviaanskloof landscape – the work of geological processes and water. In: *Baviaanskloof – a world apart*. Hattingh, L. (Ed).

Eriksson, M.G., Olley, J.M., Kilham, D.R., Pietsch, T. and Wasson, R.J. (2006). Aggradation and incision since the very late Pleistocene in the Naas River, south-eastern Australia. *Geomorphology*. 81:66–88.

Food and Agriculture Organisation of the United Nations. 1987. Soil and Water conservation in Semi-arid Areas. *Soils Bulletin*. 57:1-17.

Fey, M. (2010). *Soils of South Africa*. Cambridge University Press, South Africa.

Filmater, W. (2012). Department of Agriculture: Western Cape. Riversdale, South Africa. Personal communication over multiple occasions 2011-2012.

Fischer, E.C., Bar-Mathews, M., Jerardino, A. and Marean, C.W. (2010). Middle and Late Pleistocene paleoscape modeling along the southern Cape coast of South Africa. *Quaternary Science Reviews*. 29:1382-1398.

Gale, B. (1993). CapeNature, Riversdale office. Unpublished water quality results for the Goukou River.

Garden, S. (2008). *Wetland geomorphology and floodplain dynamics on the hydrologically variable Mfolozi River, KwaZulu-Natal, South Africa*. Unpublished PhD Thesis submitted to University of KwaZulu-Natal, Durban.

Gaudig, G., Couwenberg, J. and Joosten, H. (2006). Peat accumulation in kettle holes: bottom up or top down? *Mires and Peat*. 1(6):1-16.

Gee, G.W. and Bauder, J.W. (1986). Particle size analysis. In A. Klute (Ed.), *Methods of soil analysis. Agronomy Monogograph No. 9 Part 1*. American Society of Agronomy, Madison, Wisconsin, USA.

Goldblatt, P. and Manning, J.C. (2000). *Cape Plants; A conspectus of the Cape flora of South Africa*. National Botanical Institute of South Africa. ABC Press, Epping, South Africa.

Grenfell, M.C., Ellery, W.N. and Grenfell, S.E. (2008). Tributary valley impoundment by trunk river floodplain development: a case study from the Drakensberg foothills, eastern South Africa. *Earth Surface Processes and Landforms*, 33:2029–2044.

Grenfell, S.E., Ellery, W.N., Grenfell, M.C., Ramsay, L.F. and Flugel, T.J. (2010). Sedimentary facies and geomorphic evolution of a blocked-valley lake: Lake Futululu, northern Kwazulu-Natal, South Africa. *Sedimentology*. 57(5):1159-1174.

Grundling, A. (2011). *Analysis of organic wetland soils from 3 wetlands in the Kleinmond area, Western Cape*. ARC- Institute for Soil, Climate and Water: Soil Health and Remediation, Pretoria.

Grundling, P-L. and Grobler, R. (2005). Peatlands and mires of South Africa. In: *Mires from Siberia to Tierra Del Fuego*. Steiner, G.M. (Ed.) Stapfia 85, Landesmuseen Neue Serie.

Haigh, E.A., Grundling, P-L., Illgner, P.M. (2002). *Scoping study on the status of the Kromme River Peatland complex and recommended mitigatory measures*. Report No. 832633. Department of Water Affairs and Forestry.

Henshilwood, C.S. (1995). *Holocene Archaeology of the Coastal Garcia State Forest, Southern Cape, South Africa*. Unpublished PhD Thesis submitted to University of Cambridge, U.K.

Holmes, P.M., Richardson, D.M., Esler, K.J., Witkowski, E.T.F., and Fourie, S. (2005). A decision-making framework for restoring riparian zones degraded by invasive alien plants in South Africa. *South African Journal of Science*. 101:553-564.

Johnson, M.R., Theron, J.N. and Loock, J.C. (2006). *Witteberg Group*. Catalogue of South African Lithostratigraphic Units. SA Committee for Stratigraphy.

Johnson, M.R., Theron, J.N. and Rust, I.C. (1999). *Table Mountain Group*. Catalogue of South African Lithostratigraphic Units. SA Committee for Stratigraphy.

Jones, C.G., Lawton, J.H., Shachak, M. (1994). Organisms as eco-system engineers. *Oikos*. 69:373–386

Joosten, H. and Clarke, D. (2002). *Wise use of mires and peatlands*. International Mire Conservation Group and International Peat Society, Saarijärven Offset Oy, Saarijärvi, Finland.

Joubert, R. and Ellery, W.N. (2013). Controls on the formation of WakkerstroomVlei, Mpumalanga Province, South Africa. *African Journal of Aquatic Science*. 38(2):135-151.

King, L.C. (1963). *South African Scenery: A Textbook of Geomorphology*, 3rd edition. Oliver and Boyd: Edinburgh.

Knighton, D. (1998). *Fluvial forms and processes – A new perspective*. Arnold Publishers. London.

