



RHODES UNIVERSITY

Grahamstown • 6140 • South Africa

**An investigation into the origin and evolution of the Tierkloof
Wetland, a peatland dominated by *Prionium serratum*, in the
Western Cape**

Thesis

Submitted in fulfilment of the requirements for the degree of Master of Science

Rhodes University

By

Debra Jane Bekker

Department of Environmental Science

Rhodes University

P.O. Box 94

Grahamstown

6140

December 2016

ABSTRACT

The Tierkloof Wetland in the Western Cape has been damaged through erosion down to bedrock with gullies that are up to 50 m wide and 7 m deep. The purpose of this study was to investigate the origin and evolution of the Tierkloof Wetland and consider the role both natural and human-induced processes have played in its degradation. The main methods used were digital mapping using GIS software, satellite and aerial photographic interpretation of past and current land use, detailed topographic surveying, coring to bedrock, stratigraphic analysis of valley-fill sediments, and radio carbon dating of peat samples.

Nine GIS-produced topographic profiles across the valley were plotted to analyse downstream changes in valley width and morphology along the length of the Tierkloof valley. Detailed cross sections of the stream channel were produced using topographic survey data. Depth to bedrock analysis indicated that there is evidence of a degree of planing of bedrock over geological time periods.

Survey data indicates that the longitudinal slope of the former wetland surface is remarkably uniform over most of its length and there is an overall thinning of the valley fill from the head to the toe of the wetland. The stratigraphy and associated organic matter content of the wetland soils showed that the sedimentary fill varies considerably. There are appreciable accumulations of organic sediment, including sandy peat and peat layers with organic content of up to 50 %. The two radio carbon dates obtained from the gully wall midway down the Tierkloof Wetland suggest that peat accumulation started following the last glacial maximum. The peat has accumulated consistently and is mostly associated with the growth of the palmiet, *Prionium serratum*.

Evidence from past and current land-use activities from aerial photographic interpretation show that natural vegetation in the Tierkloof Wetland has been severely degraded, alien plants are extremely common, and road-building and artificial drainage in the wetland have influenced fluvial processes. It is likely that these activities, exacerbated by the high rainfall events in the early 2000s, have triggered the erosional phase that was initiated a few decades ago. However, longer term processes (thousands to tens-of-thousands of years), such as the planing of the bedrock, also indicate that erosional processes have been a natural part of the

Tierkloof Wetland development. A conceptual model of wetland development is thus proposed, based on long-term erosional and depositional processes that are linked with climate change and the current aggradation phase of peat formation that is being driven by the ecosystem engineering processes of palmiet plant growth. It is further suggested that relatively recent land-use activities have resulted in an already vulnerable wetland, in geomorphological terms, to cross a threshold to become a severely degraded, gully-dominated wetland.

Keywords: *erosion, peat; Prionium serratum, ecosystem engineer, wetland*

TABLE OF CONTENTS

CHAPTER 1 - INTRODUCTION.....	1
CHAPTER 2 - THEORETICAL FRAMEWORK	3
2.1 Wetland formation.....	3
2.1.1 Hydrology, erosion and deposition	3
2.1.2 Longitudinal characteristics of rivers: the concept of a graded longitudinal profile.....	4
2.1.3 The depth to which a river can erode its bed: the concept of the base level	5
2.2 Current concepts of wetland origin in South Africa:	6
2.2.1 Resistant lithologies	7
2.2.2 Trunk-tributary relationships	7
2.2.3 Faulted Basins	9
2.2.4 Sagging	9
2.2.5 Ecosystem Engineers	9
2.3 Peat Formation	11
2.4 Causes of degradation in wetlands	11
2.4.1 Human impacts	11
2.4.2 Natural dynamics of erosion in wetlands	12
2.4.3 Wetland thresholds and vulnerability.....	13
2.5 Conclusion.....	16
CHAPTER 3 – STUDY AREA	17
3.1 Location and topography of the region	17
3.2 Socio-economic characteristics of the region.....	20
3.3 Tierkloof Wetland	20
3.3.1 Geology	21

3.3.2	Climate and water quality.....	22
3.3.3	Regional and local vegetation.....	24
3.3.4	Conservation Context	26
3.3.5	Land-use in the Tierkloof Wetland.....	26
CHAPTER 4 – METHODS		27
4.1	Desk-top analysis	27
4.2	Field Work.....	27
4.2.1	Topographic surveying	27
4.2.2	Cores to bedrock	28
4.2.3	Sediment sampling and water analysis	28
4.3	Laboratory work.....	30
4.3.1	Preparation.....	30
4.3.2	Organic matter content: Loss-on-ignition (LOI) method	30
4.3.3	Carbon dating.....	30
CHAPTER 5 - RESULTS.....		31
5.1	Description of the valley	31
5.2	Longitudinal characteristics	32
5.3	Valley cross-sectional characteristics.....	35
5.4	Gully cross-sectional characteristics	37
5.5	Stratigraphy of valley fill sediments	39
5.6	Peat age and rate of peat formation.....	45
5.7	Depth to bedrock across the valley	45
5.8	Land use and land cover change	46
5.8.1	Development of roads, drains, gullies and depositional features.....	46
5.8.2	Changes in catchment land cover and land use over time.....	50

5.8.3	Changes in wetland land cover and land use over time	52
CHAPTER 6 - DISCUSSION		56
6.1	Characteristics of wetlands.....	56
6.2	Models of wetland formation in South Africa	58
6.3	Insights from carbon-dating of Tierkloof Wetland peat deposits	59
6.4	A conceptual model of the natural origin and evolution of the Tierkloof Wetland ..	60
6.5	The role of anthropogenic factors	62
CHAPTER 7 – FUTURE RESEARCH.....		64
REFERENCES		66

LIST OF FIGURES

<i>Figure 2-1: Schematic diagram of a graded stream (solid line) relative to sea level, and a stepped river longitudinal profile (dashed line) achieved through the presence of a resistant lithology acting as a local base-level.....</i>	<i>6</i>
<i>Figure 2-2: The relationship between slope and wetland area for valley bottom wetlands in South Africa, showing those that are incised and non-incised, and the threshold line (Ellery et al. 2009).</i>	<i>14</i>
<i>Figure 2-3: Diagram showing the cycles of erosion and deposition in the Manalana Wetland (Kotze et al. 2009[b])......</i>	<i>16</i>
<i>Figure 3-1: Map showing the location of Riversdale regionally, and the location of the Tierkloof in relation to Riversdale.</i>	<i>17</i>
<i>Figure 3-2: Contour map of the Tierkloof catchment, showing the catchment boundary and the extent of the wetland.</i>	<i>19</i>
<i>Figure 3-3: Photograph showing the erosion down to bedrock that has occurred in the Tierkloof Wetland.....</i>	<i>21</i>
<i>Figure 3-4: Map showing the geology of the Tierkloof tributary catchment and wetland.....</i>	<i>22</i>
<i>Figure 3-5: Flow on the Goukou River as determined at the gauging station H9H005 to the east of Riversdale. Data provided by the Department of Water Affairs.</i>	<i>23</i>
<i>Figure 3-6: Map showing the vegetation types in the Tierkloof Wetland catchment (Mucina and Rutherford 2008).....</i>	<i>25</i>
<i>Figure 3-7: Photographs of the infestation of Acacia mearnsii in the Tierkloof Wetland.</i>	<i>25</i>
<i>Figure 4-1: Locations of surveyed cross sections and valley cross sections in the Tierkloof Wetland.</i>	<i>29</i>
<i>Figure 5-1: The Tierkloof Wetland and its catchment which drains into the Goukou River... </i>	<i>31</i>
<i>Figure 5-2: The longitudinal profiles of the gully bed and bank, also showing tributaries and areas of contact with valley side</i>	<i>34</i>

<i>Figure 5-3: Changes in valley form from the head of the Tierkloof Wetland to the toe. Cross-sections are displayed looking downstream and locations illustrated in Figure 4-1.</i>	<i>36</i>
<i>Figure 5-4: Changes in valley floor width with distance downstream in the Tierkloof (taken from valley cross sections; figure 5-3).</i>	<i>37</i>
<i>Figure 5-5: Gully cross-sections looking downstream</i>	<i>38</i>
<i>Figure 5-6: The relationship between gully width and distance downstream from the head of the wetland.</i>	<i>39</i>
<i>Figure 5-7: The relationship between gully depth and distance downstream from the head of the wetland</i>	<i>39</i>
<i>Figure 5-8: Left bank cores (T1 LB; T2 LB; T3 LB; T4 LB) along the wetland and the organic matter percentage of material in the cores</i>	<i>41</i>
<i>Figure 5-9: Cores (T5 RB; T6 LB; T7 RB; T8 LB) along the wetland and the organic matter percentage of material in the cores.</i>	<i>42</i>
<i>Figure 5-10: Cores (T9 LB; T10 LB; T11 LB; T11 RB) along the wetland and the organic matter percentage of material in the cores</i>	<i>43</i>
<i>Figure 5-11: Cores (T12 LB; T14 RB; T15 LB) along the wetland and the organic matter percentage of material in the cores</i>	<i>44</i>
<i>Figure 5-12: Age of peat samples taken from the left gully bank of T4 at two depths in the Tierkloof wetland</i>	<i>45</i>
<i>Figure 5-13: Graph showing the three bedrock profiles that were conducted. The brown line indicates the depth to bedrock, while the green line depicts the surveyed land surface</i>	<i>46</i>
<i>Figure 5-14: Map showing drains, gullies and depositional features within the Tierkloof Wetland for 1942, 1967, 1991, 2006 and 2010.</i>	<i>49</i>
<i>Figure 5-15: Land cover and land use in the Tierkloof catchment for years 1942, 1967, 1991, 2006 and 2010.</i>	<i>51</i>

<i>Figure 5-16: Changes in land use and land cover in the Tierkloof Wetland catchment between 1942 and 2010</i>	<i>52</i>
<i>Figure 5-17: Land cover and land use in the wetland in 1942, 1967, 1991, 2006 and 2010..</i>	<i>54</i>
<i>Figure 5-18: Changes in land use and land cover in the Tierkloof Wetland between 1942 and 2010.....</i>	<i>55</i>
<i>Figure 6-1: The vulnerability of the Tierkloof Wetland to incision based on the relationship between longitudinal slope and area (Modified from Macfarlane et al. 2007).</i>	<i>57</i>
<i>Figure 6-2: Graph showing the climate variability as revealed from the DOME-C ice core (EPICA 2004).</i>	<i>61</i>

ACKNOWLEDGEMENTS

This project would not have been possible without the invaluable supervision of Prof. Fred Ellery. I am also extremely grateful to the many colleagues who assisted me during field work. In addition, the continued support of loving friends and family (particularly from Colin Fordham) has helped me when times were challenging.

CHAPTER 1 - INTRODUCTION

Society is increasingly realising the importance of wetlands and better understanding their beneficial contribution to human well-being. The functions performed by these ecosystems are invaluable to the management of both water quantity and quality, and of the catchments in which they are situated (Grenfell *et al.* 2005). Despite these realisations, wetlands are still under great threat around the world. As signatories to the international RAMSAR Convention, South Africa is obliged to manage wetlands wisely, yet more than half the wetlands in our country have already been damaged or destroyed (Kotze and Breen 1994).

It is mainly human activities that cause degradation in South African wetlands through inappropriate land-use (Sinchembe and Ellery 2010). Artificial drainage structures such as ditches and furrows increase and concentrate flows within wetlands and cause drying out and erosion. This was found by Grenfell *et al.* (2009) in the Hlatikulu Wetland. Roads are also linked to artificial drainage structures and have the same effect. Inter basin transfers into a catchment, such as in the Klip River studied by McCarthy *et al.* (2007), increase flows and lead to increased capacity to transport sediment, which results in erosion. Overgrazing in wetlands reduces vegetation cover and increases erosion risk, as found by Kotze and Breen (1994). Alien invasive plants outcompete natural wetland vegetation and reduce fine root biomass that holds soils in place, according to Sieben (2011), leading to erosion. Neal (1998) shows that urbanisation increases runoff and discharge of peak flows, also leading to erosion. Although sometimes the effects of these impacts may seem minor, and go unnoticed, they can have drastic individual and cumulative impacts.

Our current understanding as to why wetlands degrade mostly focuses around human impacts, but caution needs to be applied in linking erosion to simple causes because it is a complex process and there are many contributing factors (Sinchembe and Ellery 2010). Since erosion is also part of the natural dynamic in many wetlands, it is important to also take these natural factors into consideration as well. However, these dynamics can easily be affected by human activities, which can accelerate the processes of degradation (Tooth *et al.* 2009).

The Tierkloof Wetland in the Western Cape has been damaged through erosion down to bedrock and has gully walls up to 7 m high and the gully itself up to 50 m wide. The purpose of this study was to investigate the origin and evolution of Tierkloof Wetland and consider the role both natural and human-induced processes have played in its degradation.

The objectives of the study were to:

- Understand the geomorphic setting in which the Tierkloof Wetland has formed by examining variation in wetland topography and stratigraphy longitudinally and in cross-section.
- Determine the climatic and discharge history of the Tierkloof Wetland area over the period of the available historical record.
- Investigate recent changes in land cover characteristics in the wetland and its catchment as seen in historical and current aerial photography.
- Develop a conceptual model of the origin and dynamics of the Tierkloof Wetland based on the above information.

CHAPTER 2 - THEORETICAL FRAMEWORK

2.1 Wetland formation

2.1.1 Hydrology, erosion and deposition

Hydrology is the defining characteristic of wetlands (Mitsch and Gosselink 2000). In order for a wetland to form, a surplus water supply for a sufficient period of time is essential for shallow flooding of soils. Prolonged flooding leads to anaerobic conditions in the soils, initiating conditions suitable for the development of wetland vegetation. Therefore, it is a positive water balance that results in wetland formation and persistence (Gosselink and Turner 1978; Ellery *et al.* 2009).

In areas where the climatic conditions do not favour a positive water balance (such as a semi-arid country like South Africa), fluvial inputs of water are generally the primary source of water for wetlands, such that factors limiting water outputs from a wetland are critical to support prolonged flooding. The geomorphic characteristics of the landscape thus work in conjunction with hydrology in the formation of wetlands, by reducing surface water losses relative to water inputs (Mitsch and Gosselink 2000). The understanding of the existence, characteristics and maintenance of wetlands is therefore underpinned by interactions between hydrological and landscape processes (Grundling *et al.* 2013 [a]).

A fluvial system can be conceptualised by dividing the watershed into 3 longitudinal zones that relate to the contributions of different processes to stream form and function. A generalised system comprises a drainage basin with eroding headwaters, downstream of which is a sediment transport zone, while the lower reaches tend to be dominated by depositional processes (Schumm 1977). The eroding headwaters are characterised by high flow velocities and steep slopes, although discharges are typically low. The fluvial process dominating this reach is erosion. Velocity and gradient decreases downstream such that the middle reaches are characterised by sediment transfer. Although the lower reaches are

characterised by a low discharge they have a shallow gradient and low velocity, resulting in deposition (Ellery *et al.* 2009).

Rivers alter their slope and channel morphology to accommodate available discharge and transfer sediment (Knighton 1998). This is achieved through erosion, which reduces slope, or through deposition, which increases slope (Ellery *et al.* 2009). Wetland dynamics are often a result of erosional and depositional processes and in their natural state are generally regarded as sediment sinks (areas of deposition), due to net accumulation of sediment (Kotze *et al.* 2009[a]). Sedimentation results in aggradation, which means an increase in elevation over time (Ellery *et al.* 2009).

2.1.2 Longitudinal characteristics of rivers: the concept of a graded longitudinal profile

Rivers transport available sediment while using the least amount of energy possible (Schumm 1977). Thus, rivers strive to maintain an equilibrium slope for the available discharge and sediment supply through balancing transport capacity (related largely to discharge), with available sediment supply. Rivers work to achieve a longitudinal profile that is uniformly concave upwards from steep headwaters where discharge is low, to the gently sloping lower reaches where discharge is high (Figure 2-1) (Knighton 1984). In order to achieve a logarithmic longitudinal profile, rivers act by either eroding their beds where the slope is too steep, or depositing material where the slope is too gentle, for the available discharge and sediment supply. The extent to which a river achieves the desired logarithmic longitudinal profile is an indicator of the stage of river geomorphological evolution.

When, over time, slope is adjusted such that velocity and discharge are able to effectively transport the available sediment load, the system is referred to as a 'graded' river (Knighton 1984). This means that along the entire length of the river the sediment load entering any given reach is equal to the sediment leaving the reach, and thus the river effectively transports its load along its entire length. However, watercourses are dynamic in time and space and the external variables that shape rivers (such as width, depth, bed roughness, velocity, slope,

discharge, size and amount of sediment) constantly vary, causing behavioural changes such as erosion and deposition. This means that rivers seldom achieve stability.

2.1.3 The depth to which a river can erode its bed: the concept of the base level

The lowest point to which erosion of a river bed can occur, is known as its base level (Schumm 1977). For example, a river flowing into the sea can never erode its bed at any point along its course to an elevation lower than sea level (assuming a constant sea level over long periods of time). This is simply because as erosion takes place to lower the slope of the bed of the river, the slope of the river reaches a point where velocity is so low that no further erosion is possible. The ultimate base level for all rivers that flow into the sea is sea level (Leopold and Bull 1979).

However, local base levels can be found at higher elevations on the longitudinal profile of the drainage line. These are local areas along a river where the rate of erosion is severely limited (Knighton 1998), including resistant lithologies such as highly metamorphosed quartzite (Sinchembe and Ellery 2010) or dolerite dykes (Tooth *et al.* 2002; 2004). Upstream of such local base levels, rivers work to grade their longitudinal profiles, but immediately downstream of such local base levels slope typically steepens to exceed the appropriate slope for the system, creating a high degree of instability that persists because of the resistant lithology. Examples of features acting as local base levels are significant impoundments, resistant lithologies, and aggrading trunk river beds for tributary streams (Schumm 2005). Local base levels can produce a ‘stepped’ longitudinal profile (Grenfell *et al.* 2010), shown by the dotted line in Figure 2-1.

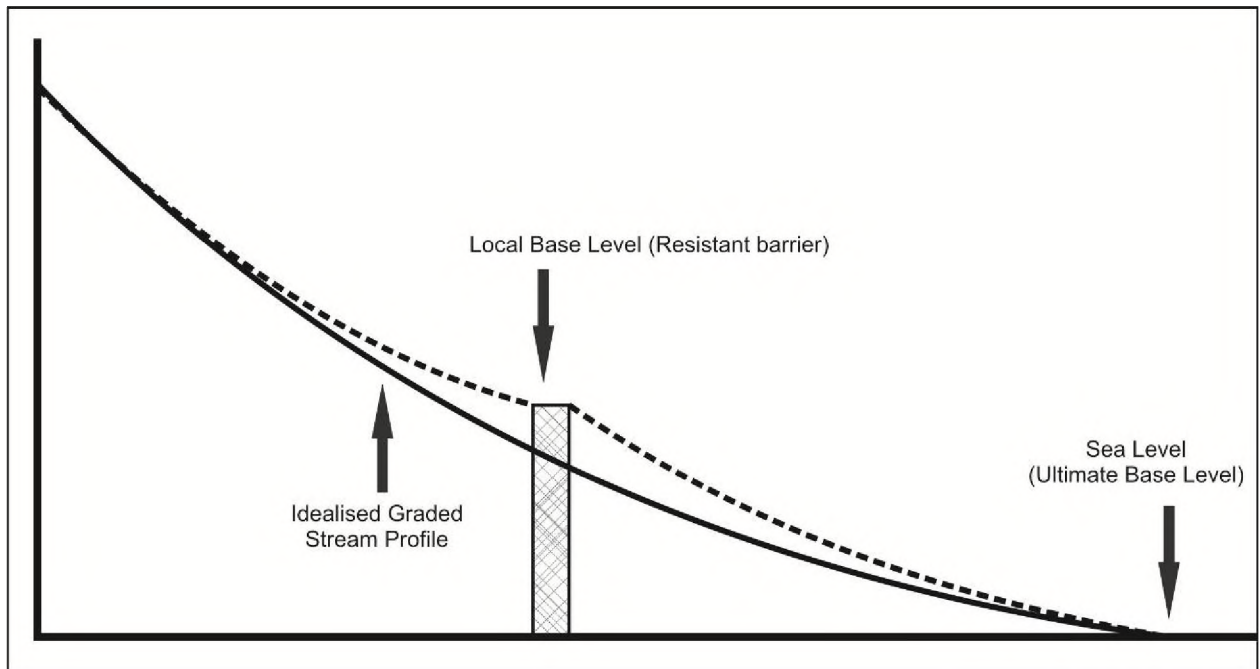


Figure 2-1: Schematic diagram of a graded stream (solid line) relative to sea level, and a stepped river longitudinal profile (dashed line) achieved through the presence of a resistant lithology acting as a local base-level.

2.2 Current concepts of wetland origin in South Africa:

Critical to understanding wetland origin is an analysis of factors that limit the amount of surface water loss from an area (Ellery *et al.* 2009). Most moderate to large wetlands in South Africa are maintained by river inflows that combine with other factors that serve to impede drainage or reduce infiltration, including faulting, erosion-resistant rock outcrops and ponding by tributary or aeolian sediments (Grenfell *et al.* 2009; Tooth and McCarthy 2007). Therefore, the most influential controls on the origin of wetlands linked to the drainage network include the formation and persistence of a local base level (Grenfell *et al.* 2009). These geological and geomorphological controls on the dispersal of water and sediment are central to understanding wetland origin (Grenfell *et al.* 2009).

Current case studies of wetland origin in southern Africa associated with local base level controls are:

- Presence of a resistant lithology that limits the rate of vertical incision in an upstream direction.

- Tributary impoundment by trunk stream, which lowers the longitudinal slope of the tributary valley upstream of its confluence with the trunk stream.
- Trunk stream impoundment by tributary such that the longitudinal slope of the trunk stream upstream of the tributary is progressively reduced over time.
- Faulted basins that are a consequence of sagging of the Earth's crust because of rifting, such as the Okavango Delta in Botswana.
- Sagging associated with deep weathering.

2.2.1 Resistant lithologies

Resistant lithologies are geological features that influence patterns of erosion in an upstream direction. Resistant lithologies form local base levels for the river in an upstream direction, so that vertical erosion of the softer lithologies upstream is limited by the rate of vertical erosion of the downstream resistant lithology. Excess energy in the river upstream of the resistant lithology, that cannot be used to cut the bed vertically, therefore planes the valley laterally, such that the widened valley hosts floodplain wetlands (Tooth *et al.* 2002; 2004). This model of wetland origin has been found to apply to the Klip River on the South African Highveld (Tooth *et al.* 2002), and the Nsonge, Kamberg, Mooi, and Blood River wetlands in KwaZulu-Natal (Grenfell 2007, 2014; Tooth and McCarthy, 2007; Tooth *et al.* 2014), and the eMthonjeni wetland in the Eastern Cape (Sinchembe and Ellery 2010).

2.2.2 Trunk-tributary relationships

The geomorphic relationship between trunk rivers and tributary streams is influenced by their relative rates of sedimentation (Grenfell *et al.* 2010). The interaction between the trunk and tributary rivers at their confluence can result in accommodation space for wetland development on either the trunk river or the tributary river. On one end of the continuum, a tributary with a large sediment supply may lower the longitudinal slope of the trunk river, thereby promoting prolonged flooding along the trunk (Joubert and Ellery 2013; Grenfell *et al.* 2010). In this case the tributary acts as a base level for the trunk river, and accommodation space for wetland development is created on the trunk river.

Trunk river impoundment by a tributary can occur through alluvial fans and coarse sediments introduced by tributary streams onto trunk rivers. The tributaries introduce large deposits of sediment due to steep, well-connected catchments (Grenfell *et al.* 2010). The tributary sediments expand across the floodplain of the trunk river, forming barriers that impound the flow of the trunk river and reduce gradient in an upstream direction (Grenfell *et al.* 2009). Thus the laterally imposing streams modify the behaviour of the trunk river with the result of prolonged flooding conditions suitable for peat formation. Wetlands have originated through this process on the Blood River in KwaZulu-Natal (Tooth and McCarthy 2007); Wakkerstrom Vlei (Joubert and Ellery 2013); and the floodplain of the Nyl River (Tooth *et al.* 2002; McCarthy *et al.* 2011), both of which are in Mpumalanga Province.

On the other end of the continuum, sedimentation along the trunk river acts as a local base level for a tributary stream, thereby disconnecting the tributary from the drainage system (Brierley and Fryirs 1997; 1999). The trunk river dominates the relationship and causes the formation of valley bottom wetlands along the tributary upstream of the impoundment.

Whilst studying the evolution the Futululu Wetland in northern KwaZulu-Natal, Grenfell *et al.* (2010) described a tributary-by-trunk impoundment. The Futululu tributary stream yields limited clastic sediment compared to rates of sedimentation on the trunk Mfolozi River floodplain. The Futululu is thus impounded by sediment deposition on the trunk stream, which disconnects it from the drainage network. The Mfolozi floodplain raises the local base level of the Futululu stream through aggradation, lowering the tributary gradient, and providing a setting for peat formation on the Futululu stream (Grenfell *et al.* 2010).

Tributary-by-trunk impoundment is also observed in the Hlatikulu Vlei and Stillrust Vlei in KwaZulu-Natal (Grenfell *et al.* 2008) as the systems are dominated by the trunk river floodplain. Sediment deposition along the trunk streams forms alluvial ridges, raising the local base levels of the tributary stream, which impound the tributary streams. Once again, such blockage of a tributary by a trunk stream may be associated with peat formation along the tributary stream. These examples show that from a geomorphological perspective, these wetlands have depositional origins and dynamics.

In the Mdlanzi Wetland that forms a tributary of the Mkuze Floodplain, a setting favourable to peat formation was created through aggradation on the Mkuze floodplain in KwaZulu-

Natal (Ellery *et al.* 2012). The rate of sedimentation on the trunk river controls the dynamics of sedimentation on the tributary. Due to the Mkuze aggrading, and blocking the tributary, the gradient on the tributary Mdlanzi stream was lowered, creating accommodation space such that organic sedimentation occurred.

2.2.3 Faulted Basins

Haddon and McCarthy (2005) describe how the extensive wetlands in the Okavango originated due to faulted basins. The extension of the East African Rift System into southern Africa caused continental fault systems and associated large scale subsidence, which counteracted the effects of uplift, and formed gentle basins. Sediment in the form of alluvial fans was deposited in these basins, due to loss of confinement as the stream enters the rifted basin, and created a setting favourable for the formation of the current large wetland system.

2.2.4 Sagging

Sagging is a result of deep weathering and mass loss of volcanic rocks, which lead to the creation of accommodation space and therefore wetland formation. Case studies in South Africa have identified this process in Dartmoor Vlei (Edwards 2009; 2016) and a depression wetland near Grahamstown (Alistoun 2013). In Dartmoor Vlei, sagging amounted to volume loss of close to 3 %, leading to a depth loss of approximately 8 %. Given that weathering took place to a depth of almost 10 m, the wetland surface had sagged by about 0.8 m, which roughly matched the depth of the peat deposit in Dartmoor Vlei (Edwards 2009).

2.2.5 Ecosystem Engineers

A concept lacking investigation is the role of ecosystem engineers in wetland development. The process of certain organisms generating and transforming ecosystems has been well recognised. For example, Darwin knew in 1842 that atolls were formed by coral colonies (Pearce 2011). Similarly, Lewontin stated that “organisms do not experience environments passively; they create and define the environment in which they live” (1978, p. 215). However, the concept of ecosystem engineers was only defined more recently by Jones *et al.*

as “organisms that directly or indirectly modulate the availability of resources (other than themselves) to other species, by causing physical state changes in biotic or abiotic materials. In so doing they modify, maintain and/or create habitats” (1994, p. 374).

Ecosystem engineers were grouped into two categories by Jones *et al.* (1994; 1997); autogenic and allogenic engineers, based upon the two basic ways they bring about state changes. Autogenic engineers cause state changes in the environment through their own physical structures (such as tree growth and development). Allogenic engineers alter the environment by converting living or non-living materials from one physical state to another, such as beavers constructing a beaver dam (Jones *et al.* 1994; 1997).

Ecosystem engineers that change hydrology, soil and sediments are inclined to have large ecosystem level-effects. These impacts alter the way that resources are used by many other species, and they therefore affect the distribution and abundance of many other species (Jones *et al.* 1994; 1997).

In South Africa, a plant called *Prionium serratum* (L.F.) Drège ex E.Mey. (palmiet) is thought to act as an ecosystem engineer (Sieben 2012; Job 2013), but neither author provided evidence to support this claim. It is suggested that palmiet may modify the environment to control fluvial form and dynamics in the valley, thus possessing the traits of an ecosystem engineer as described by Jones *et al.* (1994; 1997). Palmiet is a sedge-like plant with a woody stem (Sieben 2012). The deep and robust roots, in association with a clonal growth form, secure the plant during large flood events and possibly limit erosion in erosional events and aid in changing its environment to suit its own needs. Palmiet has been observed to act as a ‘plug’ in rivers through binding soil, limiting erosion and ultimately changing the hydrology (Sieben 2012). The resulting conditions lead to prolonged flooding and consequent peat formation (Sieben 2012).

2.3 Peat Formation

In wetlands, the rate of organic production exceeds that of decomposition such that organic matter is typically exported or buried in association with clastic sediment. However, in very low energy hydrodynamic situations, excess organic matter may accumulate as peat (Bragg 2002). The vegetation of peat-forming wetlands is characterised by plants which require wet conditions (hydrophytes); whilst complete decomposition of their dead remains (peat) is prevented because they remain saturated with water throughout the year. Therefore, a situation of prolonged flooding is necessary for peat formation (Bragg 2002). It is often an elevated base level that promotes this prolonged flooding environment as it reduces longitudinal slope in an upstream direction, which leads to ponding. Therefore, peat wetlands often have geomorphological reasons for their formation (Edwards, 2009; Grenfell *et al.* 2010; Ellery *et al.* 2012; Joubert and Ellery 2013, Edwards *et al.* 2016).

Together with permanent saturation, organic sediment tends to accumulate in low energy environments where clastic sediment supply is low or absent and where accommodation space exists for deposition to occur (Ellery *et al.* 2004). Peat is defined as an organic soil which consists of at least 30 % organic matter. When peat that meets this definition has a depth of at least 300 mm it is referred to as a peatland (Joosten and Clark, 2002).

In southern Africa, peat has formed over long periods (hundreds to thousands of years) and has been destroyed over relatively short time periods. This can occur due to regional droughts and channel abandonment (that lead to a lowering of the water table), which results in the peat drying such that it may burn (Ellery *et al.* 2009; McCarthy 2006). Therefore, many peat deposits have layers of ash interspersed in the profile (Tooth and McCarthy 2007). Peat fires may therefore constitute an important part of the natural dynamic of peatland systems.

2.4 Causes of degradation in wetlands

2.4.1 Human impacts

Up until the 1980s, agricultural policy in South Africa encouraged draining and cultivation of wetlands (Nel and Driver 2012). Darwall *et al.* (2009) found that water abstraction for agriculture constituted about 70 % of the total water consumption from rivers and ground water. Agriculture often uses more water abstracted from groundwater reserves than water inputs can replenish, which causes the water table to drop, and initiates wetland desiccation (Darwall *et al.* 2009).

Human impacts along drainage lines that change the flow pattern of a wetland can cause erosion. The construction of impoundments, such as dams, creates sediment traps that have a drastic, direct impact on wetlands. Sediment is deposited in impoundments, resulting in downstream erosion due to the out-flowing water having a higher sediment transport capacity than load (Ellery *et al.* 2009). Inter basin transfers into a catchment, such as in the Klip River studied by McCarthy *et al.* (2007), increase flows and lead to increased capacity to transport sediment, which result in erosion.

Artificial drainage structures such as ditches and furrows increase and concentrate flows locally within wetlands. This results in less water storage capacity and a lowering of the water table, which leads to drying out and erosion (Ellery *et al.* 2009). This was found by Grenfell *et al.* (2009) in the Hlatikulu Wetland. Roads are also linked to artificial drainage structures and have the same effect on erosion and flow pattern.

The replacement of natural vegetation in wetlands has a high impact on water storage functions. Overgrazing in wetlands reduces vegetation cover and increases erosion risk, as found by Kotze and Breen (1994). Alien invasive plants outcompete natural wetland vegetation and reduce fine root biomass that holds soils in place (Sieben 2011), leading to erosion. Urbanisation increases runoff and elevates peak flows, which leads to erosion, as shown by Neal (1998). Although, sometimes the effects of these impacts may seem minor, and go unnoticed, they can have drastic individual and cumulative impacts on wetlands (Darwall *et al.* 2009).

2.4.2 Natural dynamics of erosion in wetlands

Our current understanding as to why wetlands degrade mostly focuses on human impacts, but caution needs to be applied in linking erosion to simple causes, because it is a complex process and there are many factors that may contribute to it (Sinchembe and Ellery 2010). It is important to consider what natural factors might initiate erosion, as it may be part of the natural dynamic in many wetlands and may occur without human impacts.

Research relating to natural influences contributing to gully erosion has investigated factors such as climate (Dotterweich 2008) and intrinsic controls (geomorphic slope threshold; Schumm 1979). More recently, Grenfell *et al.* (2012), whilst investigating episodic gullying due to floodouts in the semi-arid Karoo, suggested that the palaeo-floodouts within the gullies indicate that the process of erosion is a long-term landscape process and not limited to recent land degradation. However, these dynamics can be easily affected by human activities, which can accelerate processes of degradation (Tooth *et al.* 2009). Therefore, it is often difficult to identify a single cause as multiple intertwining factors, with varying levels of influence, may be responsible (Grenfell *et al.* 2012).

2.4.3 Wetland thresholds and vulnerability

When studying the dynamics of degradation in wetlands, concepts of wetland thresholds and vulnerability must be understood. In South Africa, wetlands have longitudinal slopes that are broadly related to their size, as generally, small wetlands are steep while large wetlands are more gently sloped (Figure 2-2; Ellery *et al.* 2009). Wetland size in this scenario is used as a proxy for discharge as large wetlands generally have a larger catchment and discharge than small ones. Considering this relationship, it has been found that valley bottom wetlands that have a high slope for their size are more susceptible to erosion than those with a low slope for their size.

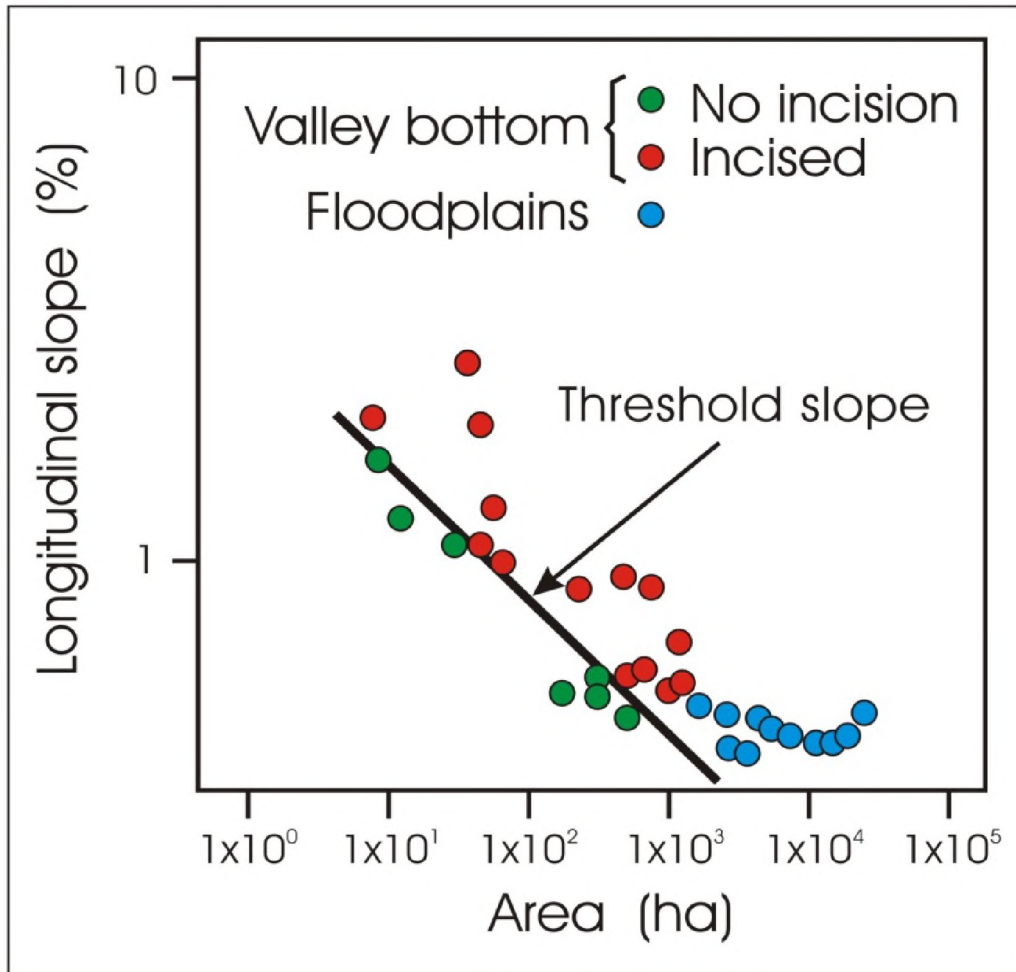


Figure 2-2: The relationship between slope and wetland area for valley bottom wetlands in South Africa, showing those that are incised and non-incised, and the threshold line (Ellery *et al.* 2009).

2.4.3.1 Cycles of erosion and deposition

In the Manalana Wetland in Mpumalanga Province, it was the popular perception that the extensive gully erosion through much of the wetland was a result of changes in catchment land-use, especially the construction of roads (Pollard *et al.* 2009). However, depth analysis of the wetland indicated that the gullies were present before any infrastructure was developed and that, in fact, the wetland showed a long history of erosion (Ngetar 2013). In this case, erosion and deposition cycles were part of the geomorphic evolution of the wetland (Ngetar 2013; Kotze *et al.* 2009 [b]).

Furthermore, it has been observed that these cycles of erosion and deposition could be strongly related to long term climatic cycles (Ellery *et al.* 2009). It is thought that erosional cycles occur in valley bottom settings during warm, wet phases of southern Africa's climatic history; whereas depositional cycles occur during dry periods. This is explained by examining the relationship between rainfall, water supply and vegetation cover in the catchment: in warm, wet phases there is more vegetation cover in the catchments which binds soils and lessens sediment yield from the hillslopes to the watercourses. Given the abundant runoff but lower sediment yield from the hillslopes, water reaching the valley floor has a high capacity to transport sediment, which leads to erosion of the valley bottom. However, in dryer phases, vegetation cover on hillslopes in the catchment is reduced. Despite lower rainfall and runoff, more sediment enters the streams but their capacity to transport sediment is reduced due to lower flows, leading to deposition. Currently southern Africa is in a wet phase of its climatic history, and wetlands are therefore likely to be naturally prone to erosion due to the presence of high discharges and low sediment yields from their catchments (Ellery *et al.* 2009).

Figure 2-3 shows the 3 cycles of cutting and 2 cycles of filling in the Manalana Wetland in Mpumalanga Province. The valley was initially carved to bedrock (“1. *Initial erosion surface*”), and then infilling of the valley occurred due to surplus sediment production in the catchment that could not be removed (“2. *First deposition phase partly filled valley*”). Erosion occurred a second time and carved out a portion of the sedimentary fill in the valley (“3. *Erosion surface from second cycle of erosion*”), which was followed by a second cycle of deposition that partially filled the eroded secondary fill from the previous cycle of erosion (“4. *Second depositional phase partly filled valley*”). The current cycle of erosion has removed a portion of this sedimentary fill (“5. *Erosion surface from present cycle of erosion*”), giving rise to the current morphology of the wetland.

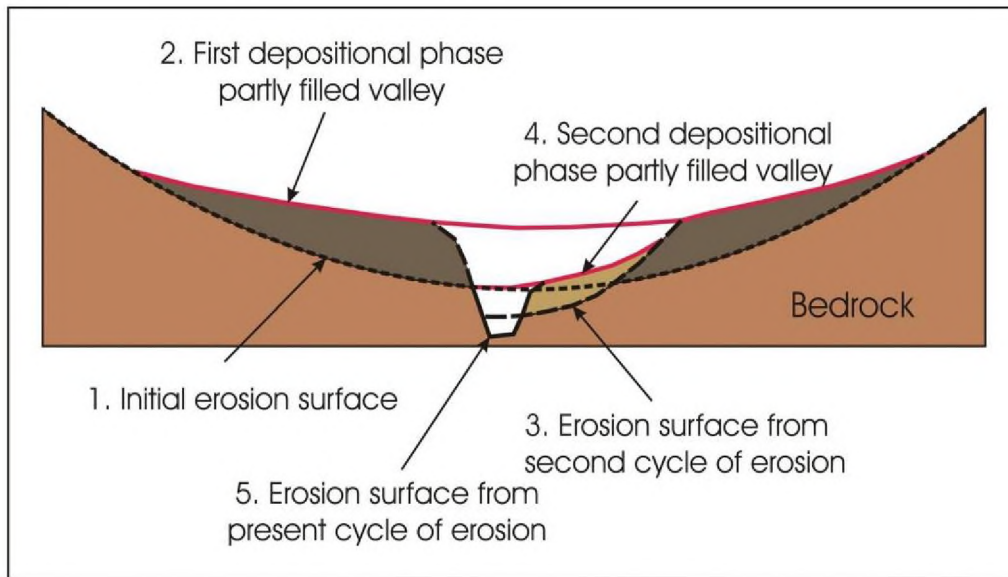


Figure 2-3: Diagram showing the cycles of erosion and deposition in the Manalana Wetland (Kotze *et al.* 2009[b]).

2.5 Conclusion

Wetlands are the most threatened of all South Africa's ecosystems (Nel and Driver 2012). It is mainly human activities that cause degradation in South African wetlands through inappropriate land-use. Yet it is important to consider what natural factors might initiate erosion, as it is part of the natural dynamic in many wetlands and may occur without human impacts (Grenfell *et al.* 2012). Ellery *et al.* (2009) found that wetlands that have a high slope for their size are more susceptible to erosion than those with a low slope for their size. When viewed in the context of inherent wetland vulnerability to erosion and climate change much of the erosion found in South Africa is due to natural processes rather than human disturbances (Ellery *et al.* 2009). The crossing of a threshold from aggradational characteristics to degradational characteristics in a wetland can be accelerated by human activities (Tooth *et al.* 2009). The Tierkloof Wetland, in the Western Cape, has eroded to bedrock and therefore offers an opportunity to investigate both natural processes and human activities that may lead to erosion.

CHAPTER 3 – STUDY AREA

3.1 Location and topography of the region

The 67 km long Goukou River originates on the southern slopes of the Langeberg Mountains and enters the sea at the coastal town of Stilbaai, Western Cape, South Africa. The Goukou Wetland (including tributaries) is situated north and east of the town of Riversdale in the Western Cape (Figure 3-1) and has peat deposits up to 10 m thick (Job 2014). The rivers in the area, such as the Goukou River, have been modified through reclamation for agricultural use, and through flow regulation to improve water security for farming activities (Maree and Vromans, 2010).

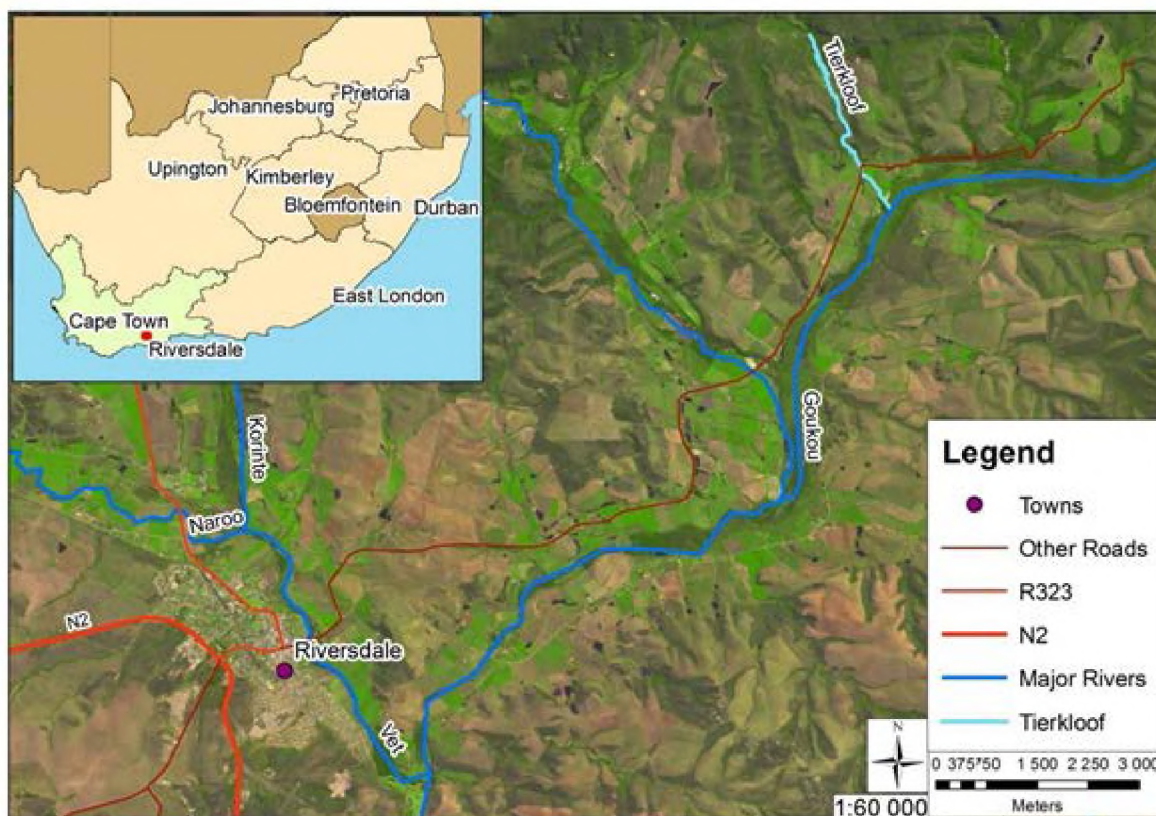


Figure 3-1: Map showing the location of Riversdale regionally, and the location of the Tierkloof in relation to Riversdale.