Kotze, D.C., Marneweck, G.C., Batchelor, A.L., Lindley, D.S. and Collins, N.B. (2008). *WET Ecoservices: A Technique for Rapidly Assessing Ecosystem Services Supplied by Wetlands*. WRC Report No. TT 339/08. Water Research Commission, Pretoria, South Africa.

Larsen, L.G. and Harvey, J.W. (2010). Modeling of hydroecological feedbacks predicts distinct classes of landscape pattern, process, and restoration potential in shallow aquatic ecosystems, *Geomorphology*. 126:279-296.

Lewis, C.A. (2008). *Late Quaternary climatic changes, and associated human responses, during the last 45 000 years in the Eastern and adjoining Western Cape, South Africa*. Rhodes University.

Malan, J. and Viljoen, J. (2008). *Southern Cape Geology: Evolution of a Rifted margin*. AAPG International Conference. Council for Geoscience. Cape Town, South Africa.

Marker, M. and Holmes, P. (2005). Landscape evolution and landscape sensitivity: the case of the southern Cape. *South African Journal of Science*. 101:53-60

Marker, M. and Holmes, P. (2010). The geomorphology of the Coastal Platform in the southern Cape. *South African Geographical Journal*. 92(2):105-116

Marker, M.E. and McFarlane, M.J. (1997). The geomorphology of the Coastal Platform in the southern Cape. *South African Journal of Geology*. 100(3):185-194

Marneweck, G.C., Grundling, P-L. and Muller, J.L. (2001). *Defining and classification of peat wetland eco-regions in South Africa*. Wetland Consulting Services (Pty) Ltd. Report to the

Institute for Soil, Climate and Water (ISCW), Agricultural Research Council for the Directorate for Land and Resources Management (DLRM), Department of Agriculture, Pretoria.

McCarthy T.S. (2009). *How on earth? Answers to the puzzles of our planet*. Struik Publishers, Cape Town.

McCarthy, T., Barry, M., Bloem, A., Ellery, W.N., Heister, H., Merry, C.L., Ruther, H. and Sternberg, H. (1997). The gradient of the Okavango fan, Botswana, and its sedimentological and tectonic implications. *Journal of African Earth Sciences.* 24(1/2):65-78.

McCarthy, T., Cairncross, B., Huizenga, J and Batchelor, A. (2007). *Conservation of the Mpumalanga Lakes District*. Technical Report. School of Geosciences, University of the Witwatersrand, Johannesburg; Department of Geology, University of Johannesburg; and Wetland Consulting Services (Pty) Ltd.

McCarthy,T.S. and Hancox, P.J. (2000). Wetlands. In T.C. Partridge and R.R. Maud. (Eds.). *The Cenozoic of Southern Africa.* Oxford Monographs on Geology and Geophysics. Oxford University Press, Oxford.

McCarthy, T.S. and Rubidge, B. (2005). *The story of Earth and Life: A southern African perspective on a 4.6-billion-year journey*. Struik Publishers, Cape Town.

Mills, A.J., Birch, S.C., Stephenson, J.D., Bailey, R.V. (2012). Carbon stocks in fynbos, pastures and vineyards on the Agulhas Plain, South Africa: a preliminary assessment. *South African Journal of Plant and Soil.* 29(3-4):191-193.

Mitsch W.J. and Gosselink J.G. (2000). *Wetlands, third edition*. John Wiley & Sons, New York, NY, USA.

Morisawa, M. (1968). *Streams: their dynamics and morphology*. McGraw-Hill New York.

Mucina, L. and Rutherford, M.C. (Eds.). (2006). *Vegetation Map of South Africa, Lesotho and Swaziland*. South African National Biodiversity Institute, Pretoria.

Munro, S.L, Kirschnerm J. and Linder, H.P. (2001). *Prioniaceae*, Species Plantarum: Flora of the World Part 5: 1–7.

Ngetar, N. (2012). *Causes of wetland erosion at Craigieburn, Mpumulanga Province, South Africa.* Unpublished PhD Thesis submitted to University of KwaZulu-Natal, Durban.

Nsor, C. A. and Gambiza, J. (2013). Land Use Changes and Their Impacts on the Vegetation Kromme River Peat Basin, South Africa. *Science Journal of Environmental Engineering Research*. 3:1-12.

Ollis, D.J., Snaddon, C.D., Job, N.M. & Mbona, N. (2013). *Classification System for Wetlands and other Aquatic Ecosystems in South Africa. User Manual: Inland Systems.* SANBI Biodiversity Series 22. South African National Biodiversity Institute, Pretoria.

Price, P. (2010). *Flooding in the Eden District*. Powerpoint presentation, 2010.

Ramsay, P.J. (1995). 9 000 years of sea-level change along the southern African coastline. *Quaternary International*. 31:71–75.