The Langeberg is a steep mountain range that gives way in the south to gently rolling topography. The steep mountain range is associated with orographic rainfall, often associated with heavy downpours and flooding. The wetlands originate immediately at the southern base of the steep mountain range and are distributed from the Vet River in the west, to the Goukou River in the east of the Goukou catchment (Figure 3-1). The Tierkloof River is a tributary of the Goukou River and is associated with a wetland that occupies a relatively gently sloping valley to the south of the Langeberg Mountain range (Figure 3-2).

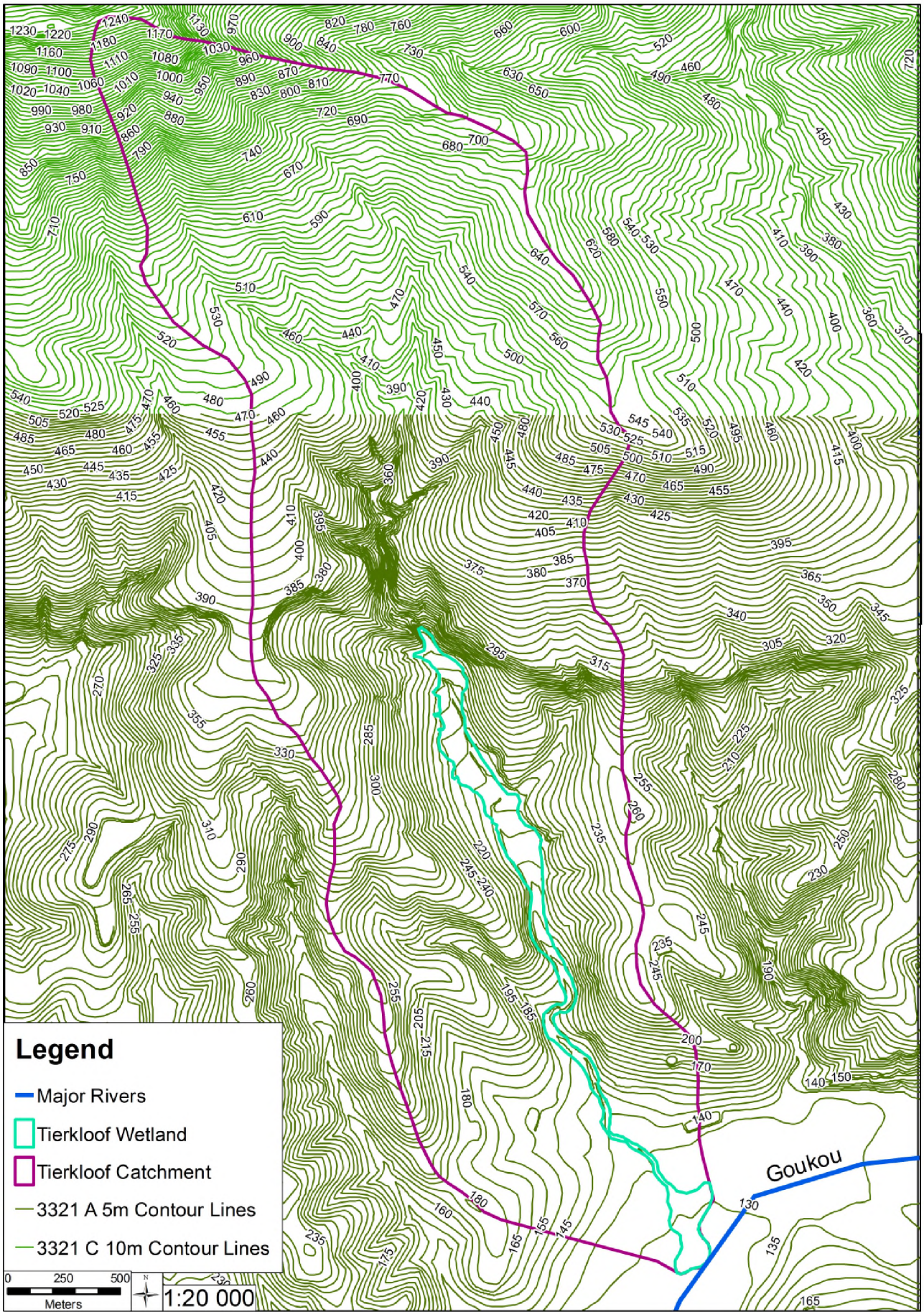


Figure 3-2: Contour map of the Tierkloof catchment, showing the catchment boundary and the extent of the wetland.

3.2 Socio-economic characteristics of the region

Riversdale is a town located on the National Road (N2) 300 km east of Cape Town and 133 km west of George in the Western Cape Province of South Africa. It is the headquarters of the Hessequa Local Municipality. Prior to occupation by descendants of European settlers in the Western Cape, the area was inhabited by the nomadic Khoi people. Settlement by descendants of European settlers began in the area in 1772 due to the establishment of five cattle posts. The population increased and a church was founded on Doornkraal farm in 1837. This led to Riversdale being proclaimed a town in 1838 (Floyd 1960). Farming activity turned mostly towards sheep farming and the Agricultural Society was founded in 1858.

In the 2011 census, Riversdale (area of 100.45 km²) had a total population of 16176. The population of the Hessequa Local Municipality is 78 % urban and 22 % rural. Agricultural households mostly engage in livestock production (1224 households in the Hessequa Local Municipality in 2011). The primary language is Afrikaans. The town currently caters mainly for the local farming communities through agricultural services, and it serves as a regional centre providing goods and services not available in nearby smaller towns and coastal resorts. The town has schools, churches, museums, hotels and bed and breakfast establishments.

The economy of the area is agricultural. Agriculture accounts for approximately 35 % of the land-cover of the Goukou River catchment, which is made up of a combination of commercial dryland agriculture, commercial forestry, commercial irrigated agriculture and improved grassland (CSIR 2011). Approximately 2 % of the catchment is degraded shrubland, with just 1 % in the form of urban land cover comprising residential and industrial developments in the towns of Stilbaai and Riversdale (CSIR 2011).

3.3 Tierkloof Wetland

The Tierkloof Wetland is a right (north) bank tributary of the Goukou River (confluence at 34°01'55.55''S 21°21'26.60''E). It is an unchannelled valley bottom wetland as defined by Kotze *et al.* (2009[a]) and occupies quaternary catchment H90A. The system has incised (by

approximately 7 m in areas) down to bedrock (Figure 3-3). It has 6 unnamed tributaries that enter from both the east and the west.



Figure 3-3: Photograph showing the erosion down to bedrock that has occurred in the Tierkloof Wetland.

3.3.1 Geology

The highest point in the catchment is at an altitude of 1240 masl. in the east-west oriented Langeberg mountain range. The Langeberg Mountains are part of the Cape Fold Mountain Belt, generally comprising resistant quartzite lithologies and thin shale bands of the Table Mountain Group of the Cape Supergroup. The Table Mountain Group is subdivided into eight formations and the Tierkloof Wetland begins in the Peninsula Formation, which consists of a uniformly light-grey, medium- to coarse- grained, well-bedded quartzitic sandstone. The rocks of the Table Mountain Group make up the high-lying mountain range and have a thin soil cover, which is nutrient poor and produces acidic runoff. A network of joints and fractures control the infiltration, recharge, storage and movement of groundwater in the units of the Table Mountain Group (Meyer 1999). An abundance of springs arise in the Table Mountain Group sandstones, such as fault controlled springs and springs seeping from small

fractures and joints (Meyer 1999). A fault is located half way down the catchment, abruptly dividing the Peninsula Formation from the Bokkeveld Group (Figure 3-4).

Most of the Tierkloof Wetland occurs on rocks of the Bokkeveld Group (Figure 3-4), which comprise metamorphosed green-grey to brown shale and siltstone with thin sandstone beds that are grey to blue-black when fresh. Based on their mineralogy, rocks of the Bokkeveld Group are more susceptible to weathering and erosion than the highly resistant quartzite lithologies of the Table Mountain Group (Malan *et al.* 1994). The toe of the Tierkloof Wetland exists on Quaternary Alluvium, which is predominantly peat and clastic sediment associated with the Goukou wetland.

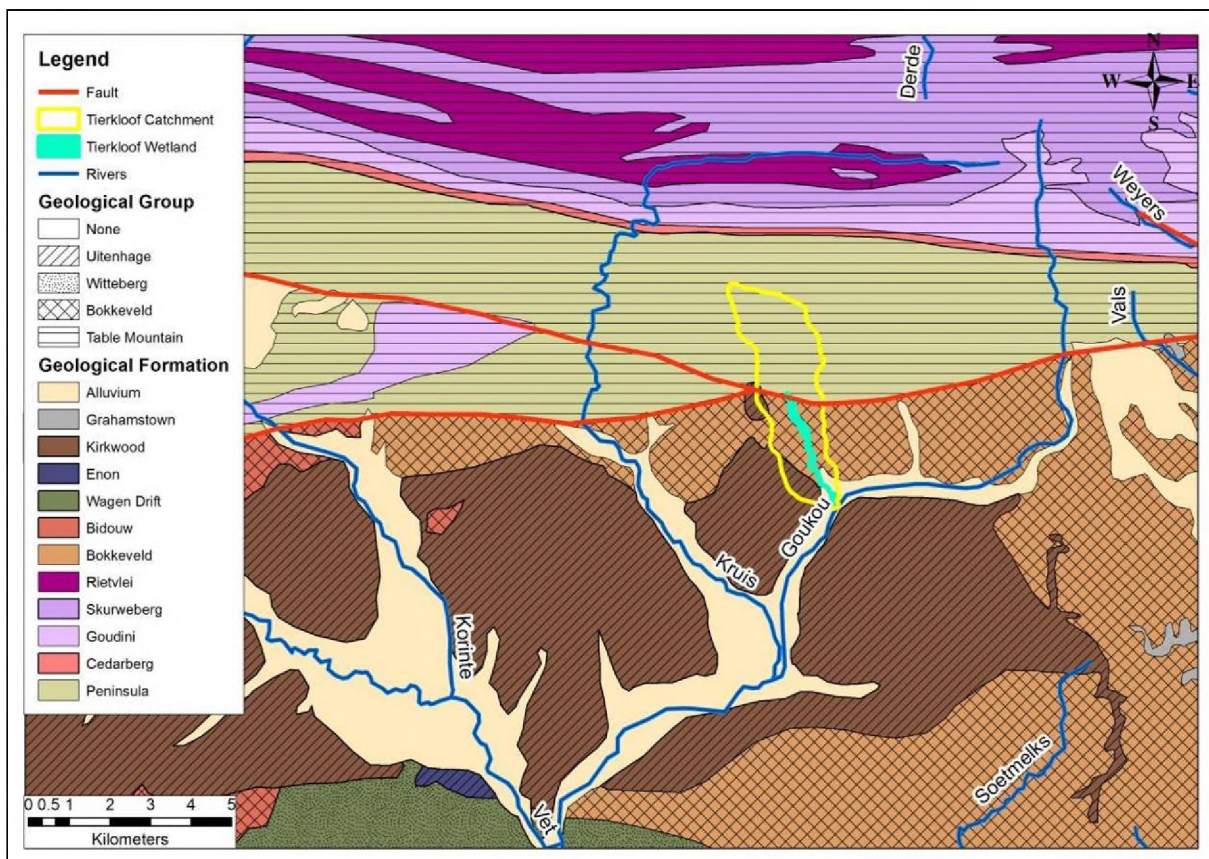


Figure 3-4: Map showing the geology of the Tierkloof tributary catchment and wetland

3.3.2 Climate and water quality

The mean annual potential evaporation (1869 mm) for the area is more than triple the mean annual precipitation (524 mm; Munica and Rutherford 2006). There is no distinct rainfall

peak, but rainfall in December and January is generally lower than in other months of the year such that summers can be described as warm and dry while winters are cool and moist. Average daily temperatures vary between 28 °C and 5.5 °C for January and July respectively. Due to the influence of the mountains, a large spatial variability in the mean annual precipitation is experienced.

The Goukou River experienced extremely variable flows over the period 1969 to 2011 (Figure 3-5), with flows as high as greater than 400 cumecs and as low as 0 cumecs. The flows suggest that the Goukou River is a stream that typically experiences fairly low flows, with occasional very high flows. Flows greater than 200 cumecs seem to be experienced once every two to three years.

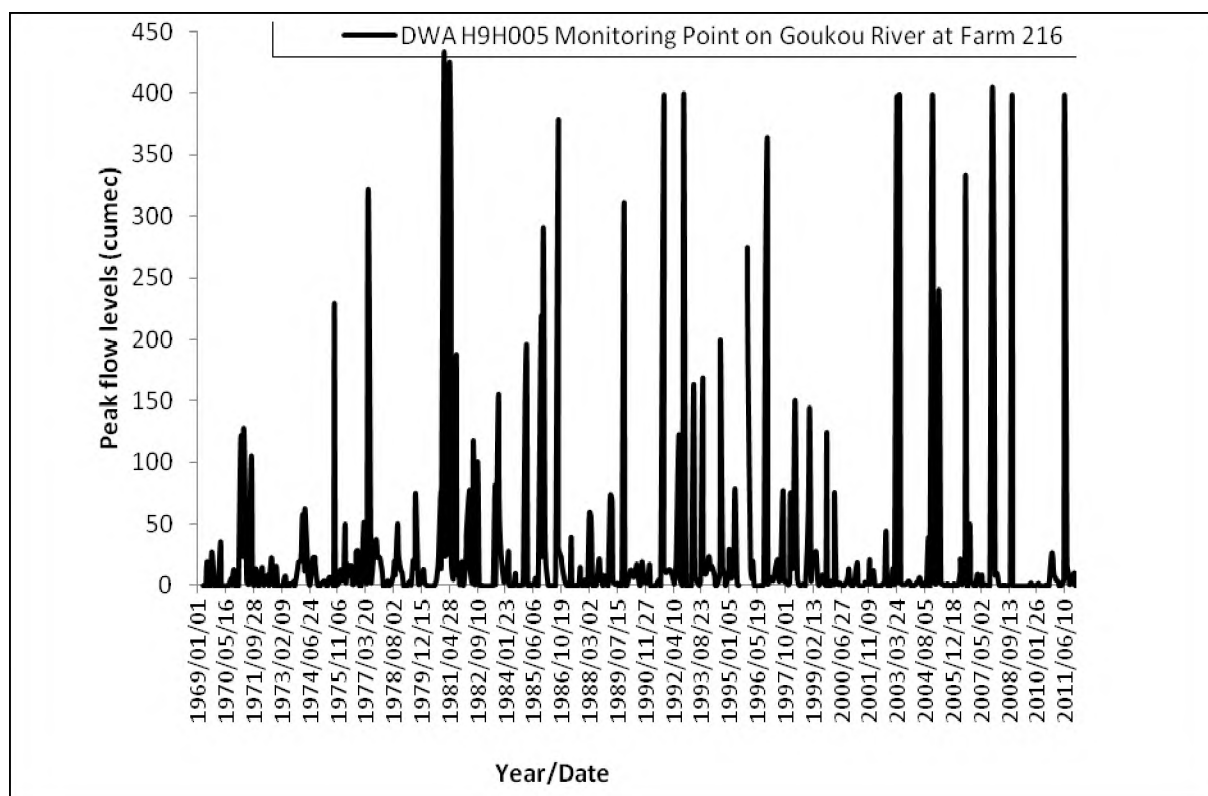


Figure 3-5: Flow on the Goukou River as determined at the gauging station H9H005 to the east of Riversdale. Data provided by the Department of Water Affairs.

The rivers in the area can be described as southern Cape acid rivers, which are brown due to humic acids and have a low pH (Davies and Day 1998). The Tierkloof has extensive peat

beds that are dominated by the peat forming plant palmiet (*Prionium serratum*), although the wetland has been damaged by the formation of massive gullies that extend most of the way down the length of the wetland (Job 2014).

3.3.3 Regional and local vegetation

Hessequa Municipality lies within the Cape Floristic Region (CFR) which is an internationally recognised biodiversity hotspot (Maree and Vromans, 2010). Within the area, the rivers are characterized by a high density of palmiet. As in many areas in South Africa, alien vegetation such as *Acacia mearnsii* De Wild., *Acacia saligna* (Labill.) H.L.Wendl., *Cirsium vulgare* (Savi) Ten. and *Solanum mauritianum* Scop. have invaded the rivers (Maree and Vromans, 2010).

According to Munica and Rutherford (2006), the Tierkloof Wetland is situated in the Southern Fynbos bioregion. As can be seen in Figure 3-6, the head of the wetland falls within the South Langeberg Sandstone Fynbos vegetation type FFs16, while a small portion at the toe of the wetland falls in the Mossel Bay Shale Renosterveldt unit FRs14. The majority of the wetland's vegetation falls in the Swellendam Silcrete Fynbos unit FFc1. South Langeberg Sandstone Fynbos has a conservation status of 'endangered' by the National Spatial Biodiversity Assessment (NSBA), as 40 % has been transformed for cultivation and commercial pine plantations, while only 4 % is formally conserved. *Acacia cyclops* A.Cunn. ex G.Don occurs in places in this vegetation type and poses a threat to its conservation.

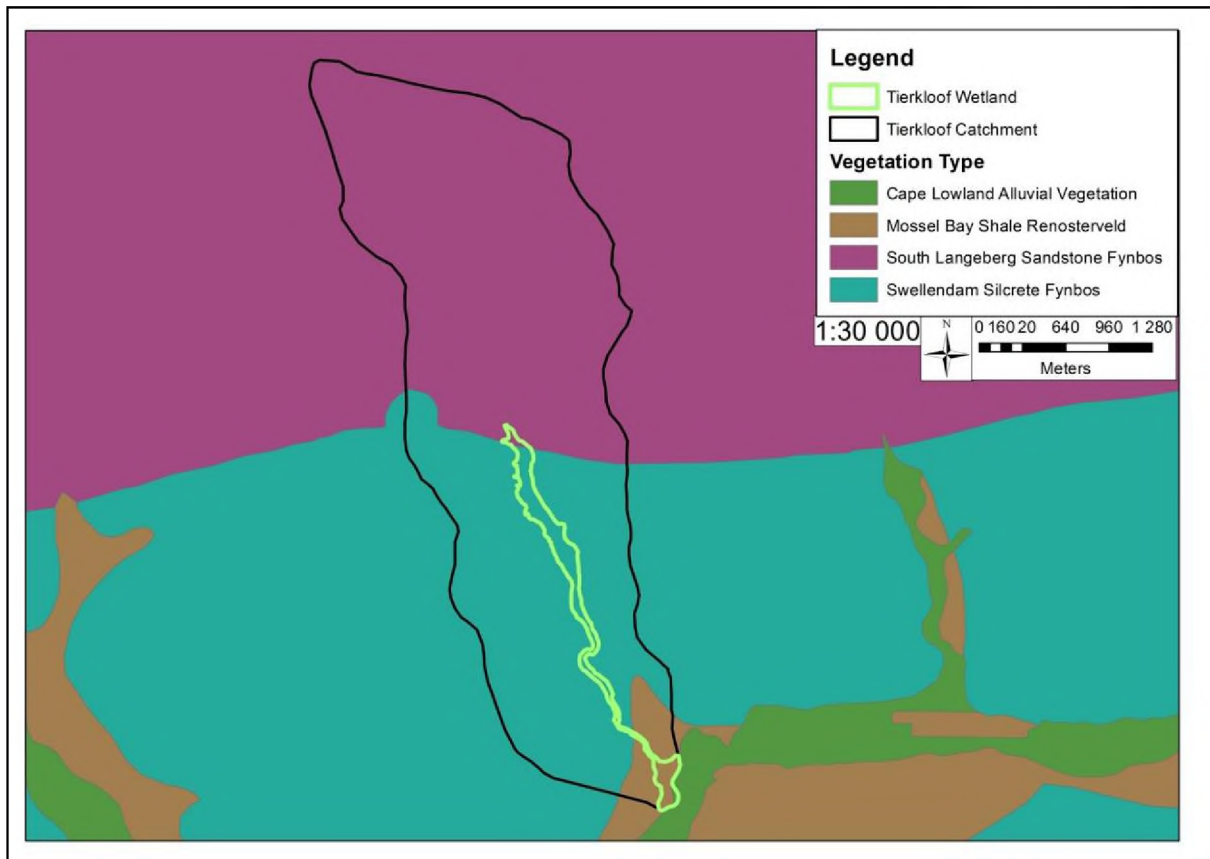


Figure 3-6: Map showing the vegetation types in the Tierkloof Wetland catchment (Mucina and Rutherford 2008)

Palmiet and members of the family Restionaceae would naturally be the dominant species of the Tierkloof Wetland (Sieben 2012), but it is currently dominated by alien species such as *Acacia mearnsii* (Figure 3-7).



Figure 3-7: Photographs of the infestation of *Acacia mearnsii* in the Tierkloof Wetland.

3.3.4 Conservation Context

The wetland is classified as a terrestrial and aquatic Critical Biodiversity Area (Pence 2014). The objective of this classification is to maintain natural land, rehabilitate degraded land, and monitor for further degradation. The Tierkloof Wetland is classified as a Critical Biodiversity Area (CBA) as it is considered threatened wetland habitat, irreplaceable wetland habitat, and is in a threatened vegetation type. Additionally, the upper portion of the system falls within a Mountain Catchment Area, where water is naturally collected and channelled to rivers. Mountain Catchment Areas are managed to ensure a sustainable water supply for communities while protecting natural resources.

The Tierkloof Wetland is classified as a National Freshwater Ecosystem Priority Area (NFEPA) meaning that it has been identified as a priority area for conservation (Nel *et al.* 2011).

3.3.5 Land-use in the Tierkloof Wetland

Before the 1940s the wetlands of the Goukou River system (including wetlands with cultivated peat soils) were planted with vegetable crops. Thereafter, dairy farming occurred on the area's wetlands (Job 2014). Currently, land in the wetland catchment is mostly privately owned and used for farming, including irrigated pasture and crops, dairy cattle, equestrian estates, and pine plantations. In the Tierkloof Wetland itself, the main land use is grazing for horses in the middle reaches, and irrigated pasture for dairy cattle near the toe.

CHAPTER 4 – METHODS

4.1 Desk-top analysis

Aerial photography and rectified orthophotography with 5 m contours were digitally mapped using the GIS programme ArcMap 10.2 (ESRI, Redlands California). Elevation, catchment area, wetland area, land use, land cover, and physiographic features were mapped from the most recent (2010) orthophotography.

Historical aerial photographs of the study area, obtained from the Surveyor General of South Africa, for the available photographic record since 1942, were imported into ArcMap 10.2 and were rectified and georeferenced. The geographical projection used was WGS 1984 (world sphere). Land use, land cover, and changes in any physiographic features over time were mapped from historical photography using the 2010 orthophotographic map as the base map. This made it possible to determine changes in land cover and land use, as well as changes in the location and size of gullies and depositional features over time, and relate them to each other. The delineation of land cover was conducted at the finest scale that the images would allow. However, the encroachment of alien invasive plants did impose a constraint to accurately mapping areas affected by erosion.

Nine topographic profiles across the valley were plotted from the 2010 orthophotography in order to analyse downstream changes in valley width and morphology down the length of the Tierkloof valley (Figure 4-1).

4.2 Field Work

4.2.1 Topographic surveying

In order to investigate the longitudinal and cross sectional characteristics of the Tierkloof Wetland, surveying was undertaken with a dumpy level and staff. Beginning at the head of the wetland and working towards the confluence with the Goukou River, 18 detailed cross sections of the stream channel were undertaken (Figure 4-1). The cross sections were

surveyed to a single datum, which made it possible to plot the stream longitudinal profiles. No attempt was made to relate these measurements to points of known location or elevation, as the relative elevations of surveyed features were suitable for analysis. A GPS coordinate was recorded at each cross section and at several locations along the stream longitudinal survey for mapping purposes.

4.2.2 Cores to bedrock

Depth to bedrock was measured in three cores in each of three valley cross sectional transects using a combination of Dutch auger and gouge corer. The surveyed land surface and core locations were tied into the cross-sectional and longitudinal surveys to show the relative elevations of bedrock. GPS coordinates were also recorded at each core.

4.2.3 Sediment sampling and water analysis

At each surveyed cross section along the valley, sediment samples were taken from the eroded stream banks at 0.5 m depth intervals or when there were observable changes in stratigraphy or other stratigraphic features of interest. Each sample was qualitatively described in the field based on texture and colour (using the 'feel' method and visual analysis). Additional notes were made for sediment samples believed to be peat using the Van Post humification scale (Rydin and Jeglum, 2006). Soil profile logs were plotted on graphs showing the variation of sedimentary material with profile depth. Sediment samples were put in sealed plastic bags and labelled according to location and depth, for transportation to the laboratory. A limitation was that some variation of sediment characteristics may be due to different lateral locations across the valley floor.

Where there was surface water in the stream, pH, electrical conductivity (EC), and temperature (degrees Celsius) were recorded at the points where cross-sectional topographic profiles were undertaken.

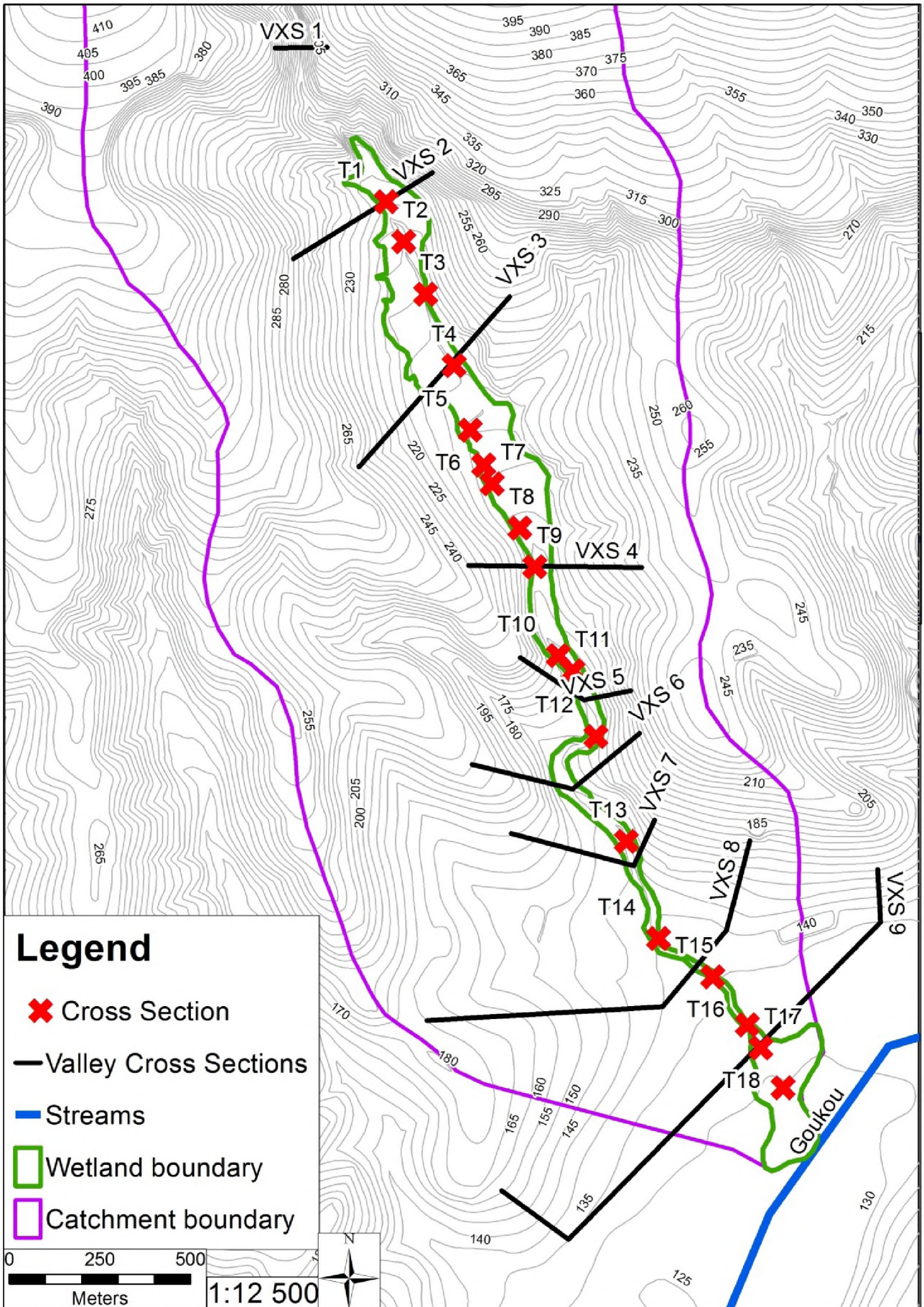


Figure 4-1: Locations of surveyed cross sections and valley cross sections in the Tierkloof Wetland.

4.3 Laboratory work

4.3.1 Preparation

The soil samples were dried for 48 hours in an oven at 90 degrees Celsius. They were then placed in a desiccator to prevent any absorption of moisture.

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

In order for percentage organic matter of the samples to be determined, the loss on ignition (LOI) method described by Heiri *et al.* (2001) was undertaken. Approximately 50g of oven-dried sediment samples was placed in a clean porcelain crucible (of known weight) and the combined weight was recorded. Each sample was then placed in a muffle furnace for 12 hours at 450°C. Following this, the samples were left to cool for one hour, removed from the furnace, and weighed immediately. The mass of the combusted sample was expressed as a percentage of the original sample mass giving the percentage organic matter content.

4.3.3 Carbon dating

Carbon dating of organic material in the wetland was undertaken for a very limited number of samples to better understand the rates of processes and place the origin and dynamics of the Tierkloof Wetland in the context of broad-scale climate change. Two peat samples from the eroded left bank at cross section 4, the first at 1.8m in depth from the surface and the second from 3.8 m below the surface, were sent for carbon dating analysis. The organic matter was dated by Beta Analytic Inc. (Miami, Florida, USA) using Accelerator Mass Spectrometry Carbon – 14 dating. The organic matter was in the form of plant residues or organic sediment, with root material discarded as potentially representing more modern contamination. Carbon – 14 ages were calibrated using the SHCAL13 database (Hogg *et al.* 2013) and the methods of Talma and Vogel (1993).

CHAPTER 5 – RESULTS

5.1 Description of the valley

The Goukou wetland has many tributaries entering the trunk valley from the north, due mostly to the presence of the Langeberg Mountains to the north. The Tierkloof tributary sits within a catchment that originates in the Langeberg Mountains and joins the Goukou wetland as the trunk stream changes orientation from westward-flowing to south-westward flowing. The Tierkloof Wetland is about 3.1 km long, covering an area of 25.4 ha. It occupies approximately 3.3 % of its 770.8 hectare catchment (Figure 5-1). The Tierkloof Wetland has eroded to bedrock along its entire length with high gully walls.

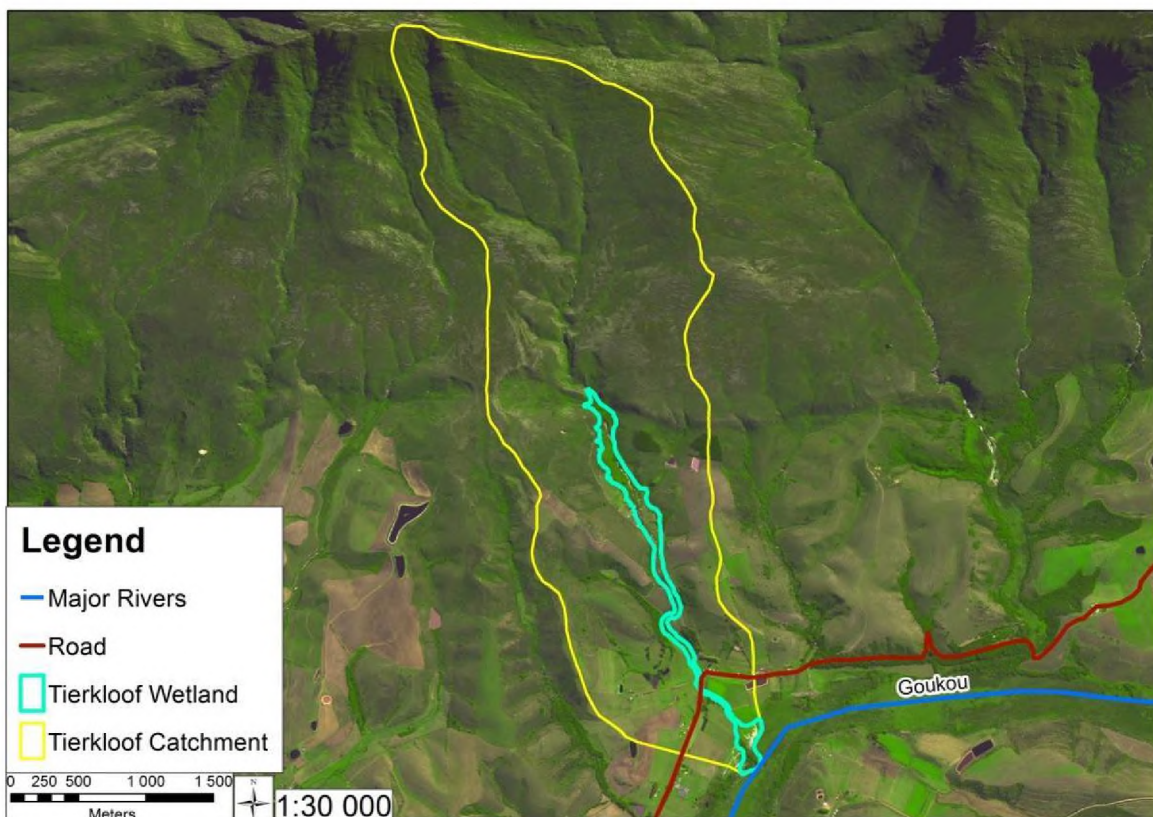


Figure 5-1: The Tierkloof Wetland and its catchment which drains into the Goukou River

5.2 Longitudinal characteristics

The Tierkloof Wetland stream channel begins at an elevation of 240 masl. and joins the Goukou River, approximately 3300 m downstream, at an elevation of 125 masl. (Figure 5-2). The Tierkloof Wetland is fed by 6 tributary streams. A major tributary joins from the west at the head of the wetland. At approximately 1000 m downstream (near stream cross section 5) another major tributary enters the system from the east, while a lesser tributary joins from the west. Further downstream, where the valley narrows, two minor tributaries enter from the east at approximately 1500 m and 1800 m (near stream cross sections 9 and 10 respectively). The final tributary to the wetland system is a major tributary from the west, entering the Tierkloof shortly before the valley loses confinement, at approximately 2125 m from the head of the wetland (between stream cross sections 12 and 13).

Despite minor irregularities in the slope of the bed of the gully bed, the longitudinal profile has a fairly uniform overall down-valley slope of 3.48 % (Figure 5-2). It is relatively steep at the head of the tributary with a slope of 5.9 %, which abruptly declines at a distance of 312 m from the head of the gully to 3.14 %. This approximates the position where the uppermost left bank tributary enters the main Tierkloof valley. There is another reduction in slope approximately 2438 m downstream of the head of the gully, where the Tierkloof tributary enters the Goukou valley and where the Tierkloof valley starts widening. At this point the slope declines to approximately 1.11 %.

There are further minor variations in slope associated with points where other tributary streams join the Tierkloof, and with man-made and natural features. An offset in slope occurs at a gravel road crossing approximately 1100 m downstream of the head of the gully (Figure 5-2). There are also two tributaries joining the wetland from the east and west at this location. Another minor offset in longitudinal profile occurs at approximately 1475 m downstream, where water has been artificially impounded to create a pool for abstraction (0.5 m deep) into an artificial diversion channel (0.5 m in width and 0.1 m in depth). Additionally, there is a minor tributary joining the system at this point. At a distance of approximately 1900 m downstream of the head of the gully, an offset in slope occurs due to the presence of a small

waterfall and resultant pool (approximate drop in elevation of 3 m). At this point the gully is superimposed on eroded shale bedrock.

Overall, the longitudinal slope of the former wetland surface is remarkably uniform over most of its length (Figure 5-2). The upper portion of the wetland has a steep slope of 5.4 %, giving way downstream to slopes of 3.59 and 3.14 %. Over the lowermost 600 m of the wetland the former wetland surface slope then diminishes to 0.89 %. There is an overall thinning of the valley fill from the head to the toe of the wetland.

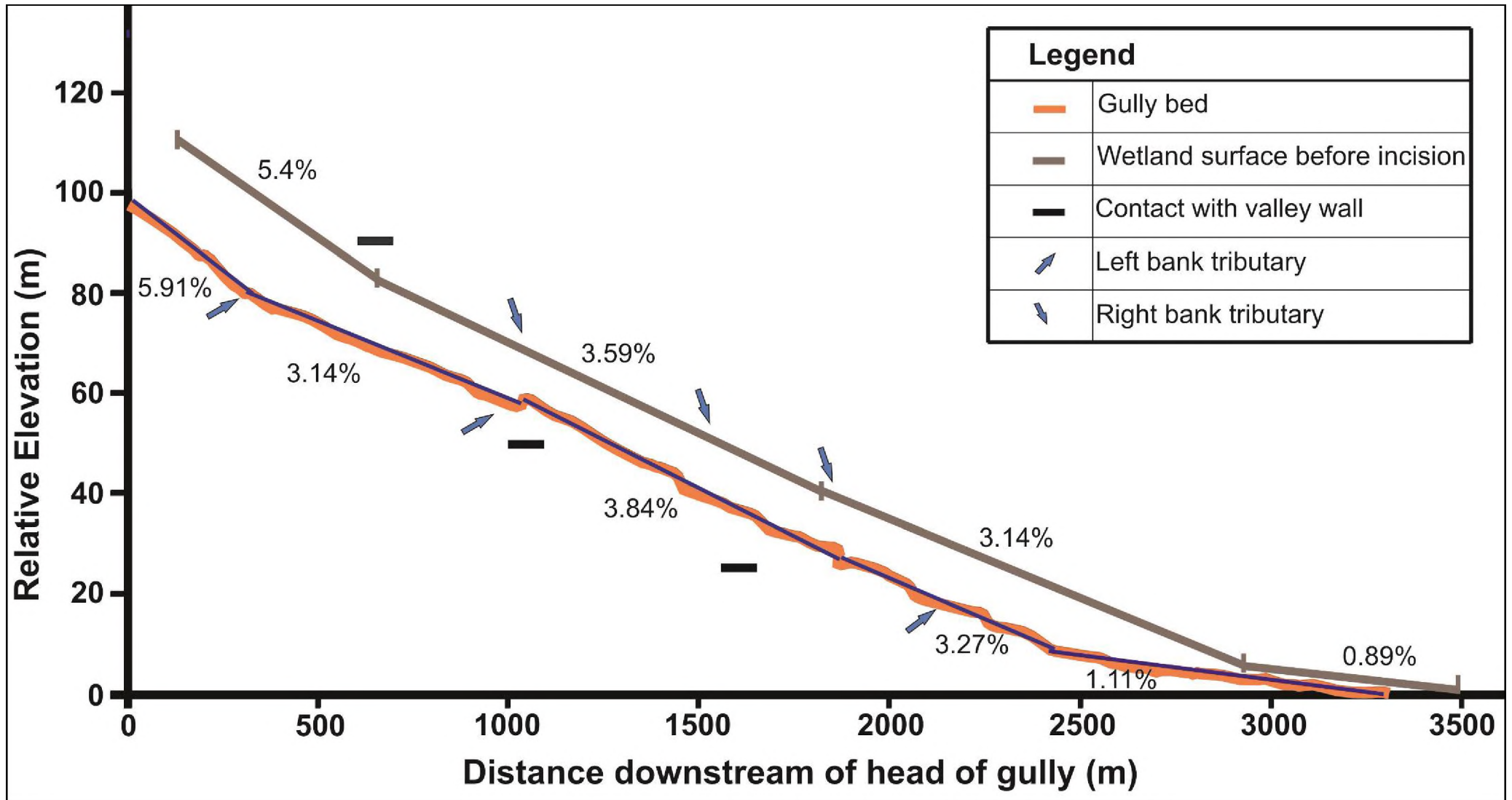


Figure 5-2: The longitudinal profiles of the gully bed and bank, also showing tributaries and areas of contact with valley side

5.3 Valley cross-sectional characteristics

The valley immediately above the Tierkloof Wetland is deep, steep-sided and narrow but widens rapidly at a distance of 400 m from the top of the valley. Downstream of the slightly widened valley reaches, up to 1 000 m downstream from the top of the wetland, the valley narrows progressively to a distance of about 2300 m from the head of the wetland (Figure 5-3). Downstream of this, the valley again widens considerably and shallows progressively, until it merges with the Goukou River floodplain. The valley floor width also varies down the Tierkloof valley (Figure 5-4). Only in the middle reaches does the valley floor widen, followed by a narrow section before widening dramatically upstream of the confluence with the Goukou River. The stream channel varies in its position laterally on the floor of the valley from close to the left margin to the right margin of the valley floor.

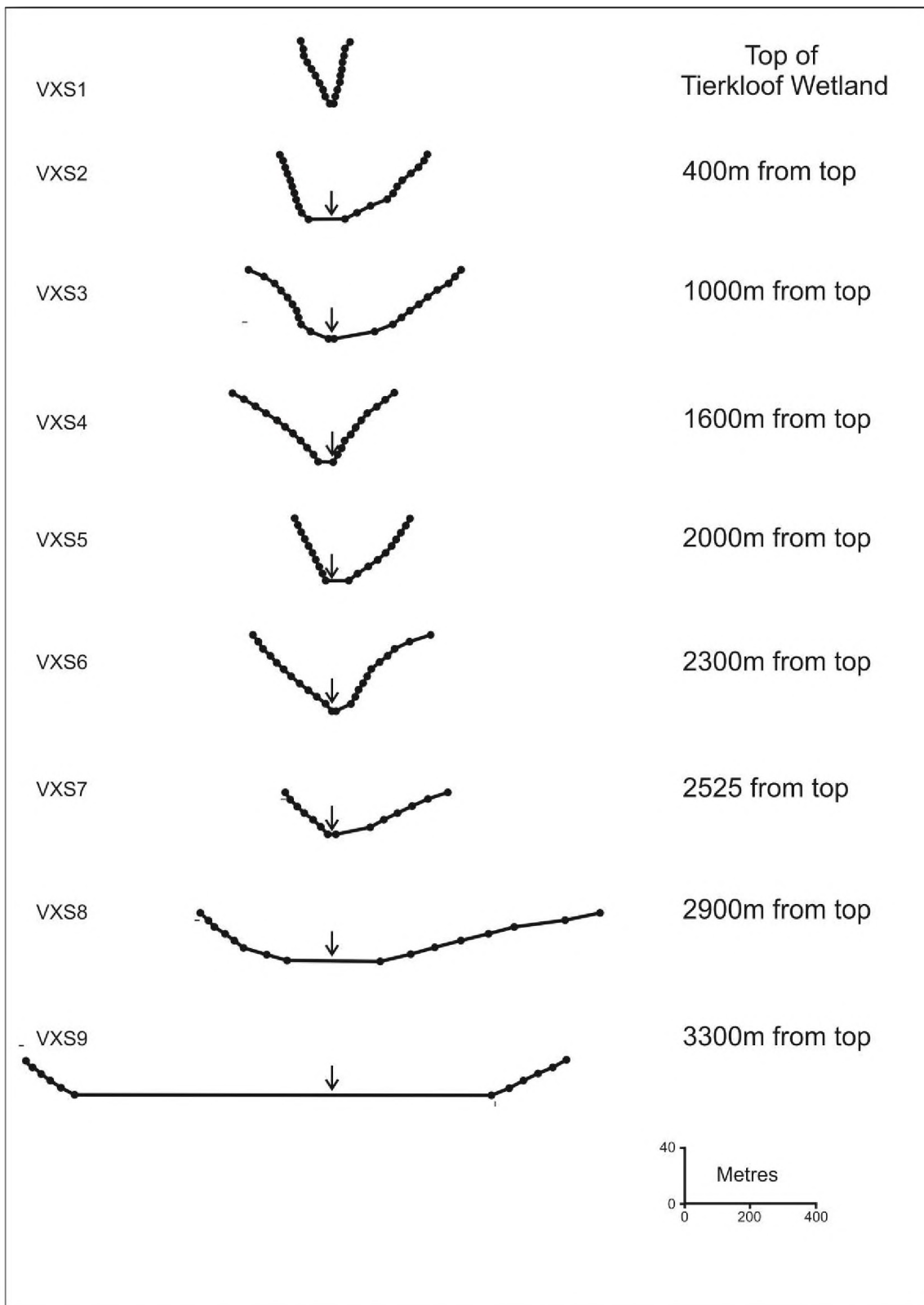


Figure 5-3: Changes in valley form from the head of the Tierkloof Wetland to the toe. Cross-sections are displayed looking downstream and locations illustrated in Figure 4-1.