Rogers, K.H. (1995). Riparian Wetlands. In: *Wetlands of South Africa*. Cowan, G.I. (Ed). Department of Environmental Affairs and Tourism: Pretoria; 41-52

Roux, J.P. (2003). *Flora of South Africa.* Compton Herbarium, Cape Town, South African National Biodiversity Institute.

Rydin, H. and Jeglum, J.K. (2006). *The Biology of Peatlands*. Oxford University Press.

Schloms, B.H.A, Ellis, F. and Lambrechts, J.N.N. (1983). Soils of the cape coastal platform. In: *Fynbos paleoecology: a preliminary synthesis*. Deacon, H.J., Hendey, Q.B. and Lambrechts, J.N.N. (Eds). South African National Scientific Programmes Report No. 75. Pretoria.

Schulze, R.E. (1997). *South African Atlas of Agrohydrology & Climatology*. Water Research Commission Report No TT82/96, Pretoria.

Schulze, R.E. (2012). *A 2011 Perspective on Climate Change and the South African Water Sector.* Water Research Commission Report No TT518/12, Pretoria.

Schumm, S.A. (1977). *The Fluvial System*. John Wiley and Sons: New York.

Schumm, S.A. (1979). Geomorphic thresholds: the concept and its applications. *Transactions of the Institute of British Geographers*. 4:485-515.

Seiben, E. J.J. (2012). Plant functional composition and ecosystem properties: the case of peatlands in South Africa. *Plant Ecology*. 213(5):809-820.

Seiben, E. and Zelany, D. (2010). *Functional Composition of South African Peatlands.* Paper presented at the South African National Wetlands Indaba Conference, Kimberley, 2010.

Sinchembe, M. and Ellery, W.N. (2010). Human impacts on hydrological health and the provision of ecosystem services: a case study of the eMthonjeni-Fairview Spring Wetland, Grahamstown, South Africa. *African Journal of Aquatic Science*. 35(3):227-239.

Soil Classification Working Group. (1991). *Classification: A Taxonomic System for South Africa.* A report on a research project carried out under the auspices of the Soil and Irrigation Research Institute. Department of Agricultural Development. Pretoria.

Summerfield, M.A. (1991). *Global geomorphology: an introduction to the study of landforms.* Longman Scientific and Technical, U.S.A.

Talma, A.S. and Vogel, J.C. (1992). Late quaternary paleotemperatures derived from a speleotherm from Cango Caves, Cape Province, South Africa. *Quaternary Research.* 37: 203-213.

Theron, J.N. and Johnson, M.R. (1991). *Bokkeveld Group (including the Ceres, Bidouw & Tarka Subgroups).* Catalogue of South African Lithostratigraphic Units. SA Committee for Stratigraphy.

Thompson, M. (2007). *CapeNature Fine-scale Conservation Project: Land cover classifications from SPOT 5 satellite imagery*. Produced by GeoTerraImage (GTI) Pty Ltd for CapeNature as part of the C.A.P.E. Fine-scale Biodiversity Planning Project. Pretoria.

Tooth S. (2000). Process, form and change in dryland rivers: a review of recent research. *Earth-Science Reviews*. 51:67–107

Tooth S., Brandt D., Hancox P.J., and McCarthy T.S. (2004). Geological controls on alluvial river behaviour: a comparative study of three rivers on the South African Highveld. *Journal of African Earth Sciences.* 38:79-97.

Tooth S. and McCarthy T.S. (2007). Wetlands in drylands: geomorphological and sedimentological characteristics, with emphasis on examples from southern Africa. *Progress in Physical Geography*. 31(1):3–41.

Tooth S., McCarthy T.S., Rodnight, H., Keen-Zebert, A., Rowberry, M. and Brandt, D. (2014). Late Holocene development of a majorfluvial discontinuity in floodplain wetlands of the Blood River, eastern South Africa. *Geomorphology*. 205:128-141.

U.S. Army Corps of Engineers. (2006*). Interim regional supplement to the Corps of Engineers Wetland Delineation Manual: Arid West Region*. (Eds.) J. S. Wakeley, R. W. Lichvar, and C.V. Noble. ERDC/EL TR-06-16. Vicksburg, MS. U.S. Army Engineer Research and Development Center.

U.S.D.A. Soil Conservation Service. (1975). *Soil Taxonomy: A basic system of soil classification for making and interpreting soil surveys.* U.S. Department of Agriculture. U.S. Government Printing Office. Washington DC.

Van Breemen, N. (1995). How Sphagnum bogs down other plants. *TREE*. 10(7).

Vlok, J.H.J. and de Villiers, M.E. (2007). *Vegetation map for the Riversdale domain*. Unpublished report supported by C.A.P.E. FSP team and CapeNature.

Watters, J.R and Stanley, E.H. (2007). Stream channels in peatlands: The role of biological processes in controlling channel form. *Geomorphology*. 89:97–110.

Yeloff D.E., Labadz, J.C. and C.O. Hunt. (2006). Causes of degradation and erosion of a blanket mire in the southern Pennines, UK. *Mires and Peat* 1(6).