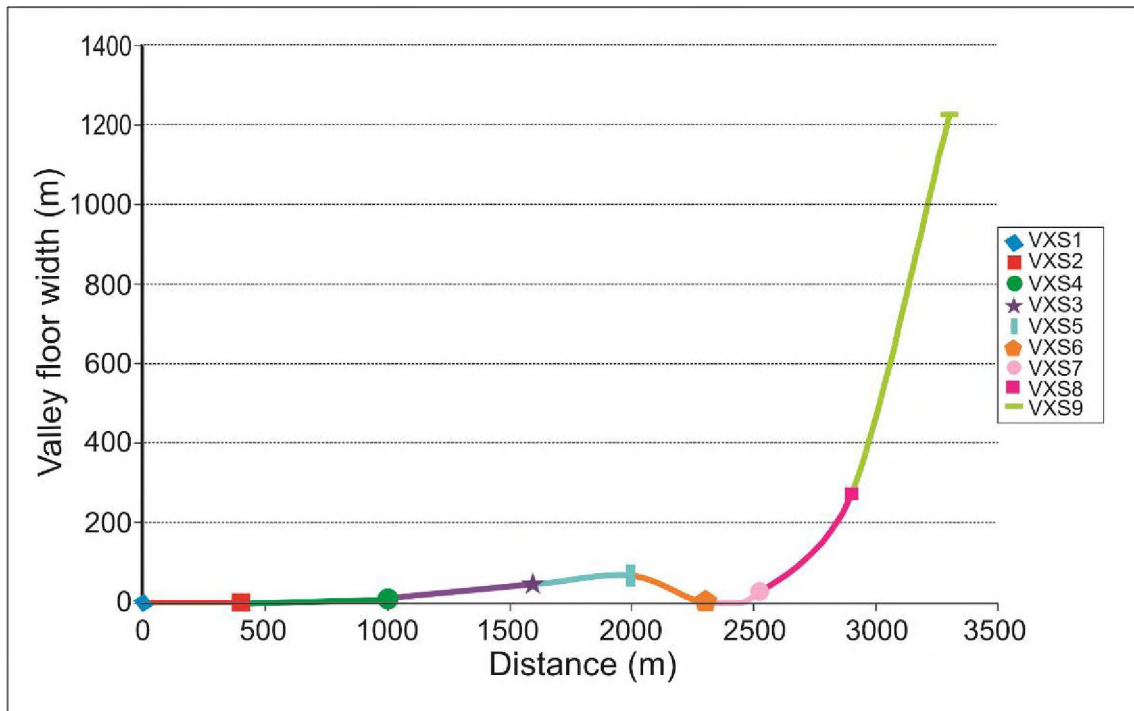


Figure 5-4: Changes in valley floor width with distance downstream in the Tierkloof (taken from valley cross sections; figure 5-3).

5.4 Gully cross-sectional characteristics

The gully bed is nearly flat in cross-section (Figure 5-5). Any variations in elevation, such as seen in the T1 and T3 cross sections, are in fact large clumps of peat that have come to rest in the gully bed from the eroded gully walls. The gully bed gets progressively narrower from the head of the gully in a downstream direction. By T14 there is rapid widening. The gully side walls are vertical, giving it a rectangular appearance (Figure 5-5). In a general sense the depth of the gully also gets progressively shallower downstream, until it disappears as it enters the Goukou River valley (Figure 5-5).

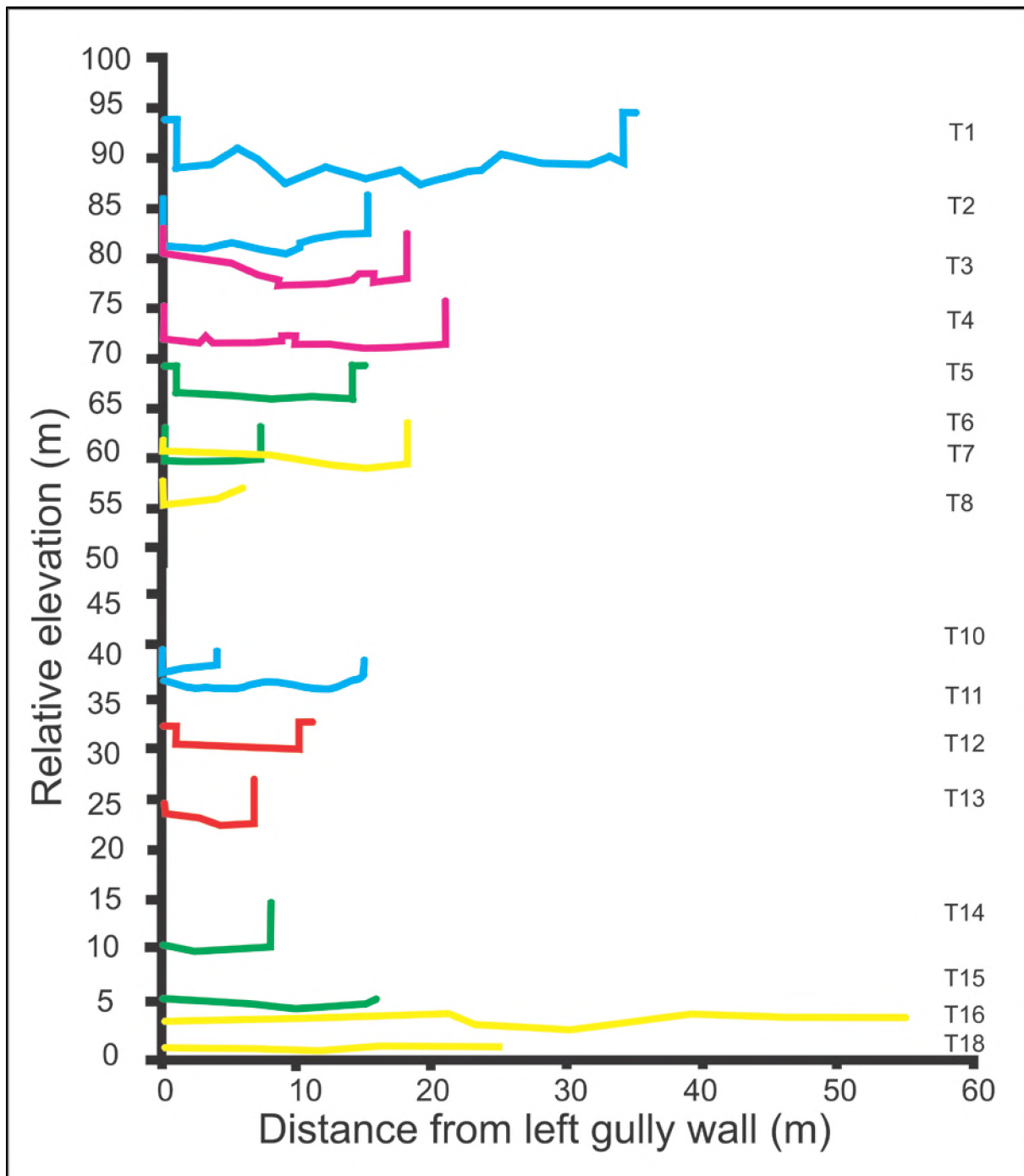


Figure 5-5: Gully cross-sections looking downstream

Figures 5-6 and 5-7 show the fairly systematic decline in gully width and depth from the head to the toe of the Tierkloof wetland. This decline is to the point where the gully disappears at the confluence of the Tierkloof valley with the Goukou Wetland.

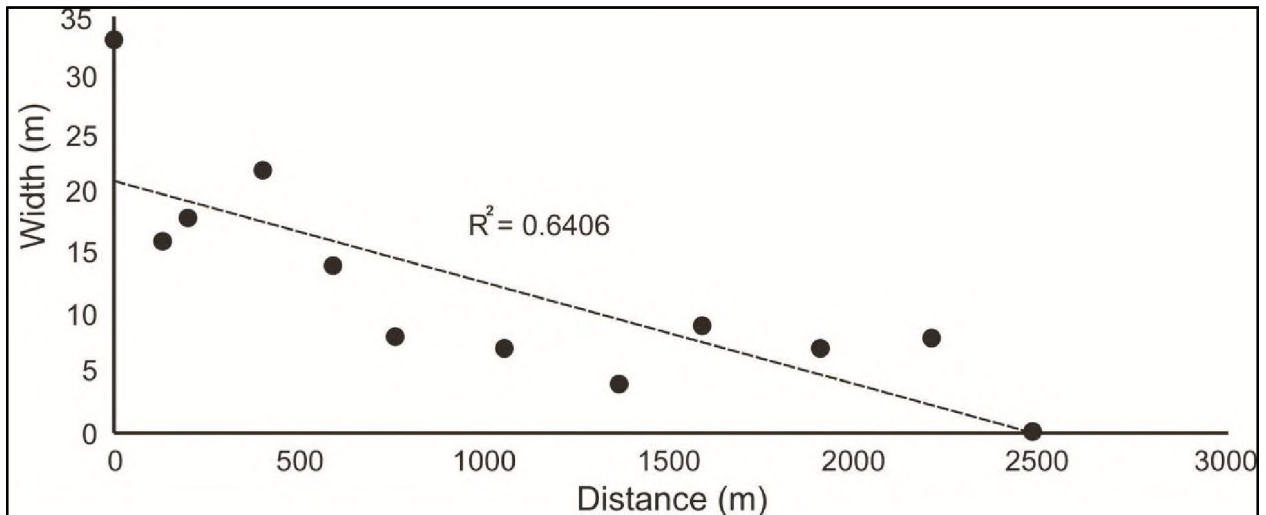


Figure 5-6: The relationship between gully width and distance downstream from the head of the wetland.

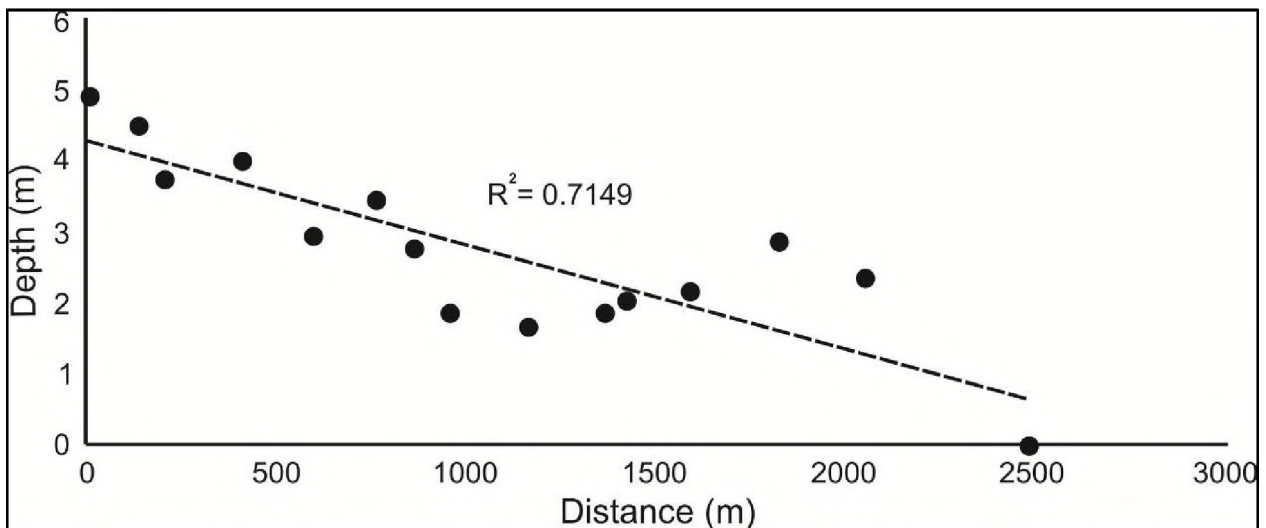


Figure 5-7: The relationship between gully depth and distance downstream from the head of the wetland

5.5 Stratigraphy of valley fill sediments

From the head of the Tierkloof Wetland to its toe at the Goukou River, the stratigraphy of sedimentary fill varies considerably. At the head of the wetland, there are appreciable accumulations of organic sediment, including sandy peat and peat layers with organic contents of up to 50 % (Figure 5-8). Further downstream (T5 to T8), peat layers decline in

their depth, and the content of the organic sediments is lower (up to 30%) than further upstream (Figure 5-9). The occurrence of minerogenic sediments in these reaches is relatively high, occupying a significant portion of the overall depth of the cores. From Transects 9 to 11 the depth of organic sediment as a proportion of the core was similar to the cores upstream of this, although the right bank of T11 comprised only minerogenic material (Figure 5-10). At this point of the Tierkloof, the gully had undercut the right bank of the valley, such that valley-fill sediments comprised material that had fallen down the bank under the influence of gravity. In the lowermost part of the valley the contribution of organic sediment to the depth of valley fill was small, and the organic content of sediments was generally less than 25 % (Figure 5-11).

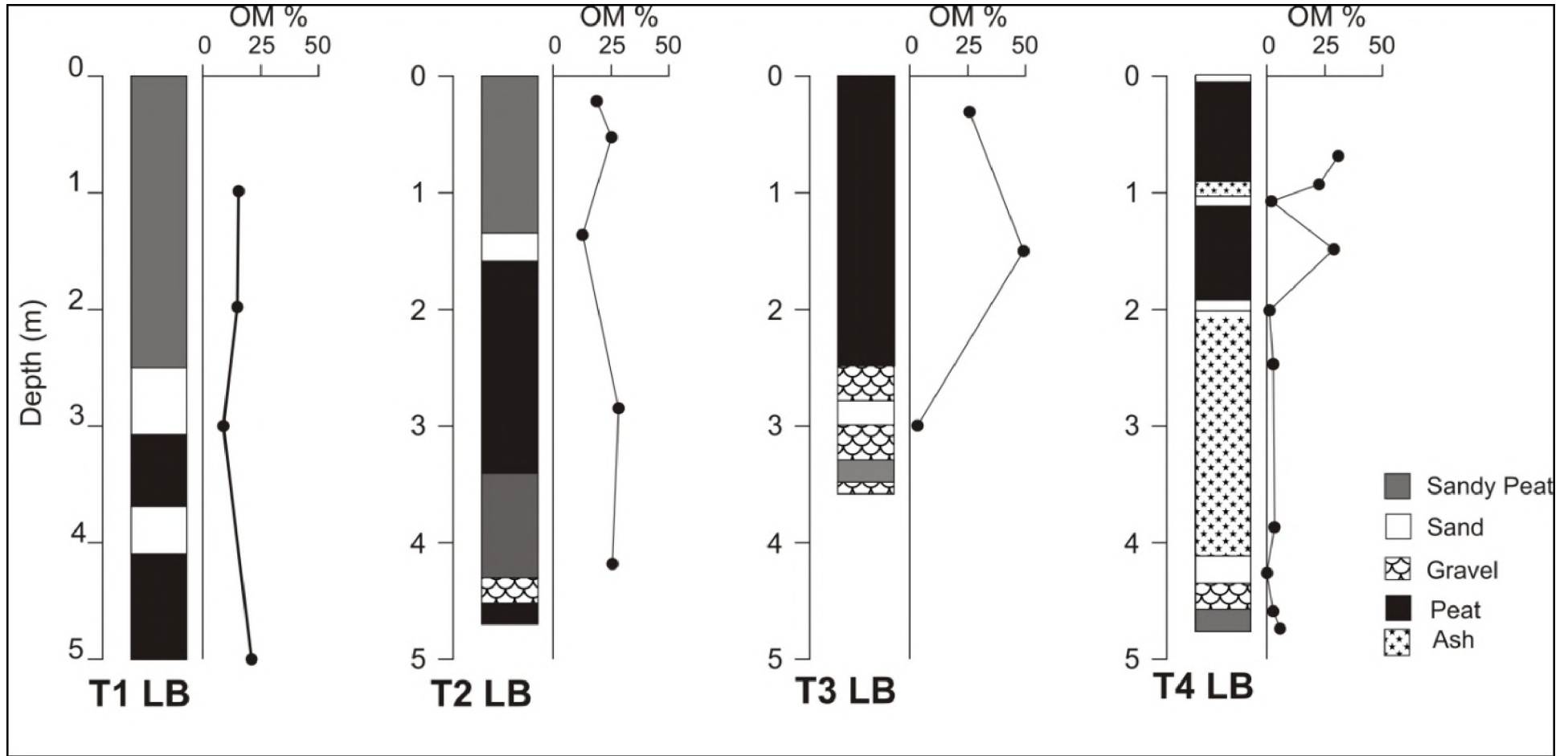


Figure 5-8: Left bank cores (T1 LB; T2 LB; T3 LB; T4 LB) along the wetland and the organic matter percentage of material in the cores

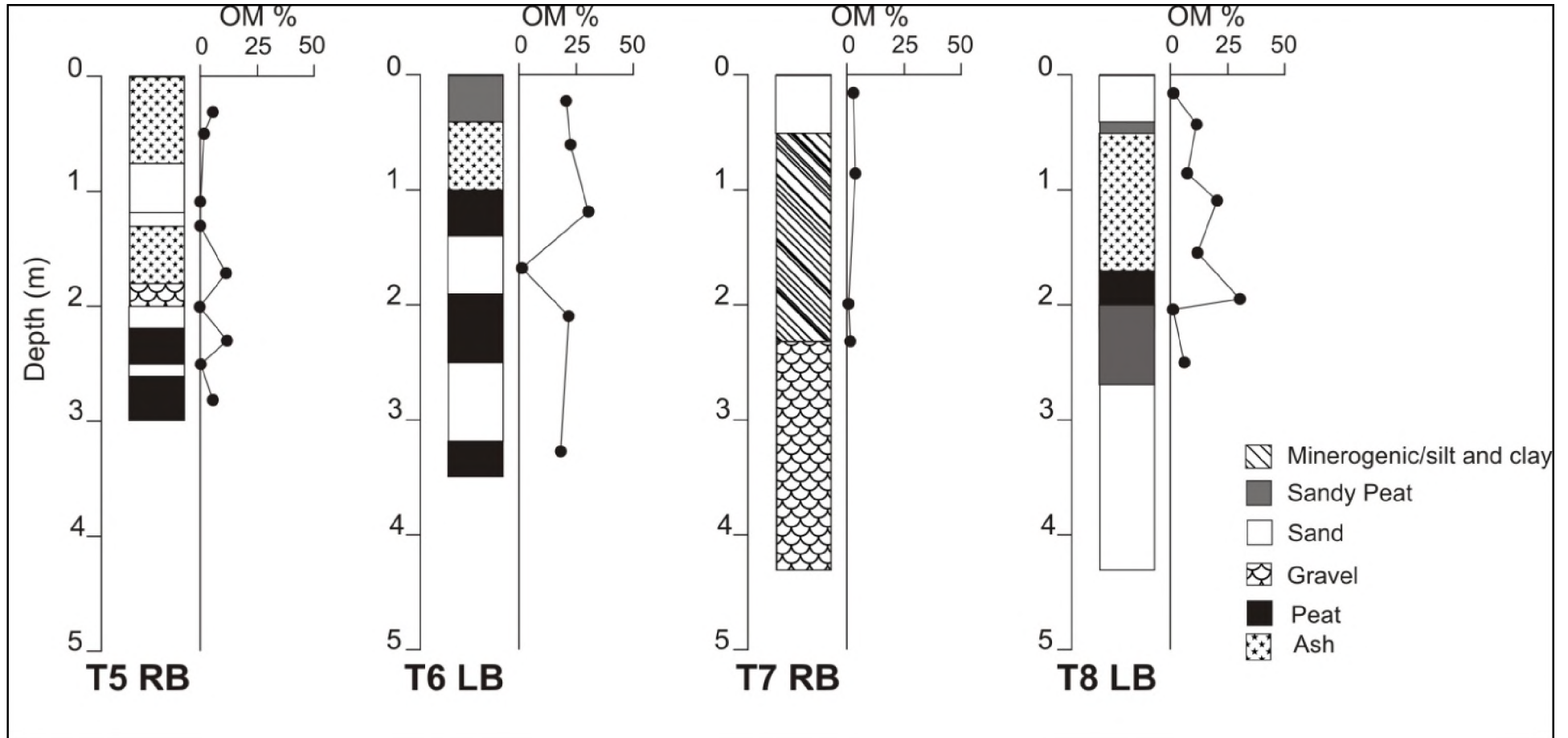


Figure 5-9: Cores (T5 RB; T6 LB; T7 RB; T8 LB) along the wetland and the organic matter percentage of material in the cores.

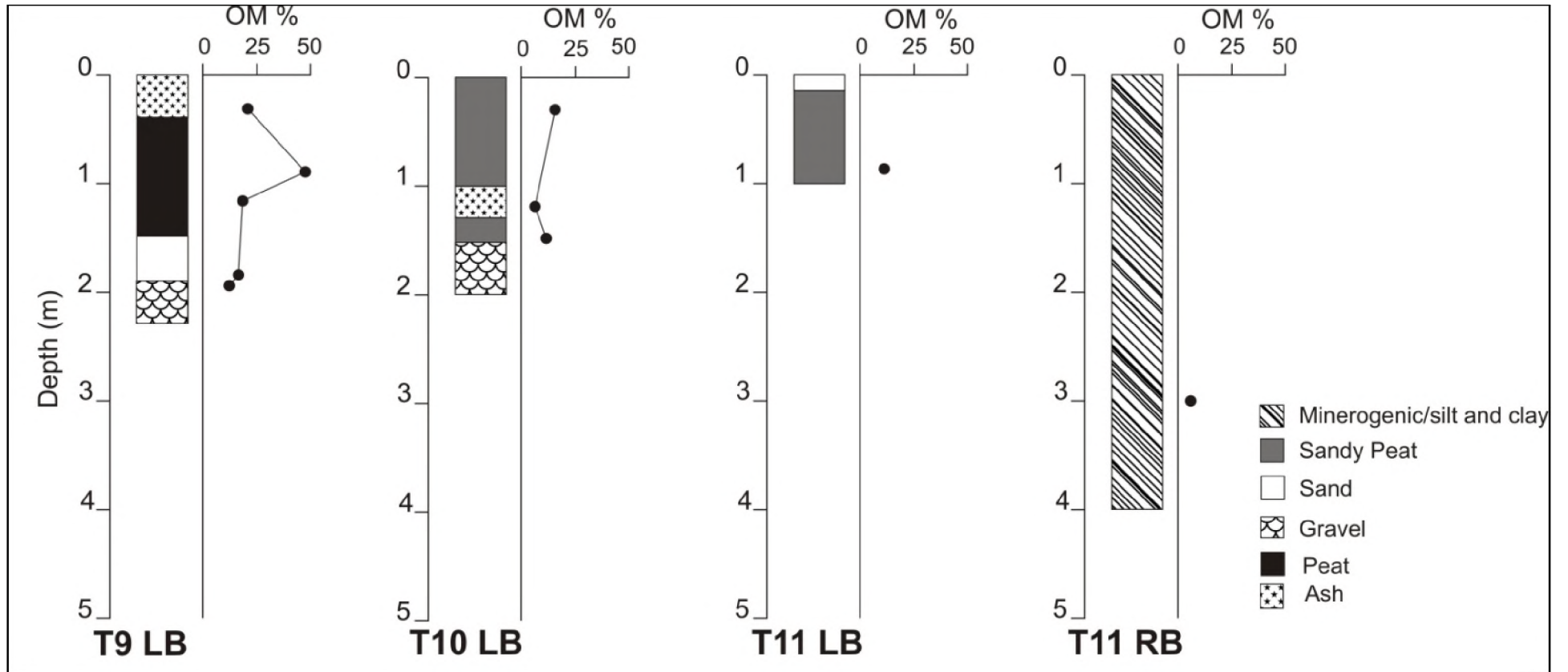


Figure 5-10: Cores (T9 LB; T10 LB; T11 LB; T11 RB) along the wetland and the organic matter percentage of material in the cores

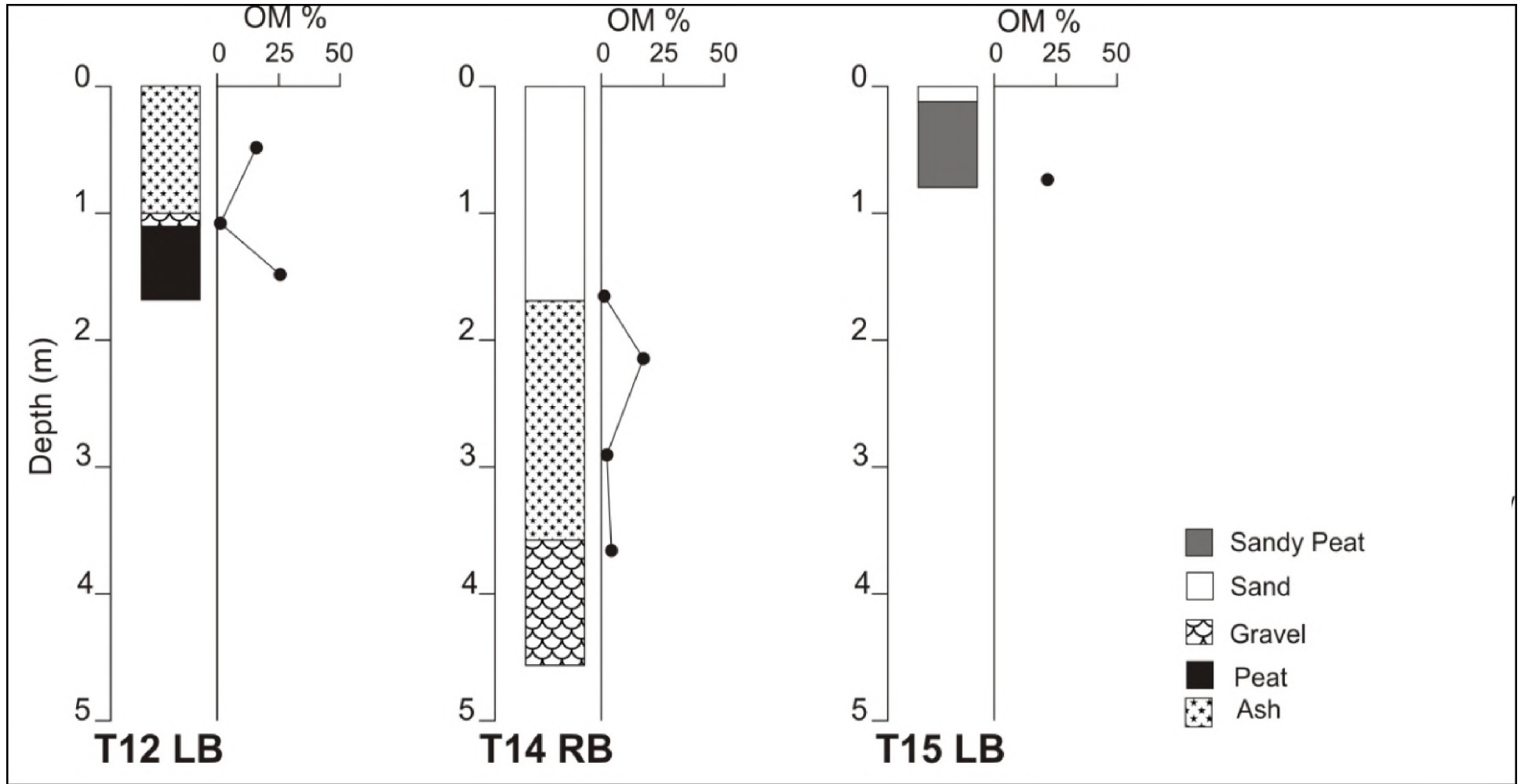


Figure 5-11: Cores (T12 LB; T14 RB; T15 LB) along the wetland and the organic matter percentage of material in the cores

5.6 Peat age and rate of peat formation

The carbon dating showed that the sample from 1800 mm below surface was deposited 3500 years before present, and the sample from 3800 mm below surface was deposited 6500 years before present (Figure 5-12). This suggests that the average accumulation rate was 0.58 mm annum⁻¹.

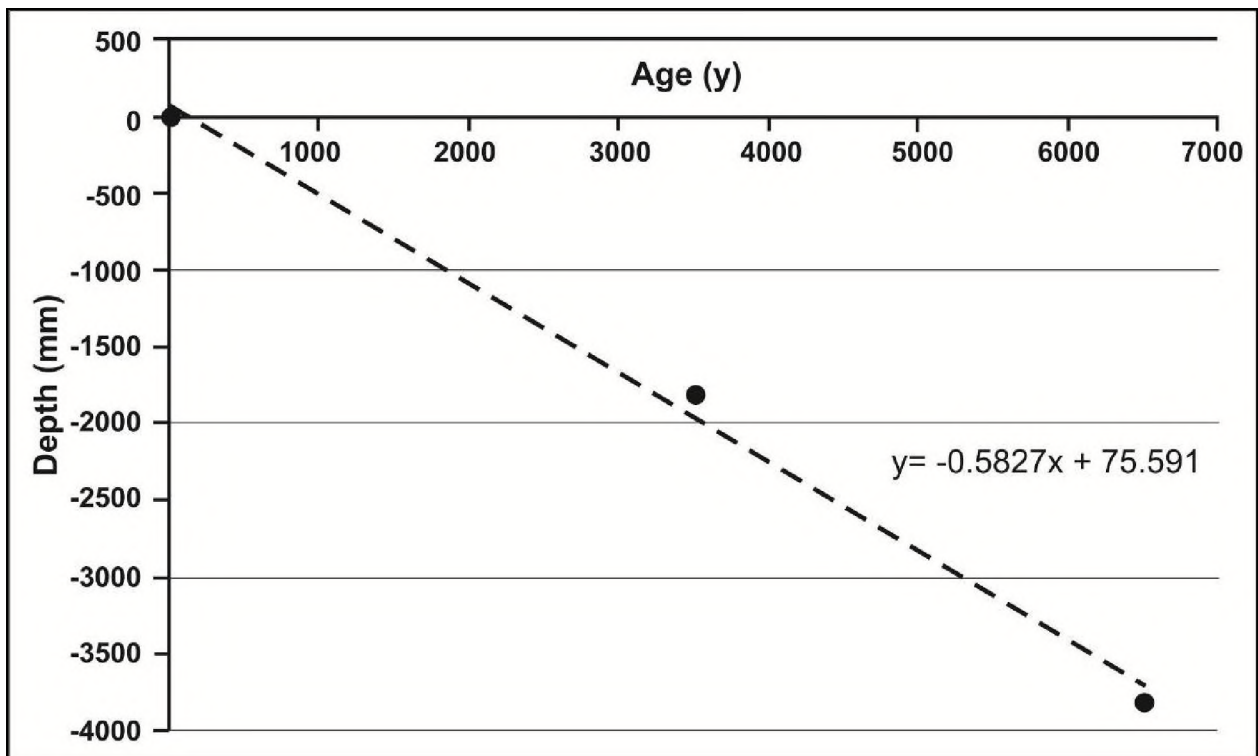


Figure 5-12: Age of peat samples taken from the left gully bank of T4 at two depths in the Tierkloof wetland

5.7 Depth to bedrock across the valley

The bedrock in the upper reaches of the wetland mainly consists of the quartzitic sandstones of the Table Mountain Group and changes to shales of the Bokkeveld Group further down. This substrate is overlain by a thin layer of coarse alluvial material through most of the system.

The elevation of bedrock across the valley is horizontal in the middle reaches of the Tierkloof wetland as shown by the survey 1300 m from the head of the wetland, but in the upper and lower reaches, the valley floor slopes gently downwards towards the bed of the gully as shown by the survey 870 and 1900 m from the head of the wetland respectively (Figure 5-13).

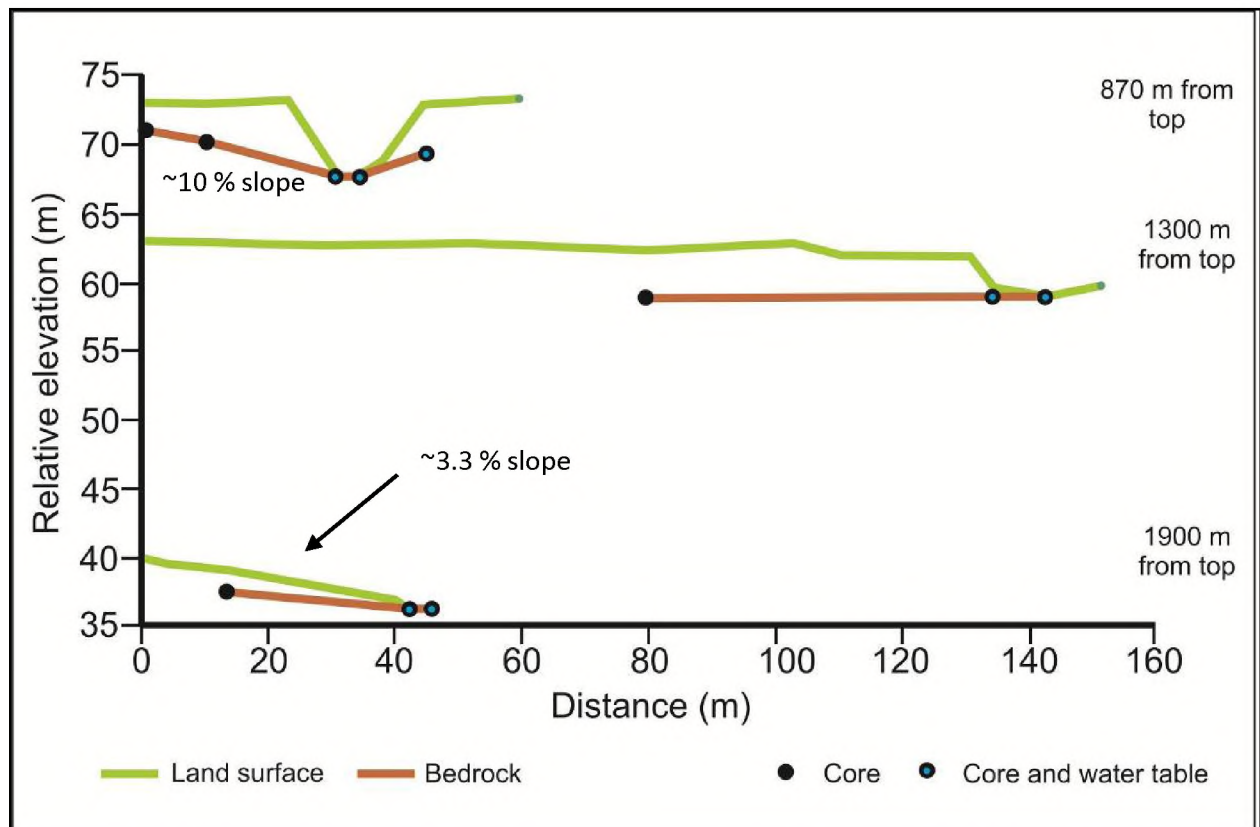


Figure 5-13: Graph showing the three bedrock profiles that were conducted. The brown line indicates the depth to bedrock, while the green line depicts the surveyed land surface

5.8 Land use and land cover change

5.8.1 Development of roads, drains, gullies and depositional features

In the 1942 aerial photograph an artificial drain was visible approximately 500 m from the head of the Tierkloof Wetland, extending over a distance of 300 m downstream (Figure 5-14; 1942). There were no obvious erosional or depositional features associated with this drain, but three erosional features were evident in the narrow lower part of the wetland, each

terminating in a depositional feature. Deposition occurred above and below the road that crosses the wetland in the lower reaches.

In the 1967 aerial photograph, only a short drain was observed, upstream of the drain visible in the earlier 1942 photograph. The later was no longer visible in the 1967 photograph (Figure 5-14; 1967). Two roads had been constructed across the middle reaches of the wetland by 1967. Two erosional features in the central reaches of the wetland in 1942 had consolidated into a larger erosional feature by 1967. The lowermost gully in the 1942 imagery was not visible by 1967, but the depositional feature at the toe of the Tierkloof wetland was still present.

By 1991 a large drain had been excavated from the head of the wetland downstream over a distance of approximately 600 m (Figure 5-14; 1991). A depositional feature was evident a small distance downstream of the toe of this drain. Additional roads had also been constructed across the wetland and running along its eastern margin. An erosional feature had formed upstream and downstream of a road crossing the central section of the wetland but other erosional features present in previous images were not visible. A large depositional feature was present in the lowermost part of the wetland, and a drain had been excavated through this feature.

Between 1991 and 2006 there was widespread degradation of the wetland in the form of additional drains, gullies and depositional features. The drain in the uppermost part of the wetland present in the 1991 imagery had undergone erosion that had widened it appreciably by 2006 (Figure 5-14; 2006). The same drain had been extended downstream between 1991 and 2006, and at its toe (and below the uppermost road across the wetland), a large amount of sediment had been deposited. A gully had also formed to the east of the drains that had been excavated in the upper wetland between 1991 and 2006, which terminated upstream of the road and the large depositional feature below the road. A gully had also formed to the west of this depositional lobe of sediment and the road crossing the wetland. Erosion had also been initiated along the entire lowermost half of the wetland, terminating in a large depositional feature near the confluence of the Tierkloof with the Goukou Wetland.

By 2010, the entire length of the wetland was occupied by a gully (Figure 5-14; 2010), which has been described in the preceding sections of this chapter. The toe of the wetland remains as a large depositional feature.

Over the years the imagery shows depositional features and gullies that occurred in different places and generally changed in size. These features tended to be located at or near roads and drains. There is an increase in depositional feature size and gully length between 1942 and 2010. Roads have been constructed over time and there are more road crossings on the wetland. However, in 2010, two of the former roads no longer existed.

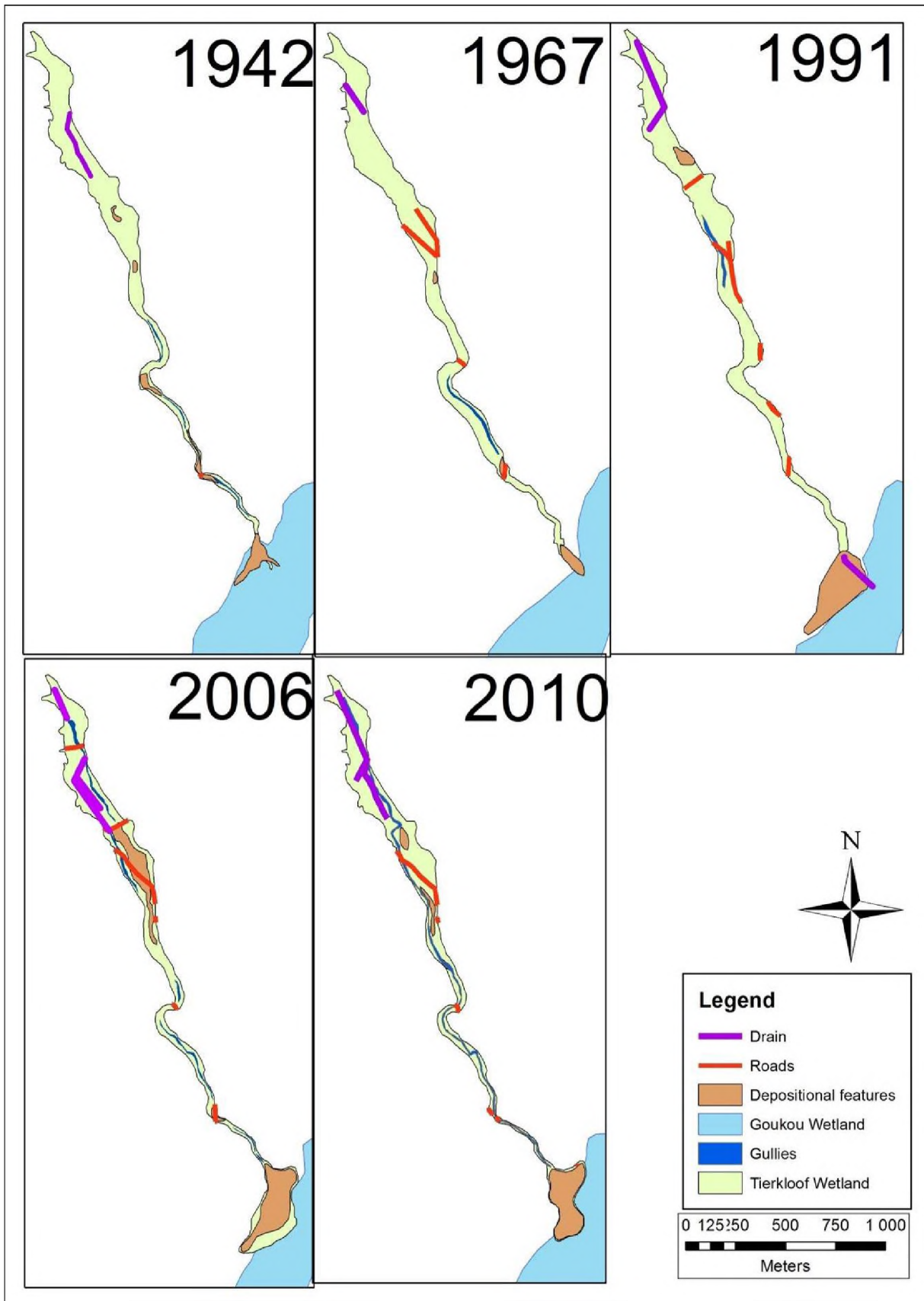


Figure 5-14: Map showing drains, gullies and depositional features within the Tierkloof Wetland for 1942, 1967, 1991, 2006 and 2010.

5.8.2 Changes in catchment land cover and land use over time

Over the period of aerial photography, the Tierkloof catchment has constantly consisted largely of natural vegetation (Figure 5-15). The portion of the catchment that is not shown in the maps does not contain any land cover change because of the mountainous nature of the terrain: it is entirely natural vegetation. In the upper, steeper areas of the catchment, which are displayed in the maps shown here, land cover has remained relatively natural. In response to the development and increase of artificial land uses and alien vegetation cover, natural vegetation in the catchment declined steadily from 87.83 % in 1942 to 73.63 % in 2010, mainly as a result of encroachment of alien vegetation and (more importantly), cultivation (Figure 5-16). In 1942 only 0.83 % of the Tierkloof catchment area consisted of alien vegetation, but alien infestation has increased steadily to 4.72 % in 2010. In 1942 alien vegetation was limited to small patches, mostly in the lower region of the catchment, but it steadily increased in and up riverine areas.

Cultivated land covered 11.19 % of the catchment in 1942. This remained roughly unchanged in 1967, 1991 and 2006, but there was an increase in the extent of cultivated land from 2006 to 2010, by which time cultivated land occupied 21.07 % of the catchment. Throughout the imagery analysed, the percentage of dams in the Tierkloof catchment area remained low; never reaching more than 0.5 % of the catchment area. However, dams did increase in number and develop further up the catchment over the time period analysed. The catchment contains very few buildings, with only 0.13 % of the catchment area having buildings visible in 2010 aerial imagery.

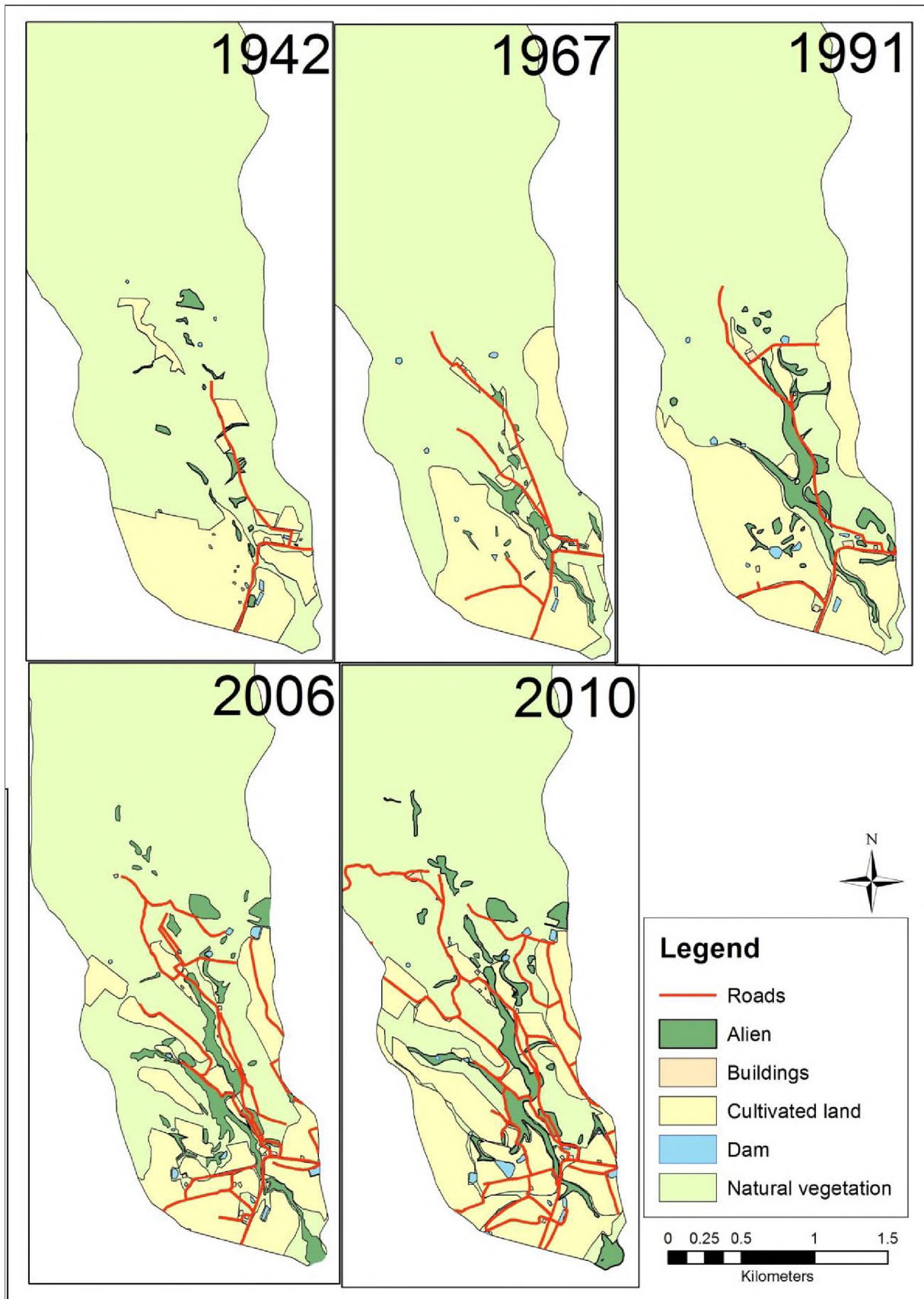


Figure 5-15: Land cover and land use in the Tierkloof catchment for years 1942, 1967, 1991, 2006 and 2010.

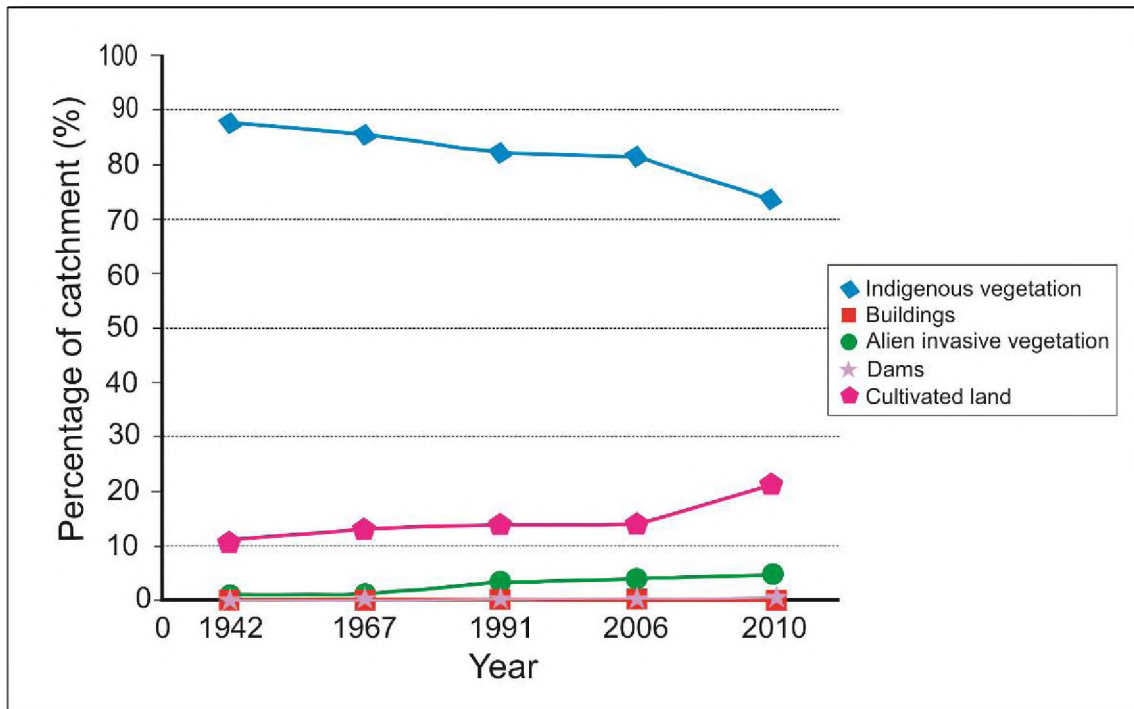


Figure 5-16: Changes in land use and land cover in the Tierkloof Wetland catchment between 1942 and 2010

5.8.3 Changes in wetland land cover and land use over time

When examining the Tierkloof Wetland, it is evident that compared to the catchment, there have been significantly more changes in land use and land cover per unit area. In 1942 the Tierkloof Wetland appears largely to have been in a pristine state, dominated by natural vegetation (96.6 % of the wetland), with the remainder comprising alien vegetation and roads (Figure 5-17; 1942). However, by 1967, alien vegetation and cultivation had significantly reduced the amount of natural vegetation in the wetland, to 74.6 % of its area (Figure 5-18). The upper reaches of the wetland, and the extreme toe, remained naturally vegetated in 1967. However, by 1991, natural vegetation had been reduced to small areas, mostly at the top of the wetland and the extreme toe, amounting to 45.83 % of the wetland area. In 2006 and 2010 imagery, the wetland appears to have become dominated by cultivated land and alien vegetation, with only 33.4 % of the wetland comprising natural vegetation.

Alien vegetation in the Tierkloof Wetland increased dramatically between 1942 and 2010, from only 1.48 % to 47.4 % of wetland area respectively. The 1967 image analysis showed

that the infestation had developed and expanded from very small and fragmented patches (1942) to 19.06 % of the wetland area, occurring in the middle and lower reaches to just above the confluence with the Goukou River. The extent of alien vegetation within this portion of the wetland continued to increase rapidly, such that in 2010 it dominated throughout the entire area.

In 1942, only 1.91 % of the wetland area comprised cultivated land. The extent of cultivated land increased progressively to 18.97 % of the wetland area by 2010. Cultivation generally occurred in the middle reaches of the wetland, where the wetland widens, and near the confluence of the Tierkloof with the Goukou River.

There were no observable dams in the wetland from 1942 to 2010. Buildings comprise a small percentage of wetland area land use. Only in 2006 and 2010 imagery can any buildings be observed in the wetland, and even then, buildings comprised less than 0.3 % of the wetland area.

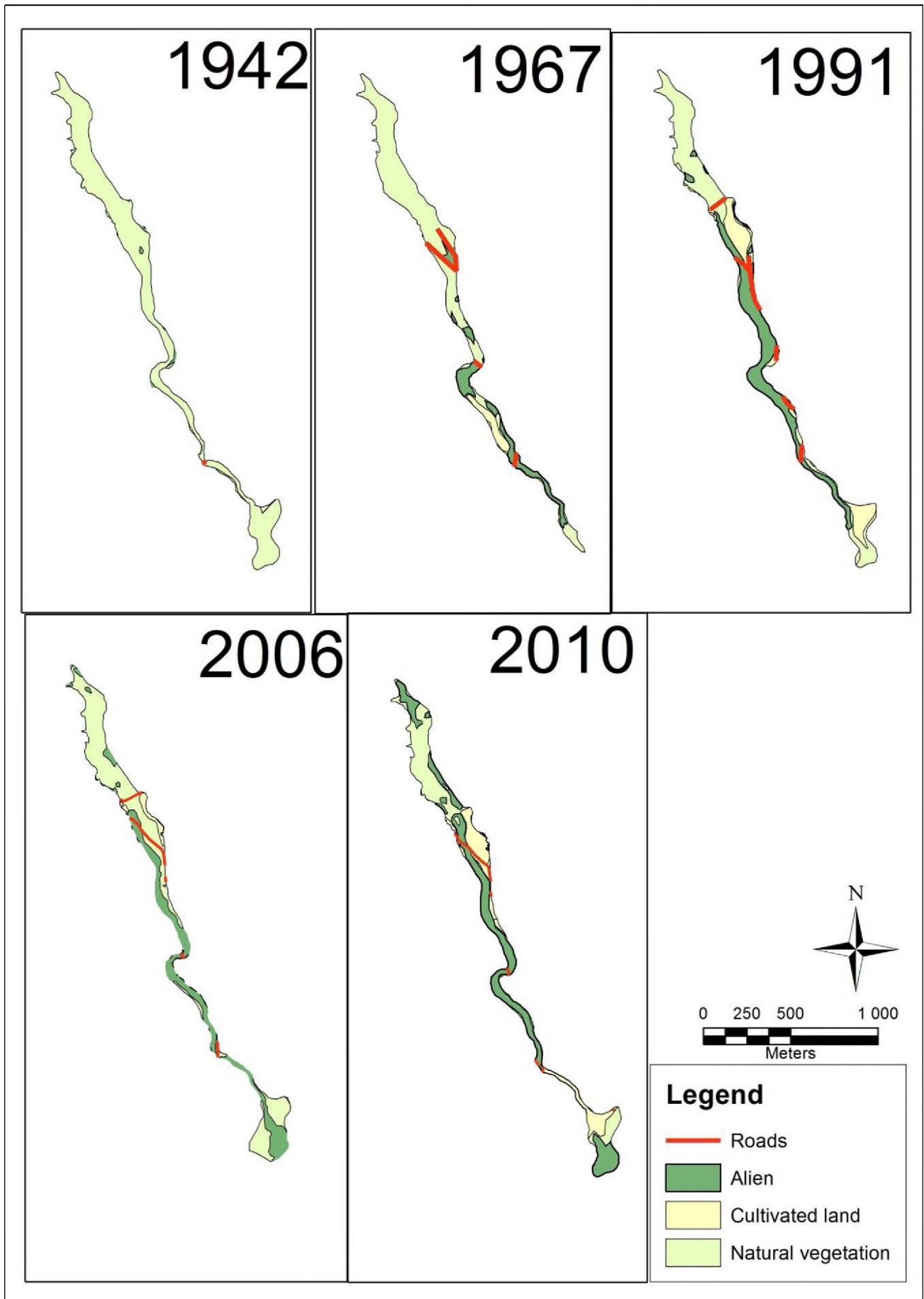


Figure 5-17: Land cover and land use in the wetland in 1942, 1967, 1991, 2006 and 2010.

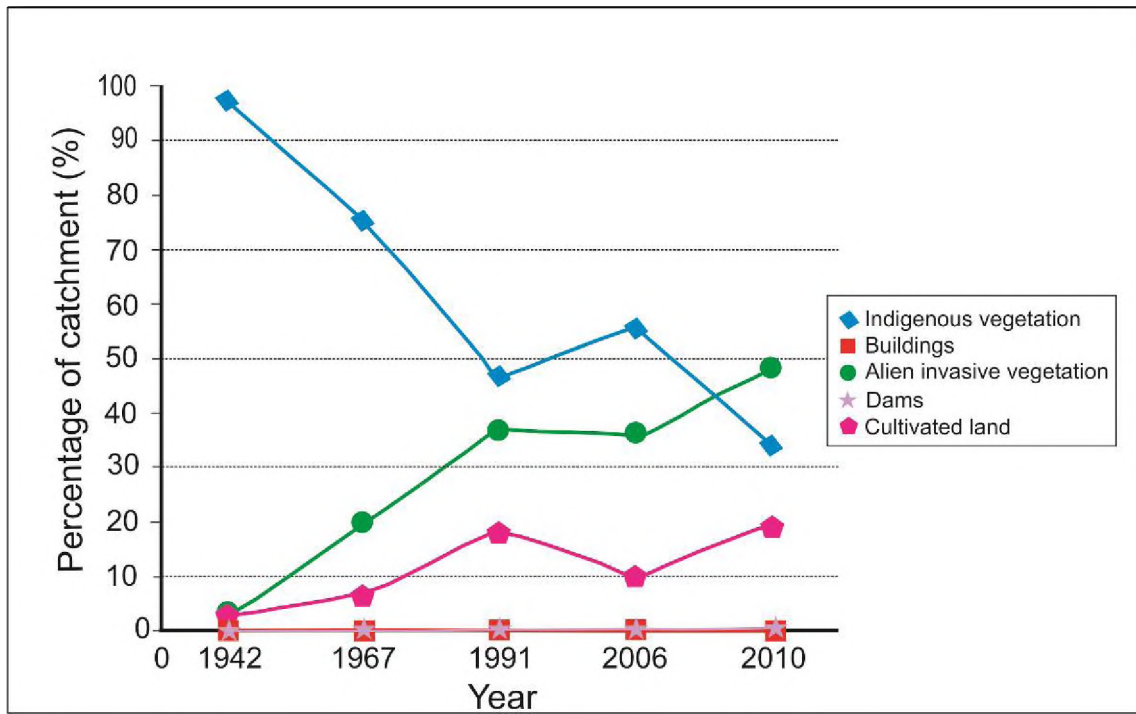


Figure 5-18: Changes in land use and land cover in the Tierkloof Wetland between 1942 and 2010.

CHAPTER 6 - DISCUSSION

6.1 Characteristics of wetlands

Our prevailing understanding of the existence, characteristics and maintenance of wetlands is underpinned by the nature of interactions between hydrological processes and their position in the landscape (Grundling *et al.* 2013 [a]). For example, the Tierklof Wetland is located in an area where the mean annual potential evaporation rate is higher than mean annual rainfall, and thus sustained surface and groundwater inputs to the water balance are necessary to support prolonged flooding. Job (2014) has suggested that the release of groundwater from fractured quartzite aquifers in the mountainous catchment of the Goukou Wetland is important in sustaining sufficiently prolonged periods of flooding to allow peat formation. This is likely to apply to the tributary Tierkloof Wetland as well.

In South Africa, as is the case in the rest of the world, wetlands are characterised by broad valleys that are flat in cross-section and have a gentle longitudinal slope (Ellery *et al.* 2009). The factors contributing to the creation of valleys with these characteristics have seldom been considered by wetland scientists. This thesis contributes to developing this kind of understanding.

Ellery *et al.* (2009) have shown that a negative relationship exists between longitudinal slope of valleys occupied by wetlands and their aerial extent. The argument is that larger discharges are required to support larger wetlands and that this is an inevitable outcome of fluvial systems working to achieve an appropriate longitudinal slope. Ellery *et al.* (2009) determined a threshold slope for wetlands in the region and this formed the basis of the diagram in Figure 6-1. Wetlands above the thick black line are too steep for the available discharge and therefore vulnerable to erosion.

The Tierkloof Wetland covers an area of 25.4 ha and it has an overall down-valley slope of 3.48 %. This is steep given the pattern for other wetlands in the region, as indicated by the position of the wetland on the plane of longitudinal slope and area (Figure 6-1; Macfarlane *et al.* 2009). Based on this it is clear that the Tierkloof Wetland is inherently vulnerable to

erosion. This means that small perturbations in the catchment or wetland that increase runoff or concentrate flow, locally in the wetland, are likely to cause erosion.

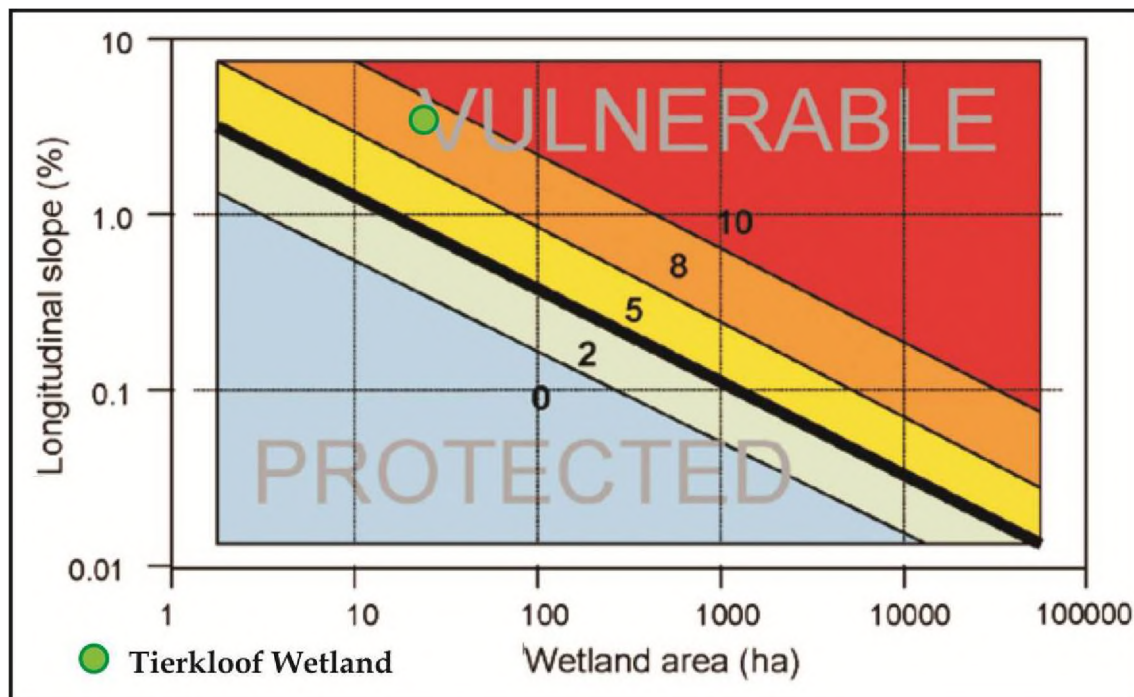


Figure 6-1: The vulnerability of the Tierkloof Wetland to incision based on the relationship between longitudinal slope and area (Modified from Macfarlane *et al.* 2007).

There is abundant evidence from the analysis of aerial and orthophotography that the recent phase of incision of the Tierkloof was initiated by human activities, particularly of road construction and artificial drainage of the wetland by landowners. The invasion of the valley floor by alien species of *Acacia* sp., with very limited fine root abundances, may also have contributed to erosion of the Tierkloof Wetland.

Although human disturbance is often believed to be the main cause of erosion in wetlands, the concept of wetland thresholds and inherent wetland vulnerability enhances understanding of the impact of human activities on wetland geomorphic stability (Ellery *et al.* 2009). It proposes that erosional and depositional changes within wetlands are at least in some way related to a wetlands inherent vulnerability to erosion and cannot simply be attributed to human activities. If the erosion in some wetlands is a natural process due to inherent geomorphic vulnerability, then factors such as long term climate change or valley steepening

by sedimentation may strongly influence the natural dynamics of wetlands. Any increase in discharge in a wetland, either natural or human induced, may lead to a geomorphic threshold being crossed, leading a stable wetland with diffuse flow to erode.

6.2 Models of wetland formation in South Africa

Along the length of the Tierkloof valley there is evidence of a degree of planing of bedrock. Wherever the relative elevation of bedrock was measured there was evidence of valley-widening, particularly in the middle reach of the wetland the valley had been planed to a near-horizontal form over a considerable width of at least 60 m. At other sites bedrock has been planed to near-horizontal (cross-sectional slope of 3.3 to 10 %) over a width of 30 m to 50 m.

In South Africa, a planed horizontal to near-horizontal valley bottom is generally attributed to valley widening from lateral erosion (Tooth *et al.* 2002; 2004). Various case studies have described how a local base level formed by a resistant lithology (such as a dolerite intrusion), limits vertical erosion upstream (as the system cannot erode lower than the local base level). The available energy erodes the valley laterally, widening the valley floor. This gives rise to a near-horizontal bedrock surface beneath a thin layer (up to 2-3 m) of clastic sediment. The Tooth *et al.* (2002) model shows a clear relationship between how meandering streams widen a valley once the appropriate longitudinal slope has been achieved in a valley dominated by easily eroded bedrock upstream of a resistant bedrock lithology. Tooth *et al.* (2002) developed this model by studying the Klip River wetlands, where vertical erosion rates on Karoo Supergroup sandstones are retarded by the slow erosion rates of the dolerites downstream, resulting in the river laterally planing bedrock. Another case is of a dolerite sill in the Stillerust Vlei on the Mooi River described by Grenfell *et al.* (2008). The resultant planed Karoo shale bedrock upstream of a resistant dolerite dyke created a wide valley in which a floodplain wetland formed. These floodplain systems are generally characterised by thin, clastic sediment deposits overlying near-horizontally planed bedrock. This model accounts for broad valleys with meandering streams, with limited to no peat formation, but it does not account for unchannelled valley bottom wetlands such as the Tierkloof, where no resistant lithology and meandering stream exists.

Tributary blockage by trunk streams (Grenfell *et al.* 2010, Ellery *et al.* 2013) and trunk blockage by tributaries (Joubert and Ellery 2013) are alternative models developed to explain the formation of low gradient valleys without channels, which are often associated with peat formation. However, there is no evidence of an alluvial ridge in the Goukou Wetland that has blocked the Tierkloof tributary stream, creating accommodation space for peat formation in the Tierkloof (Job 2014). The model of the tributary being blocked by the trunk therefore does not apply to the relatively steep Tierkloof tributary wetland.

6.3 Insights from carbon-dating of Tierkloof Wetland peat deposits

The two radio carbon dates obtained from the gully wall midway along the Tierkloof Wetland, of 6 000 years BP and 3 500 years BP, suggest that peat accumulation started following the last glacial maximum, and has accumulated consistently until the most recent cutting phase was initiated a few decades ago. There is little doubt that this phase of cutting was initiated by human activity such that its timing may have happened much earlier than may have happened naturally.

Nevertheless, it is of interest to note that the slope of the gully bed (3.42 %) is slightly lower than the slope of the original wetland surface into which the gully incised (3.45 %). This supports the notion that erosion occurs when the slope of the land surface is too high for the available discharge and sediment supply, and leads to slope reduction. It also reflects the likely outcome that sediment deposition – whether clastic or organic – leads to an increase in the longitudinal slope of the wetland. Given this, the gradual increase in slope associated with sediment deposition on a valley floor is likely to lead to a slope threshold being crossed and to eventual erosion.

A key feature of the accumulation of organic sediment is the creation of accommodation space by an elevated base level, as occurs in the Futululu tributary drainage line flowing into the Mfolozi Floodplain (Grenfell *et al.* 2010) and the similar Mdlanzi tributary drainage line flowing into the Mkuze Floodplain (Ellery *et al.* 2012). Both of these tributary streams have had accommodation space created by blockage of the tributary by the aggrading trunk Mfolozi and Mkuze floodplains respectively. Alternatively, deposition of sediment by tributary streams may block a trunk stream and create accommodation space for the

accumulation of organic sediment along the trunk stream, as happened in the Wakkerstroom Vlei (Joubert and Ellery 2013). A problem with the Tierkloof Wetland is that peat has accumulated despite there being no evidence of accommodation space being created by aggradation along the trunk Goukou valley, as indicated by process outlined above.

6.4 A conceptual model of the natural origin and evolution of the Tierkloof Wetland

It is clear from this study that valley-widening and planing of bedrock have taken place over a cross-sectional distance of tens to about 100 or 150 m in the Tierkloof wetland. There are no mechanisms yet proposed that explain how such valley widening may occur, although Job (2014) has proposed that alternating cycles of cutting (eroding) and filling (depositing) may be responsible.

It is proposed here that long term climate change may contribute to alternating episodes of cutting and filling in valleys with unchannelled valley bottom wetlands, such as the Tierkloof, as alluded to by Ellery *et al.* 2009. Figure 6-2 shows a simple summary of climate variability as revealed from the DOME-C ice core extracted from Antarctica by an international team of scientists (EPICA 2004). The deuterium concentration (δD) in precipitation is related to prevailing temperatures under which evaporation took place, such that the higher the concentration of deuterium, the higher the ambient temperature. Therefore, the δD is an indication of ambient temperatures in the southern hemisphere under which water was evaporated to produce precipitation. The dust concentration is a reflection of aridity in the southern continents, since greater amounts of atmospheric dust are generated during dry periods due to reduced vegetation cover in the southern hemisphere. The combination of δD and dust concentration in the DOME C ice core therefore provide an indication of prevailing temperature and rainfall in the southern hemisphere (at least), over the last approximately 800 000 years. These records depict prolonged periods of cooler climate conditions in the past (during glacial periods), interrupted by short warm periods approximately every 40 000 to 100 000 years (inter-glacial periods). High dust concentrations in the DOME C core indicate arid conditions dominating during the cool glacial maxima and

moist conditions during warm interglacial periods. The ice core indicates that the climate in the last 10 000 years has been unusually warm and moist.

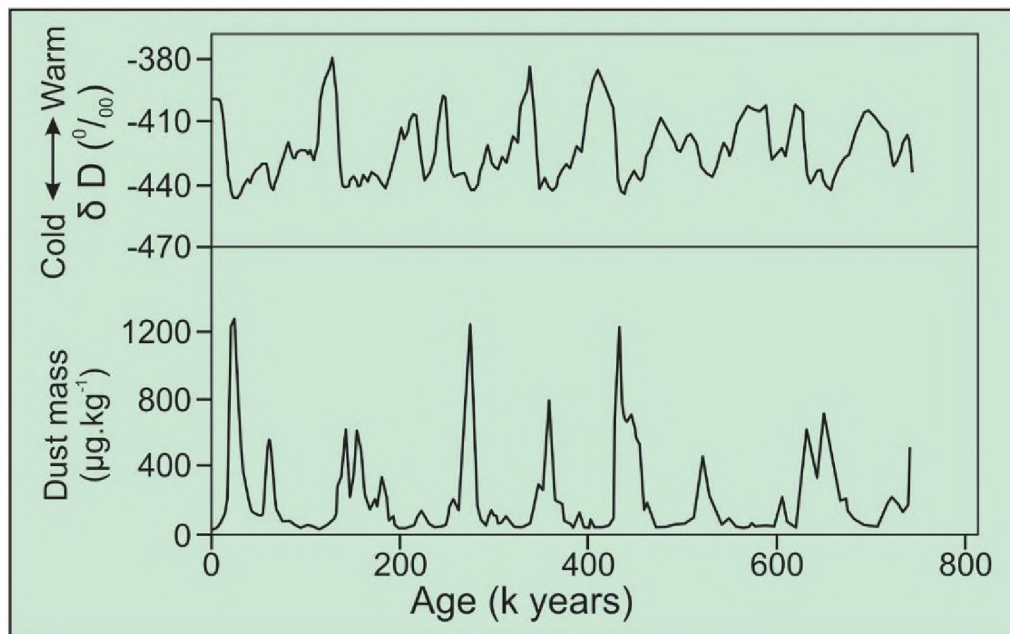


Figure 6-2: Graph showing the climate variability as revealed from the DOME-C ice core (EPICA 2004).

The dates in the core suggest that valley filling, largely through organic sediment accumulation, has taken place since the last glacial maximum. This is a period of abundant water supply that on the one hand leads to peat formation (Clymo 1983; Gorham *et al.* 2003; Grundling *et al.* 2013 [b]), but on the other may contribute to erosion due to high discharges (Ellery *et al.* 2009). Given the likely importance of groundwater discharge into wetlands from the Cape Fold Mountains (Job 2014), the discharges during wet phases of the climate history of the region may be attenuated by the slow passage of water through fractured rock such that the effect of high water releases is not as high as may be the case if the wetland was sustained directly by runoff. It is therefore proposed that peat formation takes place during wet and warm phases of the regions climate history.

Given high water availability but no obvious accommodation space having been created by aggradation along the Goukou River, it is proposed that palmiet takes hold of the valley during moist phases when an abundant water supply promotes palmiet growth. It has been recognised as an ecosystem engineer (Sieben 2012) and the mode of operation of this species

in promoting peat formation has been illuminated by Barclay (2016). Peat formation takes place as palmiet colonises a rocky stream bed when water supply is permanent or semi-permanent, and the form of the valley changes from rocky to a wetland with diffuse flow.

Palmiet is the dominant plant species of the Tierkloof Wetland. It has a deep rooting system that enables it to withstand large flood events and colonise rivers. The plant disperses flow and traps sediment, causing prolonged flooding. The prolonged flooding starves soils of the oxygen needed to decompose organic matter, which coupled with high plant productivity, leads to peat formation. Through this process a river can be transformed by palmiet into a valley bottom wetland with diffuse flow (Sieben 2012). This ability of palmiet to shape the valley and influence fluvial processes characterises it as an ecosystem engineer, as described by Jones *et al.* (2010). Furthermore, the Tierkloof wetland receives limited clastic sediment input from the quartzite rocks of the catchment, which is recognised as a prerequisite to peat formation (Ellery *et al.* 2012). It is therefore hypothesised that the warm and moist conditions associated with interglacial periods are associated with peat formation due to such conditions being favourable for palmiet establishment and growth.

A further factor to consider is the variable rainfall in the study area spatially and temporally. The fluctuating rainfall history of the Tierkloof tributary can be observed in the alternating presence of sand lenses that intersperse the peat soil profile. It is likely that wet cycles or high rainfall events lead to deposition of sandy lenses in the wetland where low energy conditions promote peat formation.

6.5 The role of anthropogenic factors

Despite appearing to be an aggradational phase in the geomorphic evolution of the Tierkloof Wetland, erosion has taken place over the last 25 years. This contradiction is probably explained by human activities such as construction of roads and drains that may have initiated erosion. A geomorphically vulnerable wetland may cross a threshold artificially and become an erosional system through anthropogenic activities in the catchment. Land uses that change the hydrological regime of a wetland, as well as sediment inputs to it, may reduce the resilience of a system. Natural events, such as high rainfall episodes, which formerly could be

absorbed by the system, result in erosion due to compromised resilience. Grenfell *et al.* (2009) suggested that the erosion within the Northington Wetland was likely accelerated by agricultural activities.

It is likely that this is also the case of the Tierkloof Wetland, which, being geomorphically vulnerable due to the steep slope, is more sensitive to human activities that increase or concentrate flow locally in the wetland. The Tierkloof shows evidence of cycles of cutting and filling, suggesting that erosion is part of the natural dynamic. However, the recent erosion of the Tierkloof seems to have been accelerated by the drain dug at the head of the wetland in 1991. The aerial photography indicates this large drain, and the increase in human land uses in the catchment, caused the erosion to begin at the head of the wetland. It is likely that this made the wetland especially vulnerable to the high rainfall events in the early 2000s, resulting in the initiation of a cutting cycle. The human manipulations of the Tierkloof system may have caused complete character and process change, forcing the system to an alternative developmental pathway than the one it followed naturally, a pathway on which the former natural dynamic cannot be reinstated (Ellery *et al.* 2009).

CHAPTER 7 – FUTURE RESEARCH

The Tierkloof Wetland is one of many peatland tributaries that join the Goukou Wetland. The Goukou Wetland is one of the last remaining intact peatlands of significant size in the Western Cape (Job 2014). For the future management of this catchment it is imperative to understand more about the relationship between these tributaries and the Goukou Wetland. Of particular importance is to develop an understanding of why some seemingly similar tributaries have not collapsed, and whether such a collapse is likely in the near future. Therefore, whilst expanding knowledge on the Tierkloof tributary, future research should also compare findings with the other tributaries in this reach of the Goukou Wetland catchment.

A further research area identified in this study is to improve our understanding of the role of palmiet in the evolution of these remarkable wetland systems. This is especially important in light of increasing human pressures that are threatening the integrity of these wetland systems.

A key area of research is to verify the dating obtained in this study, especially to determine whether the age of peat is uniform across the entire valley, or whether peat ages vary in response to alternating cycles of cutting and filling. This requires taking a series of cores across a palmiet wetland in order to determine the age structure of sedimentary deposits. If cutting and filling has taken place in the way proposed in this study, peat deposits of varying ages would be expected across the valley. This would reflect episodes of cutting and filling at different times in the history of the valley, which could lead to additional understanding regarding the cyclic collapse of this, as well as other, similar systems. Additionally, a more comprehensive investigation of stratigraphy across the width of the entire wetland could provide further insights into the local erosion and depositional processes.

An investigation of the hydrodynamics of discharges along a valley like the Tierkloof, in which the effect of valley cross-sectional and longitudinal morphology on hydrodynamic characteristics is also a key topic for further research. Studies should also provide more

insight into the formation of uncharacteristically flat bedrock in a V-shaped valley such as in the Tierkloof.

REFERENCES

- Alistoun, J. 2013. *The origin of endorheic pans on the African Erosion Surface north of Grahamstown, South Africa*. Masters Thesis submitted to Rhodes University, Grahamstown.
- Barclay, A. 2016. *Ecosystem engineering by the wetland plant palmiet: does it control fluvial form and promote diffuse flow in steep-sided valleys of the Cape Fold Mountains?* Masters Thesis submitted to Rhodes University, Grahamstown.
- Bragg, O.M. 2002. Hydrology of peat-forming wetlands in Scotland. *The Science of the Total Environment*, 294: 111-129.
- 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.
- CSIR. 2011. *Development of the Goukou estuarine management plan: Situation Assessment Report*. Version II. Report prepared for the C.A.P.E. Estuaries Programme, Stellenbosch.
- Clymo, R.S. 1983. Peat. In: Gore, A.J.P. (ed.), *Ecosystems of the world. Mires: Swamp, Bog, Fen and Moor*. Elsevier, Amsterdam, pp. 159-223.
- Darwall, W.R.T., Smith, K.G., Tweddle, D., and Skelton, P. 2009. *The Status and Distribution of Freshwater Biodiversity in Southern Africa*. Gland, Switzerland: IUCN and Grahamstown, South Africa: SAIAB.
- 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.

Dotterweich, M. 2008. The History of Soil Erosion and Fluvial Deposits in Small Catchments of Central Europe: Deciphering the Long-Term Interaction between Humans and the Environment - A Review. *Geomorphology*, 101: 192-208.

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

Edwards, R., Ellery, W.N., and Dunlevey, J. 2016. The role of the in situ weathering of dolerite on the formation of a peatland: The origin and evolution of Dartmoor Vlei in the KwaZulu-Natal Midlands, South Africa. *Catena*, 143: 232-243.

Ellery, W.N., Kotze, D.C., McCarthy, T.S., Tooth, S., Grenfell, M., Beckedahl, H., Quinn, N., and Ramsay L. 2004. *The Origin and Evolution of Wetlands*. Report submitted to the Water Research Commission Report: Pretoria, for publication.

Ellery, W.N., Grenfell, M., Grenfell, S., Kotze, D.C., McCarthy, T.S., Tooth, S., Grundling, P.L., Beckedahl, H., LeMaitre, D., and Ramsay, L. 2009. *WET-Origins: Controls on the distribution and dynamics of wetlands in South Africa*. WRC Report No. TT 334/08. Water Research Commission, Pretoria.

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.

EPICA. 2004. Eight glacial cycles from an Antarctic ice core. *Nature*. 429: 623-8.

Floyd, T.B. 1960. *Town planning in South Africa*. Shuter and Shooter, Pietermaritzburg.

Gorham, E., Janssens, J.A., and Glaser, F. H. 2003. Rates of peat accumulation during the postglacial period in 32 sites from Alaska to Newfoundland, with special emphasis on northern Minnesota. *Canadian Journal of Botany*, 81: 429-438.

Gosselink, J.G. and Turner, R.E. 1978. The role of hydrology in freshwater wetland ecosystems. In: Good, R.E., Whigham, D.F., and Simpson, R.L. (eds.), *Freshwater wetlands-Ecological processes and management potential*. Academic Press, New York, pp. 63-78.

Grenfell, M.C., Ellery, W.N. and Preston-Whyte, R.A. 2005. Wetlands as early warning (eco) systems for water resource management. *Water SA*, 31(4): 465-471.

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 M.C., Ellery W.N. and Grenfell S.E. 2009. Valley morphology and sediment cascades within a wetland system in the KwaZulu-Natal Drakensberg Foothills, Eastern South Africa. *Catena*, 78: 20-35.

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.

Grenfell, S.E., Rowntree, K.M., and Grenfell, M.C. 2012. Morphodynamics of a gully and floodout system in the Sneeu Berg Mountains of the semi-arid Karoo, South Africa: Implications for local landscape connectivity. *Catena*, 89: 8-21.

Grundling, A.T., van den Berg, E.C., and Price, J.S. 2013 (a). Assessing the distribution of wetlands over wet and dry periods and land-use change on the Maputaland Coastal Plain, north-eastern KwaZulu-Natal, South Africa. *South African Journal of Geomatics*, 2: 120-138.

Grundling, P., Grootjans, A.P., Price, J.S., and Ellery, W.N. 2013 (b). Development and persistence of an African mire: How the oldest South African fen has survived in a marginal climate. *Catena*, 110: 176-183.

Haddon, I. G. and McCarthy, T.S. 2005. The Mesozoic Cenozoic interior sag basins of Central Africa: The Late-Cretaceous Cenozoic Kalahari and Okavango basins. *Journal of African Earth Sciences*, 43(1): 316-333.

Heiri, O., Lotter, A.F., and Lemcke, G. 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *Journal of Paleolimnology*, 25: 101-110.

Hogg, A.G., Hua, Q., Blackwell, P.G., Niu, M., Buck, C.E., Guilderson, T.P., Heaton, T.J., Palmer, J.G., Reimer, P.J., Reimer, R.W., Turney, C.S.M. and Zimmerman, S.R.H. 2013. SHCal13 Southern Hemisphere calibration, 0- 50,000 years cal BP. *Radiocarbon*, 55(4): 1889–1903.

Job, R. 2014. *An investigation into the geomorphic origin and dynamics of deep, peat-filled, valley bottom wetlands dominated by palmiet (Prionium serratum) - a case study based on the Goukou Wetland, Southern Cape*. South Africa. Master's Thesis submitted to Rhodes University, Grahamstown.

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

Jones, C.G., Lawton, J.W., and Shachak, M. 1997. Positive and negative effects of organisms as physical ecosystem engineers. *Ecology*, 78(7): 1946-1957.

Jones, C.G., Gutiérrez, J.L., Byers, J.E., Crooks, J.A., Lambrinos, J.G., and Talley, T.S. 2010. A framework for understanding physical ecosystem engineering by organisms. *Oikos*, 119: 1862-1869.

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 Wakkerstroom Vlei, Mpumalanga Province, South Africa. *African Journal of Aquatic Science*, 38(2): 135-151.

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

Knighton, D. 1984. *Fluvial Forms and Processes*. Edward Arnold, London.

Kotze, D.C. and Breen, C.M. 1994. A management plan for Wakkerstroom Vlei. In: Ollermann, R.G., Darroch, M.A.G., Klug, J.R., and Kotze, D.C. (eds.). *Wetland preservation, valuation, and management practices applied to wetlands: South African case studies*, Water Research Commission Report No. 501/5/94. Water Research Commission: Pretoria.

Kotze, D.C., Marneweck, G.C., Batchelor, A.L., Lindley, D.S. and Collins, N.B. 2009 (a). *WET Ecoservices: A Technique for Rapidly Assessing Ecosystem Services Supplied by Wetlands*. WRC Report No. TT 339/08. Water Research Commission, Pretoria, South Africa.

Kotze, D.C., Ellery W.N., Rowntree, M., Grenfell, M., Marneweck, G.C., Nxele, I., Breen, C., Dini, J., Batchelor, A., and Sieben, E. 2009 (b). *WET-RehabPlan : guidelines for planning wetland rehabilitation in South Africa*. WRC Report No. TT 336/09. Water Research Commission, Pretoria, South Africa.

Leopold, L.B. and Bull, W. B. 1979. Base level, aggradation, and grade: Proc. Am. Philos. SOC, 123: 160-202.

Lewontin, R. C. 1978. 'Adaptation'. *Scientific American*, 239: 212-228.

Macfarlane, D.M., Kotze, D.C., Ellery, W.N., Walters, D., Koopman, V., Goodman, P., and Goge, C. 2007. *WET-Health: A technique for rapidly assessing wetland health*. WRC Report No TT 340/08. Water Research Commission, Pretoria.

Malan, J.A, Viljoen, J.H.A, Siegfried, H.P, and Wickens, H de V. 1994. *The Geology of the Cape Town Area, Department of mineral and Energy affairs, Geological Survey, Explanation of sheet 3420, scale 1:250 000*, Pretoria.

Maree, K.S. and Vromans, D.C. 2010. The Biodiversity Sector Plan for the Hessequa and Mossel Bay Municipalities: *Supporting land-use planning and decision-making in Critical Biodiversity Areas and Ecological Support Areas*. Produced by CapeNature as part of the C.A.P.E. Fine-scale Biodiversity Planning Project, Kirstenbosch.

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

McCarthy, T.S. 2006. Groundwater in the wetlands of the Okavango Delta, Botswana, and its contribution to the structure and function of the ecosystem. *Journal of Hydrology*, 320: 264-282.

McCarthy, T.S., Arnold, V., Venter, J., and Ellery, W.N. 2007. The collapse of Johannesburg's Klip River wetland. *South African Journal of Science*, 103(9-10): 391-397.

McCarthy, T.S., Tooth, S., Jacobs, Z., Rowberry, M.D., Thompson, M., Brandt, D., Hancox, P.J., Marren, P.M., Woodborne, S., and Ellery, W.N. 2011. The origin and development of the Nyl River floodplain wetland, Limpopo Province, South Africa: trunk-tributary river interactions in a dryland setting. *South African Geographical Journal*, 93(2): 172-190.

Meyer, P.S. 1999. *An Exploration of the 1:500000 General Hydrogeological Map, Oudtshoorn 3320*, Department of Water Affairs and Forestry, Pretoria, pp. 15-17.

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

Mucina, L. and Rutherford, M.C. 2006. *Vegetation Map of South Africa, Lesotho and Swaziland*. Strelitzia 18. South African National Biodiversity Institute, Pretoria.

Neal, M. 1998. *The hydrological impact of urbanisation: a case study of the Alfred Park Wetland, Pinetown, KwaZulu-Natal*. Unpublished Hons report. University of Natal.

Nel, J.L., Driver, A., Strydom, W. F., Maherry, A., Petersen, C., Hill, L., Roux, D.J., Nienaber, S., van Deventer, H., Swartz, E., and Smith-Adao, L.B. 2011. *Atlas of Freshwater Ecosystem Priority Areas in South Africa: Maps to support sustainable development of water resources*. WRC Report No. TT 500/11.

Nel, J.L. and Driver, A. 2012. *National Biodiversity Assessment 2011: Technical Report. Volume 2: Freshwater Component*. CSIR Report Number CSIR/NRE/ECO/IR/2012/0022/A, Council for Scientific and Industrial Research, Stellenbosch.

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

Pearce, T. 2011. Ecosystem engineering, experiment, and evolution. *Biology and Philosophy*, 26: 793-812.

Pence, G.Q.K., 2014. *Western Cape Biodiversity Framework 2014. Status Update: Critical Biodiversity Areas of the Western Cape*. Unpublished CapeNature report.

Pollard, S.R., du Toit, D., Cousins, T., Kotze, D., Riddell, E., Davis, C., Addey, S and Mkhabela, B. 2009. *Sustainability indicators in communal wetlands and their catchments: Lessons from Craigieburn wetland, Mpumalanga, Pretoria*. Water Research Commission, Pretoria.

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

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*, NS 4: 485-515.

Schumm, S.A. 2005. *River variability and complexity*. Cambridge. Cambridge University Press.

Sieben, E.J.J., Ellery, W.N., Kotze, D.C., and Rountree, M. 2011. Hierarchical spatial organization and prioritization of wetlands: a conceptual model for wetland rehabilitation in South Africa. *Wetlands Ecology & Management*, 19: 209-222.

Sieben, E.J.J. 2012. Plant functional composition and ecosystem properties: the case of peatlands in South Africa. *Plant Ecology*, 1007.

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.

Talma, A.S. and Vogel, J.C. 1993. A Simplified Approach to Calibrating C14 Dates. *Radiocarbon*, 35(2): 317-322.

Tooth, S., McCarthy T.S., Brandt D., Hancox P.J., and Morris R. 2002. Geological controls on the formation of alluvial meanders and floodplain wetlands: the example of the Klip River, eastern Free State, South Africa. *Earth Surface Processes and Landforms*, 27: 797-815.

Tooth, S., Brandt, D., Hancox, P.J., and McCarthy, T.S. 2004. Geological controls on alluvial river behavior: a comparative study of three rivers on the South African Highveld. *Journal of African and 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., Rodnight, H., McCarthy, T.S., Duller, G.A.T., and Grundling, A.T. 2009. Late Quaternary dynamics of a South African floodplain wetland and the implications for assessing recent human impacts. *Geomorphology*, 106: 278-291.

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

Tyson, P.D. 1986. *Climate Change and Variability in Southern Africa*. Oxford University Press: Cape Town.